INDOOR AIR QUALITY IN TIGHT HOUSES:

A LITERATURE REVIEW

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HOUSING CONSERVATION UNIT

ONTARIO MINISTRY OF MUNICIPAL AFFAIRS AND HOUSING

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INTRODUCTION

In order to reduce heating costs and increase comfort levels there has been a move towards building more tightly sealed houses and reducing air leakage in existing dwellings. This trend has raised questions regarding the possible adverse effects of lower ventilation rates on indoor air quality and on the health of occupants.

The salient question that needs to be answered would appear to be: how tight is too tight? Or how much air leakage can be eliminated without compromising health, safety and comfort? But the air in most homes already contains a host of chemicals that are present in low concentrations. Outdoor air pollution, combustion appliances, building materials, furnishings, and human activities such as smoking, all contribute noxious gases to the indoor environment. So a better question might be: how does air sealing affect indoor pollutant levels?

If there are existing indoor air quality problems, are these a result of inadequate ventilation or do the emission rates of the pollutants themselves play a more significant role? Perhaps pollutants simply accumulate in those areas of a house where there is poor circulation, creating local "hot spots."

We are exposed to a plethora of chemicals everyday in the food we eat, the water we drink and in the air we breathe; at work, outdoors and inside our homes. Perhaps current concerns over the quality of indoor air are simply a reaction to the effect of low levels of contaminants on a few hypersensitive people, or to some of the sensationalized media coverage the subject has received. Headlines such as: "Energy Conservers Nearly Lose Lives In Insulated House," "Homes So Airtight They Make People Sick" and "A Snug, Warm House May

Be A Health Hazard" don't instill a lot of confidence in the benefits of air sealing and other energy conservation measures.

Air sealing and controlled ventilation are strategies that are being used to improve air quality inside homes that have been insulated with urea formaldehyde insulation. Perhaps air sealing is part of the solution to other indoor air quality problems. For example, much of the radon gas that is found indoors, enters the house from outside.

The objectives of this literature review are to provide an overview of the existing body of knowledge on the effects of air sealing on indoor air quality, to identify the gaps in our knowledge and make suggestions regarding possible research efforts in the future. While it is recognized that other energy conservation activities, such as the installation of urea formaldehyde insulation, can affect the air quality in houses, an examination of these measures is beyond the scope of this paper.

Low ventilation rates can contribute to furnace backdrafting, particularly where fireplaces, exhaust fans and clothes dryers lack a sufficient supply of air, so that carbon monoxide and other noxious products of combustion are drawn down the furnace flue and into the house. This kind of acute indoor air quality problem will not be addressed in this paper. Rather, the emphasis will be on the build-up of contaminants which, over time, can lead to chronic health problems. The following papers provide a good overview of the air requirements of fuel burning appliances and the backdrafting problem:

B.C. Research. A Study of Residential Combustion-Air Requirements and Air Supplies, prepared for Gas Safety Branch, Ministry of Labour, British Columbia, 1983.

Hatch Associates Ltd. Hazardous Heating and Ventilation Conditions In Housing, prepared for Canada Mortgage and Housing Corporation, 1983.

Moffat, S. Evaluation Of A Residential Chimney Backdraft Checklist, under preparation for Canada Mortgage and Housing Corporation, 1984.

Part 1 of this review will briefly examine the nature and sources of contaminants found in indoor air, and their effects on human health and comfort. The levels or air pollutants that have been measured in conventional housing stock will be summarized, and the existing guidelines and standards for indoor air pollutants will be described.

The second section will review the methods of determining the airtightness of a house's structure and its air change rate. Empirical data on the airtightness and air change rates of conventional housing stock will be described. Case studies that assess the actual impact of air sealing on air leakage will be presented, along with the effects of lower air change rates on contaminant levels in both new and existing housing.

Finally, this paper will review the literature pertaining to those measures that can be taken to improve indoor air quality. The effectiveness and desirability of such remedial measures as reducing the source strength of pollutants, adding controlled mechanical ventilation and installing air cleaning equipment, will be described and evaluated.

An emphasis has been placed on incorporating Canadian literature into this review. To make this paper as relevant as possible, an issues-oriented format has been used.

PART 1: INDOOR AIR QUALITY IN CONVENTIONAL HOUSING STOCK

In order to assess the impact of air sealing measures on indoor air quality, it's necessary to characterize the quality of the air in conventional housing stock.

In his exhaustive review of the indoor air quality literature, Bruce Small (CMHC[a], 1983) concluded that indoor air pollution is, in fact, a problem in Canada. He reviewed hundreds of research reports which clearly established that indoor air is typically more polluted than outdoor air.

> Typical indoor air in most buildings is like a thin chemical soup. Most dwellings contain many air contaminants at relatively low concentrations, below present industrial and outdoor exposure limits. (However) these levels of exposure can pose a health problem at least for certain high-risk groups. The long term risk to the general population is unknown.
> (CMHC[a], 1983)

What follows is a brief summary of the nature of the contaminants, their sources, possible health effects, average and maximum levels of contaminants measured in the housing stock, and existing or proposed indoor standards.

1.1 NATURE OF THE CONTAMINANTS AND THEIR SOURCES

Indoor air contains trace amounts of hundreds of chemicals but few have been investigated with respect to home environments. The indoor air contaminants that have received most of the attention in the literature are those chemicals that have already created health problems, such as carbon monoxide and formaldehyde, and those that have been frequently measured at levels that exceed either existing outdoor standards or occupational exposure limits, such as carbon dioxide, the oxides of nitrogen and radon. The health effects that have been attributed to these chemicals range from feelings of uneasiness due to exposure to formaldehyde, to cancer induced by radon.

Table 1.1 summarizes the major sources of indoor air contaminants.

What follows is a brief summary of the nature of the contaminants that are currently recognized as being important, their sources, possible health effects, average and maximum levels measured in the housing stock, and existing or proposed standards (for quick reference, consult Table 1.2). This topic area has recently been reviewed in two comprehensive publications. Readers are encouraged to consult:

C.M.H.C. Indoor Air Pollution and Housing Technology. Prepared by Bruce Small and Associates, 1983.

National Research Council (U.S.) Committee on Indoor Pollutants. Indoor Pollutants. National Academy Press, Washington, D.C. 1981 NTIS Report PB82180563.

Table 1.1

Major Sources of Indoor Air Contaminants

SOURCES	MAJOR POLLUTANT TYPES
OUTDOOR	
Automobile Exhaust	Carbon Monoxide
Soil and Groundwater	Radon Gas - Radon Daughters
INDOOR	
Gas Ranges Kerosene Heaters Gas Clothes Dryers	Carbon Monoxide, Nitrogen Dioxide, Carbon Dioxide
Malfunctioning Fossil Fuel Furnaces	Carbon Monoxide, Nitrogen Dioxide
Wood Stoves, Fireplaces	Carbon Monoxide, Nitrogen Dioxide, Benzo(a)pyrene
Particleboard, Plywood	Formaldehyde
Furnishings	Formaldehyde
Urea Formaldehyde Foam Insulation	Formaldehyde
Concrete	Radon Gas - Radon Daughters

Table 1.1 (cont'd)

Tobacco Smoke	Carbon Monoxide, Nitrogen Dioxide, Benzo(a)pyrene, Formaldehyde
Human/Animal Metabolic Activity	Carbon Dioxide

1.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is a gaseous by-product of combustion and animal metabolism. The major outdoor sources of CO_2 are related to the combustion of fossil fuels and industrial processes. Significant indoor sources include humans, pets and unvented gas appliances such as ranges, clothes dryers and space heaters. High levels of CO_2 are generally found in the areas of a house where the occupants spend most of their time, and appears to be directly related to the occupant density (IEC Beak, 1983).

CO_2 reduces the flow of oxygen to the brain and can cause headaches, dizziness and nausea at high concentrations above 30,000 parts per million (ppm). In occupied houses, CO_2 concentrations range between 300 and 2,000 ppm (NRC (U.S.), 1981). The long-term health effects of exposure to moderate concentrations (1,000 - 5,000 ppm) of CO_2 are not well documented. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has stated that levels of indoor CO_2 should not exceed 2,500 ppm in residences. The Ontario Ministry of Labour uses an average 8 hour concentration of 600 ppm as its guideline for CO_2 in office buildings.

1.1.2 Carbon Monoxide

Carbon monoxide (CO) is a product of the incomplete combustion of fossil fuels. This occurs when insufficient oxygen is mixed with the fuel during combustion. The largest outdoor source of carbon monoxide is the automobile, followed by power plants and industrial processes (Gas Research Institute, 1981). Major indoor sources include cigarette smoking, gas ranges, malfunctioning gas-fired heating systems, unvented kerosene space heaters, fireplaces, misfiring oil furnaces, and idling cars in attached garages (Traynor et al, 1981). Unvented gas or kerosene space heaters appear to be the most significant indoor source of CO in the housing stock although gas ranges are the predominant source in houses that contain them (Sitwell, 1982).

CO combines with hemoglobin in the blood and inhibits oxygen uptake. Symptoms of CO poisoning include impaired vision, headache and nausea; coma and death can result at levels above 400 parts per million (ppm) depending on the duration of exposure and concentration of CO (Kent, 1979). As reported by Small (CMHC[a], 1983), CO levels above 35 ppm have been found, in some studies, to decrease the amount of oxygen taken up by the blood during exercise, resulting in a reduction in endurance. The long-term effects of exposure to CO are not well established, but studies of children whose mothers were heavy smokers during pregnancy, have found indications that these children lag a few months behind children of non-smokers in general reading and mathematical ability (Butler and Goldstein, 1973).

Indoor levels of CO can exceed 100 ppm in kitchens where unvented gas stoves are used (Sitwell, 1983). Sterling et al (1981) reported that indoor levels are between 6 and 7 ppm near medium-sized thoroughfares. Indoor levels of CO typically vary from 0.5 to 5 ppm as an average (Yocum et al, 1970). Outdoor levels in Toronto, for example, range between 10 and 50 ppm (Sitwell, 1983).

There are currently no residential indoor air standards for CO. The Ontario Ministry of Consumer and Commercial Relations (1981) review of air quality standards reports that the U.S. Navy has a 90 day average of 15 ppm as the allowable limit in submarine environments. Ontario has an eight hour average ambient air quality criteria of 13 ppm for outdoor air.

1.1.3 Oxides of Nitrogen

Nitric oxide (NO) and smaller amounts of nitrogen dioxide (NO_2) are produced during combustion. After mixing with air, the nitric oxide combines with oxygen to produce nitrogen dioxide. The principle outdoor sources are automobiles and industrial furnaces, while indoor sources include unvented fuel burning appliances such as gas ranges and kerosene space heaters, and tobacco smoking.

The short-term health effects of exposure to NO_2 include irritation of the mucous membranes of the respiratory tract, changes in sensory perception at levels as low as 0.1 ppm, and aggravation of respiratory illnesses at concentrations of 13 ppm or more (CMHC[a], 1983).

The long-term health effects of NO_2 have been the subject of vigorous debate. Melia et al (1977) (as reported in Hollowell and Traynor, 1978) found that children living in homes with gas cooking had significantly more respiratory illnesses than did children from homes where electric ranges were used. This study has been widely quoted in the literature as evidence of a link between exposure to NO_2 and respiratory ailments but as Young (Gas Research Institute, 1981) noted, the smoking habits of the parents and the room temperatures in the houses were not considered in Melia's analysis. Young also noted that the authors themselves felt their results were inconsistent and that any association between the indoor levels of NO_2 and the health of the children had been exaggerated and misinterpreted. There is no doubt that homes with gas ranges have higher levels of NO_2 than homes with electric ranges but the evidence of an association between respiratory illness and gas cooking remains inconclusive (Dockery, 1981).

In typical houses the indoor concentrations of NO_2 range from 100 to 530 parts per billion (ppb) with reported peaks of 900 ppb (CMHC[a], 1983). The Canadian Ambient Air Quality Standards for NO_2 are a one hour average of 0 to 20 ppb and a 24 hour average of 1 - 110 ppb. There are no standards for NO_2 in residential indoor air.

1.1.4 Benzo(a)pyrene

Benzo(a)pyrene (BaP) is a gaseous compound that is formed during the combustion of organic materials. BaP is just one of a number of polycyclic aromatic hydrocarbons (PAH) that result from combustion, but it is the most commonly measured compound from this group and is used as an indicator for the presence of these compounds. Wood burning and tobacco smoke are the major indoor sources of BaP, while unvented gas appliances and kerosene space heaters are less important sources. The most important outdoor sources of BaP include coal-fired industrial processes and electrical power plants. BaP, like many of the PAH compounds, is known to be a potent carcinogen. Some of the risk of developing lung cancer from smoking may come from exposure to BaP (Bonneville Power Administration, 1983).

BaP has been measured in urban locations at .002 micrograms per cubic metre (ug/m^3), at .002 to .004 ug/m^3 in a medium-sized room with three smoking occupants, and in a restaurant at levels ranging between 0.3 to 0.14 ug/m^3 (as reported in CMHC[a], 1983). There are no standards or guidelines for exposure to BaP.

BaP readily attaches itself to particulates which are also a by-product of combustion. Particulates are either classified as respirable suspended particulates (RSP) or total suspended particulates (TSP). Respirable suspended particulates are thought to be more damaging to the lungs than TSP because they are small enough to become trapped in the lungs. There are no standards for RSP. The U. S. Environmental Protection Agency's standard for maximum allowable levels of TSP in outdoor air is 75 ug/m^3 on an annual basis (time-averaged) and 240 ug/m^3 for a single 24-hour period (NRC, 1981).

1.1.5 Formaldehyde

Formaldehyde (HCHO) is a colourless gas with a pungent odour. It is commonly used in the manufacture of urea formaldehyde resins which are used as adhesives in particleboard, plywood, carpet backing, furnishings, and are major components of urea formaldehyde foam insulation (UFFI). These materials release the gas into the air at a variable rate, depending on their age, surrounding humidity and temperature. It has been reported that the rate of formaldehyde released from most materials decreases by 50 percent within five years of their manufacture (NRC (U.S.), 1981). Formaldehyde is also a by-product of combustion, with gas stoves and tobacco smoking as the major indoor sources.

Eye, nose and throat irritation, coughing and asthma-like symptoms, headaches, dizziness, nausea, vomiting, and nose bleeds have all been reported by people living in houses with elevated formaldehyde levels (Chown, 1981). Most of the known short-term health effects related to formaldehyde exposure are transitory in nature and disappear when the pollutant is eliminated, however, repeated or long-term exposure may increase a person's sensitivity to the gas, and to allergens such as dust. Chronic exposure to formaldehyde may cause changes in the structure and performance of the respiratory system (Bonneville Power

Administration, 1983). Formaldehyde is a suspected carcinogen since animal studies have shown that it can produce nasal cancer.

Average indoor levels of formaldehyde in homes with UFFI or a significant amount of particleboard, range from 0.01 ppm to 1.0 ppm. This is the range in which health effects have occurred (NRC (U.S.), 1981). Most people can smell formaldehyde gas at concentrations of less than 1.0 ppm. Canada, Norway, Denmark and West Germany have established 0.1 ppm as the acceptable level of formaldehyde in residential indoor air while Sweden and Czechoslovakia have set a standard of 0.08 ppm (CMHC[a], 1983 and Consumer and Commercial Relations, 1981).

For a comprehensive review of the literature pertaining to formaldehyde and other organic (carbon-containing) compounds that can have adverse health effects in indoor environments see:

> Lepman, S.R., Miksch, R.R., Hollowell, C.D. Organic Contaminants: A Bibliography. Lawrence Berkeley Laboratory, LBL-12199, 1981.

1.1.6 Radon

Radon is a radioactive gas that is released by the decay of radium, which itself is a decay product of uranium. Radium is a naturally occurring trace element found in soil, rock and groundwater, and to a lesser extent, in building materials such as concrete and brick. Radon gas enters houses by diffusing through the basement floor slab and foundation walls, by leaking through cracks in the basement, around loose fitting pipes and floor drains, and via tap water taken from wells (Budnitz, 1979). Radon can also be released by radium-containing building materials.

Radon gas in itself doesn't pose a significant health threat but its decay products, or radon daughters, can cause lung cancer. Radon gas has four daughters, which can attach themselves to dust or other airborne particles. When inhaled, these particles may become trapped in the lung, irradiating the surrounding tissue (Budnitz, 1979). Since radon gas usually enters the house from outdoors, a careful sealing job in the basement should reduce the flow of radon into the house. Also because radon daughters readily attach themselves to dust particles, electrostatic air cleaners or particle filters could be effective in reducing the concentrations of radon daughters.

Harley (1980) suggests that the lung cancer which appears to be spontaneously induced (not related to smoking or known carcinogens in the work environment) may be the result of exposure to radon daughters in the environment. He developed a model which predicts an upper limit of 30 to 60 lung cancers per year per million persons resulting from exposure to radon. The Bonneville Power Administration (1983) has estimated that between 22 and 257 radon-induced lung cancers occur in the Pacific Northwest (Washington, Oregon, western Montana) each year.

Concentrations of radon gas are conventionally expressed in pico-Curies per litre of air (pCi/L). (The Curie is a measure of radio-activity and pico is simply a prefix meaning one trillionth.) Radon daughter concentrations are expressed in working levels (WL), a unit designed to indicate the relative health hazard of the radon daughters. The concentration of radon gas in a house is not a good indication of the health hazard associated with its daughters.

McGregor (1980) measured the concentrations of radon gas and radon daughters in the basements of 9,999 homes in 14 Canadian cities. Approximately 64 percent of all homes measured had radon gas concentrations of 1 pCi/L or less and about 95 percent had radon daughter concentrations of 0.2 WL or less. The highest concentration of radon gas was 75 pCi/L in St. Lawrence, Newfoundland and the highest concentration of radon daughters was 0.233 WL in Sherbrooke, Quebec. Of the 14 cities sampled, Sudbury had the highest average level of radon daughters, with Thunder Bay ranking fourth and Toronto in seventh position.

The Atomic Energy Control Board (AECB) and the Ontario Ministry of Labour have adopted an average annual concentration of 0.02 WL as the level above which remedial measures must be taken in housing in uranium mining and processing communities (Primary Criterion). AECB has also adopted two single measurement criteria: 0.15 WL to identify houses that require immediate attention and 0.01 WL to identify houses that warrant further investigation. Based on an "equilibrium factor" that was selected by AECB, the corresponding concentrations of radon gas are 7 pCi/L, 50 pCi/L and 3 pCi/L (IEC Beak, 1983). Most of the literature assumes a range of 3 to 6 pCi/L corresponds to 0.02 WL, depending on the source strength of the radon and the household rate of air change that were assumed.

For a comprehensive review of the radon literature see:

Lepman, S.R., Doegel, M.L., Hollowell, C.D. Radon: A Bibliography, Lawrence Berkeley Laboratory, LBL 12200, 1981.

Table 1.2

Standard, Reported Data and Typical Sources

Contaminant	Outdoor Standards		Reported Outdoor Levels			Indoor Guidelines		Reported Indoor Level		Typical Sources
	Time Span	Level (ppm)	Time Span	Range (ppm)	Average (ppm)	Time Span	Level (ppm)	Range (ppm)	Maximum (ppm)	
	Canada					ACGIH				
Carbon Monoxide	-8 hour	5.5-14	Annual	0.8-3.2	1.7	-8 hour	50	0.05-5	100	Unvented kerosene heater gas ranges, automobiles, tobacco smoking, mal-functioning furnaces
	-1 hour	14-32						Kitchens		
			8 hour	0-17	NA	-STEL	400	34.5-120	-	
	U.S.									
	-8 hour	9	1 hour	0-31	NA					
	-1 hour	25								
						ACGIH		1 hour		
Carbon Dioxide	NA	NA	1 hour	NA	400	-8 hour	5000	0-3000	NA	Human metabolic activity unvented fuel burning appliances
						STEL	15000			
						ASHRAE	2500			
						MOL (8hr)	600			
Nitric Oxide	NA	NA	NA	NA	0.002	ACGIH		1 hour		
						-8 hour	25	-.03-0.3	0.5	Unvented fuel burning appliances, tobacco smoking, automobile exhaust
						-STEL	35			
	Canada									
Nitrogen Dioxide	-Annual	0.032	Annual	0.01-0.0	0.026	-8 hour	3.0	0.1-0.53		
	-24 hour	0.110	-24 hour	NA	0.011	-STEL	5.0	0.05-0.5 (1hr)	0.9	
	-1 hour	0.220	-1 hour	NA	0.530					
						UFFI/ICC				
Formaldehyde	NA	NA	-2 hour	0.01-0.05	NA	-7 day	0.05	0.02-0.4	0.4	Urea Formaldehyde Foam Insulation, particle-board, plywood, furnishings
						Health & Welfare	0.1			
						ACGIH (8 hr)	2.0			
Radon	NA	NA	-30 days	0.01-1.0 pCi/L		-Annual AECB	0.02WL (3-6pCi/L)	0.1-1140 pCi/L	?	Soil, rock, groundwater
						-Single Measure	0.15WL-Prompt Action (50 pCi/L 0.01WL-Investigate (3 pCi/L)			

ACGIH - American Conference of Governmental Industrial Hygienists
STEL - Short Term Exposure Limit - 15 minutes maximum
ASHRAE - American Society of Heating, Refrigeration & Air Conditioning Engineers
MOL - Ontario Ministry of Labour
UFFI/ICC - Urea Formaldehyde Foam Insulation/Information-Coordination Centre
AECB - Atomic Energy Control Board

(Ontario Ministry of Municipal Affairs and Housing, 1983)

1.2 HEALTH EFFECTS OF LOW LEVEL EXPOSURE TO INDOOR AIR CONTAMINANTS

One of the objectives of Small's review of the indoor air quality literature for CMHC (CMHC[a], 1983) was to comment on the significance of the indoor air pollution problem in Canada. While he concluded that a problem existed, he found that there was not enough information available to know the extent of health damage associated with indoor air pollution.

The technology is readily available to measure the concentration of contaminants in indoor air but little is known about the emission rates of indoor pollutant sources, the rate of diffusion of the pollutants through the home, the actual contaminant concentrations that the occupants ingest, the sensitivity of different occupants, and the long-term health effects of extended exposure to low concentrations of pollutants.

There is a significant body of knowledge surrounding the risk of health effects of exposure to high levels of some of the contaminants commonly found in indoor air, and this has been used to estimate risk at lower concentrations. For example in one study, the Bonneville Power Administration in the U.S. (BPA, 1983) used occupational health data for exposure to radon, formaldehyde and Benzo(a)pyrene, in an attempt to estimate the health effects of exposure to lower concentrations of these chemicals. This was done through a downward linear extrapolation from known risks at high levels of exposure, to lower levels of exposure. It was assumed that there was no threshold below which health was not threatened and that the level of risk decreased in direct proportion to the decrease in concentration of contaminants. Residences were assumed to have a range of pollutant emission rates, volumes, and air exchange rates. On this basis it was estimated that between 1 and 18 formaldehyde-induced cancers, between 22 and 257 radon-induced cancers and 9 to 487 BaP-induced cancers occur in the Pacific Northwest of the U.S. (pop. 3.3 million) each year due to exposure in the home.

The Bonneville Power Administration notes in its report that these estimates are highly speculative because of the high degree of uncertainty in the technique used for assessing the risk. The assessment of health risk is extrapolated from occupational study groups which primarily include healthy adult males who may also be exposed to high levels of other pollutants in their work environments.

In a 1979 report to the Canadian Environmental Advisory Council, Ross Hall and Donald Chant examined some of the current limits to our knowledge of the health effects of chemicals (Hall and Chant, 1979). Toxicology conventionally deals with chemical contamination by studying a single chemical at a time, by establishing acute short-term effects, under carefully controlled laboratory conditions, with relatively high levels of substances. However the reality of chemical contamination is that humans are exposed to thousands of chemicals in their food, water and air, often at very low levels, under widely variable conditions.

It has been estimated by the U.S. Environmental Protection Agency that there are approximately 63,000 commercial chemicals in use, most of which didn't exist 25 years ago (Maugh, 1978). Paints, sealants, household fabric and furnishings contain a host of chemical additives, and the use of glue-laden particleboard and plywood in building materials and furnishings is now commonplace. This trend has contributed to a higher likelihood of increased indoor air pollution levels in houses today (CMHC[a], 1983).

Since it's difficult to quantify the risks associated with exposure to low levels of those contaminants whose health effects are known and impossible to identify the long-term health effects of other contaminants given the current state of toxicology, there is no adequate yardstick that can be used to set indoor air pollution standards or guidelines that would establish acceptably "safe" levels of contaminants. However, much of the air quality literature relies heavily on "acceptable levels" of a few standard indoor air pollutants as proof that there is or is not an indoor air quality problem.

1.3 INDOOR AIR QUALITY STANDARDS AND GUIDELINES

In 1981 the Ontario Ministry of Consumer and Commercial Relations undertook a survey of existing indoor air quality standards.

> Consumer and Commercial Relations Indoor Air Quality Standards Literature Survey, Report No. 1184/1154. DSMA ATCON LTD., 1981.

Its review surveyed ambient (outdoor) air, occupation and residential indoor air quality standards in Canada, the U.S. and other countries for a variety of contaminants including nitrogen dioxide, carbon monoxide, carbon dioxide, formaldehyde and radon daughters (see Appendix A for a summary). The review found that specific residential indoor air guidelines and standards exist only for formaldehyde and radon daughters.

The report cautions against applying occupational standards set for the workplace to the residential environment. Occupational standards permit higher levels of contaminants than ambient standards because they are primarily concerned with immediate health of the workers. These standards assume a uniformly healthy, adult population, working at a moderate rate, that is exposed to the pollutants in question for only 8 to 10 hours a day, five days a week. Some occupational standards also take into account the short-term releases of contaminants that routinely occur in some work environments. In the residential environment, the population includes the very young, the elderly, people in poor health, people who are sensitized (individuals who react to contaminants at levels far below the general population), and those who suffer from allergies. The exposure time to residential indoor air pollutants may be 24 hours a day, all year long.

It is suggested in the review that the U.S. Navy's standards for submarine environments might have some relevance to residential environments, since submarines could be compared to very tight houses with low ventilation rates. This comparison, however, has a number of pitfalls. Submarines lack many of the pollutant sources commonly found in homes, the submariners are not particularly representative of the general population, and when submarines are submerged, the occupants breathe recirculated air.

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) usually recommends that acceptable levels of contaminants in the residential environment should be one-tenth the standard or Threshold Level Value (TLV) set for the workplace (ASHRAE 62-81). It is assumed, quite arbitrarily, that the population in residential environments is 10 times as susceptible to health effects from exposure to indoor air contaminants, as the population in the workplace, because the general population may be continually exposed to chemicals in the home environment on a 24 hour basis and it is characterized by a greater variation in age and in health status.

ASHRAE Standard 62-81 is currently under review and it's expected that there will be significant revisions to the acceptable levels of indoor air contaminants that it promulgates.

1.3.1 Federal Provincial Working Group on Indoor Air Quality

In 1981 the provincial Deputy Ministers of Health from across the country approved a recommendation by the Federal Provincial Advisory

Committee on Environmental and Occupational Health to establish a Federal Provincial Working Group on Indoor Air Quality with the following objectives:

1. To develop guidelines for concentrations of selected contaminants of residential indoor air, taking into account such factors as sensitivity of groups at special risk and the sources and mechanisms of action of the contaminants.

2. To develop guidelines for ventilation requirements for domestic premises that reflect the indoor air quality guidelines in order to preserve and improve air environments.

(Armstrong, 1983)

At the time of writing, the working group has identified twelve types of contaminants that, in its opinion, warrant priority consideration. These include:

Carbon Monoxide	Nitrogen Dioxide
Formaldehyde	Aldehydes
Carbon Dioxide	Moisture
Oxides of Sulphur	Ozone
Particulates	Polycyclic Aromatic Hydrocarbons
Radon and Radon Daughters	Microbiological Hazards.

Criteria reviews to support guidelines for exposure limits are currently being prepared by the staff of Health and Welfare Canada's Bureau of Chemical Hazards.

In light of the significant gaps in our knowledge about the health effects of exposure to the low levels of contaminants found in indoor air, it may be impossible to set meaningful standards in the near future. If there is no real threshold level below which there are no health effects, as most researchers agree is the case with carcinogenic chemicals, it is impossible to establish "safe" levels of exposure. The best approach may be for people to simply minimize their exposure to environmental contaminants where possible. This could be facilitated in the indoor environment by standards that are directed at the major pollutant sources, to restrict the rate at which they emit contaminants.

1.4 SUMMARY

Air in the residential environment contains a variety of chemicals including some proven and suspected carcinogens. Some of these contaminants, such as radon, enter the house from outside the building; others, such as benzo(a)pyrene and formaldehyde, are generated indoors by combustion or are "off-gassed" by building materials and furnishings; while pollutants such as tobacco smoke are added to the air by occupants.

There are significant gaps in our knowledge about the long-term health effects of relatively continuous exposure to low levels of chemicals. The traditional methods for determining the health effects of chemicals, and consequently "safe" levels, are limited to identifying the effects of large concentrations of a single chemical on laboratory animals and extrapolating from the incidence of health problems in the workplace where the population is exposed to relatively high levels of contaminants. Serious questions have been raised about the validity of these techniques for establishing the risk of chemically-induced health problems in the general population at low levels of exposure.

Until more is known about the risks associated with long-term exposure to low levels of indoor air pollutants, meaningful residential indoor air quality standards cannot be formulated. "Safe" levels of exposure, a concentration below which no health effects occur, may not even exist for many chemicals. Often situations where health problems have been associated with exposure to indoor air pollutants have involved complex mixes of gases and particles, all at levels well below the accepted standards or guidelines. Yet,there is still a heavy reliance on "acceptable levels" of pollutants as proof that there is or is not an indoor air quality problem. Until more is known about the risks associated with exposure to low levels of chemicals, the only recourse for people at this time is to minimize their exposure to chemical contaminants wherever possible.

Smoking can be eliminated from the indoor environment, unvented and poorly maintained combustion equipment can be avoided, and building materials and furnishings can be selected to avoid pollution.

The second part of this report will examine the impact of air sealing measures, such as caulking and weatherstripping, on the levels of contaminants in indoor air.

PART 2: IMPACT OF AIR SEALING ON INDOOR AIR QUALITY

In an effort to reduce home heating bills and make the indoors more comfortable in the winter, people have been tightening their houses to reduce the uncontrolled air leakage that occurs through the cracks and holes in the building envelope. This also prevents water vapour, generated indoors, from being carried into the walls or ceiling by exfiltrating air where it can condense and reduce the effectiveness of insulation, and create conditions where dry rot (a fungus that feeds on wood) can thrive. Air sealing has also been used as a measure to improve indoor air quality by preventing contaminants, such as formaldehyde, from leaking into a house's living space.

Airtightening activities may be restricted to caulking and weatherstripping in existing homes, or may include the installation of a continuous plastic air barrier on the warm side of insulated wall and ceiling cavities during renovations or new construction. Both measures can result in less ventilation, elevated levels of indoor humidity, and presumably, higher levels of those pollutants that originate from inside the house and lower concentrations of those contaminants that originate outside the living space.

The first part of this paper pointed out that while there exists an indoor air quality problem in Canada, it's impossible to determine the extent of the associated health problems. Part 2 presents literature that has examined the extent to which air sealing and reduced rates of ventilation aggravate the indoor air quality problem. The present range of ventilation rates in new and existing buildings is surveyed, and case studies that have evaluated effects of various energy conservation measures on ventilation rates and air quality are presented.

2.1 SOURCES OF UNCONTROLLED AIR LEAKAGE

> Although the importance of air tightness has been stressed for the past 25 years in the technical literature dealing with the design of building enclosures, we still construct buildings that provide their owners with excessive energy costs, that make the occupants uncomfortable because of drafts and the infiltration of contaminated air, and that suffer from problems of condensation and the deterioration of their components and materials, which require high costs for repair and maintenance. Air tightness, accordingly, should be the primary objective in the design and construction of walls, windows, floors and roofs of buildings.
>
> (National Research Council, 1980)

The significant heat loss and condensation problems associated with uncontrolled air leakage have only generally been recognized outside the building sciences community since 1979. Consequently many homeowners and insulating contractors are still unfamiliar with the various sources of air leakage in a house.

Between 20 and 50 percent of the heat loss in typical housing can be attributed to the uncontrolled leakage of air through the building's shell (Caffey, 1979, Offerman, 1982 and EMR, 1983). Tamura (1975) tested six homes, built in Ottawa in the 1950's, to determine their air leakage characteristics. His results revealed a tremendous variation in the importance of various sources of air leakage. Air leakage through the ceilings accounted for 8 to 67 percent of the total, penetrations through walls contributed 15 to 77 percent, windows and doors accounted for 15 to 23 percent and fireplaces were responsible for 3 to 4 percent of the total air leakage in the houses. Clearly there is no "typical" house with respect to the importance of various air leakage points in a building. The Energy, Mines and Resources air sealing handbook (EMR, 1983) stresses that the relative importance of the various leakage openings in a house will vary with its design, age, quality of construction and component materials. Table 2.1 lists the locations of openings that can play a significant role in contributing to the overall air leakage in a house.

It has been suggested that there are significant differences between pre-war and post-war houses with respect to the distribution of air leakage (Moffat, 1984). As an example, Moffat suggests that in a pre-war house: 30 percent of the air leakage occurs around the sill plate, floor joist, ducts, pipes and wires in the basement; 30 percent of the leakage occurs through the attic around plumbing, wiring, partition walls and chimney flues; a further 20 percent through the walls, through cracks in the plaster, around electrical outlets, baseboard trim, window and door trim and vents; and the remaining 20 percent is accounted for by windows and doors.

In a post-war house, 20 percent of the air leakage may occur through the electrical outlets alone; 25 percent might be accounted for by the wall sill plate; 40 percent through the attic and 15 percent through windows and doors.

Table 2.1

Typical Locations of Air Leakage Points

WALLS:
- Switch Covers
- Outlet Covers
- Baseboards
- Wall Cracks
- Fireplace/Wall Joint
- TV Cable
- Bathtub/Shower
- Medicine Cabinet
- Exhaust Fans
- Plumbing Penetrations
- Dryer Vent
- Service Entrances
- Wiring to Outside Outlets
- Top of Foundation Wall

MISCELLANEOUS:
- Fireplace Damper
- Stair Risers
- Basement Floor Drains
- Floors Over Unheated Spaces

WINDOWS:
- Sashes
- Frames
- Moulding
- Weatherstripping

EXTERIOR DOORS:
- Frames
- Moulding
- Weatherstripping
- Leaks Through Doors

CEILINGS:
- Attic Hatch
- Chimney
- Ceiling Fixtures
- Partition Walls
- Exterior Walls
- Plumbing Stack
- Wiring
- Ducts
- Exhaust Fans
- Ceiling Cracks
- Dropped Ceiling

(Energy, Mines and Resources Canada, 1983)

2.1.1 Measuring Airtightness

A method to determine the airtightness of a building, that is the degree to which unintentional openings in the building structure have been avoided, was developed by researchers at the National Research Council of Canada's Division of Building Research.

Orr, H.W. and Figley, D.W. An Exhaust Fan Apparatus For Assessing the Air Leakage Characteristics of Houses. Building Research Note #156, National Research Council of Canada, 1980.

A large fan, temporarily installed into an outside door opening, is used to exhaust air from a building to create pressure differences across the building envelope. The rate at which air is exhausted by the fan is measured for a series of pressure differences and an analysis of the relationship between these two parameters provides a measure of what's called the equivalent leakage area (ELA). Often expressed in square centimetres (cm^2), the ELA represents the total area of all the unintentional openings in the building envelope.

This fan depressurization test is an inexpensive, fast and straightforward technique for rating the airtightness of buildings. The Canadian General Standards Board (CGSB) has established a standard procedure for testing homes with the fan or "blower door."

Canadian General Standards Board. Determination of Airtightness of Buildings by the Fan Depressurization Method, Standard #149-GP-10M, 1983.

To compare the relative airtightness of two houses, the ELA for each house is simply normalized by dividing by the total above ground surface areas of the respective building envelopes. This is referred to as the normalized ELA or specific leakage area (SLA) and expressed as cm^2/m^2.

Airtightness tests are not always presented in a standardized fashion in the literature. At times the ELA or rate of air flow through the fan is presented with no accounting for house size. If the ELA's are normalized, the volume or even floor area of the houses is sometimes used, instead of the surface area of the above ground building envelope. To complicate matters further, the CGSB standard is new, so fan test results in the literature have not all been obtained under similar test conditions. These inconsistencies can make it difficult to compare the results obtained by different researchers.

The major limitation of the fan depressurization test is that it provides no information about air change. Houses exposed to identical conditions, with the same SLA may experience quite different air change rates depending on the location and distribution of the air leakage points.

2.2 AIRTIGHTNESS AND NATURAL VENTILATION

In order to assess the impact of air sealing on indoor air quality, the ventilation rate of a house must be quantifiable. Determining this rate of air change is not as straightforward as might be expected.

The amount of ventilation in a house is dependent on the rate at which air flows through the accidental gaps and holes in the house shell. This rate of air exchange is dependent on wind speed and direction, the difference in temperature between indoors and outdoors, the frequency of exhaust fan and furnace operation, and the window and door opening habits of occupants. The influence of wind on air change is dependent on the shape of the building, the location and size of surrounding buildings and vegetation, the local terrain, the size and distribution of the air leakage points around the house; as well as on wind speed and direction.

The temperature difference between indoors and outdoors creates a stack effect in houses where heated air rises up through the house, leaking outside through cracks and gaps in the upper part of the house.

This creates a negative pressure in the lower part of the house so cold outside air flows into the building to replace the exhausting heated air. The greater the temperature difference and the taller the building, the stronger the stack effect (NRC, 1980).

The number of variables that influence household ventilation rates make it difficult to draw an accurate picture of a house's rate of air change. Ventilation rates will vary over the course of a year, over the course of a heating season, and even over the course of a day. Conventional techniques for assessing air change measure only what is happening at the time of the test and don't give any indication of how this changes over time. In order to analyze the relationship between ventilation rates and indoor air quality, any testing of contaminant concentrations must be done in conjunction with an assessment of the rate of air exchange.

2.2.1 Measuring Air Change

The rate of air change in houses is usually determined by mixing a tracer gas, such as sulphur hexafluoride (SF_6), with the house air and monitoring the rate at which its concentration changes. Theoretically the SF_6 serves as a tag for the indoor air so that the rate at which its concentration changes mimics the rate of air change in the house. Historically there have been three basic approaches to using tracer gases for determining air change rates. They are:

> Decay Method (Dilution Method) - a known amount of tracer gas is injected into the air of a building and distributed by the furnace fan or by fans temporarily placed around the house for that purpose. The decay in concentration of the gas is then measured as a function of time.
>
> Constant Flow Method - the tracer gas is injected continuously at a specified rate and its decay is measured as a function of time.

Constant Concentration Method - air infiltration rate is determined by measuring the rate at which the tracer gas has to be injected into the air of each room to maintain a constant concentration of gas in the air.

There are two useful reviews of these techniques:

Harrje, D.T., Grot, R.A., and Grimsrud, D.T. Air Infiltration Site Measurement Techniques. Proceedings of the 2nd Air Infiltration Centre Conference, Building Design for Minimum Air Infiltration, Stockholm, Sweden. Paper 10, p. 115, 1981.

Sherman, M.H. Air Infiltration in Buildings. Lawrence Berkeley Laboratory, Report LBL-10712, 1980.

The constant flow technique is costly, cannot run unattended and has had little application in residential buildings (Sherman, 1980). The constant concentration method (Orr, 1963) is useful for long-term unattended measurements but the technique for controlling the flow of the tracer gas and the measuring apparatus are complicated (Kumar, 1979). In fact the major drawback to this technique is that it's virtually impossible to maintain a constant concentration of tracer gas in a house (Harrje, 1981).

The decay method of tracer gas analysis has been the most popular approach to measuring air change rates because it is the least expensive and simplest of the three approaches. However it can only determine the air change rate that exists during the 45 minutes to an hour that the test takes, which as discussed in Section 4.1, may have little relevance to the "average" air change rate in the house. Serious doubts have also been raised about the reliability of the test method itself.

The SF_6 tracer gas decay technique was used to determine the air change rates in 35 houses in the Ottawa area (Cogeneration Associates, 1983). Four sets of air change tests were conducted to coincide with the four seasons, however there was no clear correlation between the measured air change rates and the measured wind speed and temperature difference between indoors and outdoors. While the overall average results reflected a tendency for changes in wind conditions and stack effect to coincide with the changes in air change, the results from many of the individual houses did not indicate any such relationship, calling into question the reliability of the testing technique.

Tracer gas analysis assumes that there is perfect mixing of the gas with the air throughout the building. SF_6 is denser than air so it has a tendency to sink and accumulate in the basement area. This stratification of SF_6 may be compounded by the inadequacy of household air circulation. Rooms at the ends of heating duct lines, the absence of cold air returns and unbalanced registers may help isolate sections of the house (Cogeneration Associates, 1983).

The furnace fan is usually used to distribute the tracer gas around the house, but operating the fan can increase the level of air change when the furnace is in a leaky furnace room or when fresh air intakes are present.

A new time-averaged technique for determining natural rates of air change that uses perfluorocarbon tracer gas sources (PFT) and passive samples (cappillary absorption tube complex - CAT) may be the most promising approach (Moffat, 1984). The PFT's emit perfluorocarbon at a known rate over a long period of time, and the CAT's absorb the gas at a rate proportional to its concentration. The average concentration of tracer gas is determined by a laboratory analysis of the CAT's and this is compared to the known emission rates of the PFT's. This time-average air change test determines the average air change rate of a house over a period of two weeks to two months, under typical operating conditions. The technique is not sensitive to sudden or short-term changes in air change so the results may be as representative of the "typical" air change rate as possible.

To overcome the problems associated with conventional tracer gas analysis, researchers have been attempting to develop a mathematical model of air change that would use the results of a fan depressurization test to predict the natural rate of air change.

2.2.2 Correlating Airtightness with Air Change Rates

To use the data from fan depressurization tests in a mathematical model to predict air change rates, information about the site location, building details and weather data are necessary and must be quantifiable. Such theoretical models have to account for wind speed and direction, and the nature of the terrain, shape of the building, size, shape and location of surrounding buildings and vegetation, and the temperature difference between inside and outside, the size and distribution of points of air leakage throughout the house, the height of the building, the location of the neutral plane (where air neither moves in or out of openings in the building envelope), and the frequency of operation of exhausting devices, including vented heating systems. Creating a mathematical model to account for all these variables is a complicated task, but numerous models have been developed to predict air change rates from fan tests.

Wilson (1983) suggests that there are as many models as there are investigators, but recent work tends to break down into two basic models:

Shaw, C.Y. A Correlation Between Air Infiltration and Air Tightness for Houses in a Developed Residential Area. ASHRAE Transactions, V. 87, Pt. 2, 1981.

Sherman, M.H., Grimsrud, D.T. Measurement of Infiltration Using Fan Depressurization and Weather Data. Lawrence Berkeley Laboratory, LBL-10852, 1980.

Air exchange can be caused by the stack effect alone, or by wind acting alone, or by the combined action of the two. Shaw found that when the wind speed is less than 12.6 km/hr, the air change rate (measured by tracer gas test) was primarily dependent on the inside/outside temperature difference. When the temperature difference was less than 20°C and the wind speed was greater than 12.6 km/hr, then wind was the dominant force driving air change. When the temperature difference was between 20°C and 40°C, and the wind speed was greater than 12.5 km/hr but less than 25.2 km/hr, Shaw found no direct relationship between the rate of air change and wind speed or temperature difference. He developed three equations to predict air change rates to account for the relative importance of wind and temperature difference in driving ventilation.

Temperature Caused Infiltration

$$I = 0.32\ (A/v)\ C\ (t)^n$$

where

I = natural infiltration rate in air changes per hour (ach)
v = volume, m^3
A = area of building envelope calculated for fan test
C = flow coefficient as calculated from fan test results
n = flow exponent as calculated for fan test results.

Wind Induced Infiltration

$$I = a\ (A/v)\ C\ V^{bn}$$

where

V = on-site wind speed, m/s
a = a constant
b = a constant that depends on whether the building is shielded or not.

Wind and Temperature Caused Infiltration

$$I = 4.31\ (A/v)\ C$$

Shaw used his model to predict the air change rates of 25 houses whose air change rates and ELA's had been reported in the literature.

The infiltration rates predicted by this model were within $\pm$ 25 percent of the measured rates. He suggested that if the effect of furnace operation, house shape, distribution of the leakage openings and the height of the neutral plane could be accounted for, the accuracy of the model would be improved, at the expense of the simplicity of the correlation. Shaw's model has been field tested on three identical houses in one subdivision to date (Moffat, 1984).

Sherman and Grimsrud (1980) developed an infiltration model, that uses the equivalent leakage area (ELA) determined by a fan depressurization test, that accounts for many more variables than Shaw's model. The model considers the terrain, shielding from local sources, the leakage area that is directly exposed to the wind (assumed to be located in the walls) versus the leakage area that is inaccessible to the wind (assumed to be located in the floors and ceiling), the height of the building, the height at which wind speed is recorded, and the height of the neutral plane.

The infiltration due to the temperature difference and the infiltration rate induced by wind are calculated separately and then combined in the following manner: $Q_{total} = \sqrt{Q^2 \text{ stack} + Q^2 \text{ wind}}$.

The model was used to predict the air change rates of 15 houses that had previously been subjected to fan tests and tracer gas analysis. In most cases the predicted change rate came within $\pm$ 35 percent of the measured results although in a few houses the rate of air change was drastically over or under predicted.

Sherman and Grimsrud noted that the accuracy of their model could be improved by including parameters to account for more local shielding, leakage through vents and flues running out the roof, the effect of wind direction and furnace operation. They also noted that the model did not account for occupant effects such as opening windows, but concluded that the need to incorporate this into the model was minimal since, in the author's opinion, people are most likely to open windows when the outside temperature is in the comfort range.

Blomsterberg (1982) used Sherman and Grimsrud's infiltration model to predict the rate of air change in three houses. The predicted air change was overestimated in one house by 47 percent, underestimated in a second house by 42 percent and coincided with the measured rate of air change in the remaining house.

Of the two models, the Sherman model has been used more widely because it accounts for more variables. However it still neglects to account for wind direction and furnace operation; two variables that can have significant impact on air leakage. Most studies of air change rates in housing continue to rely on tracer gas analysis.

2.3 AIRTIGHTNESS OF NEW AND EXISTING HOUSING STOCK

A number of studies have been carried out to characterize the airtightness of the Canadian housing stock. The results are generally expressed as specific leakage areas (SLA) that have been adjusted for differences in house size by dividing their equivalent leakage areas (ELA) by the above ground surface area of the building envelope to yield units of cm^2/m^2. Airtightness test results are also expressed as air changes per hour (ach) at a fan-induced pressure differential of 50 Pascals (Pa). This is the number of times in one hour that the entire volume of air in a house is replaced with outside air under the conditions of a fan depressurization test. The major airtightness studies that have been carried out in Canada are:

Dumont, R.S., Orr, H.W., Figley, D.A. Airtightness Measurements of Detached Houses in the Saskatoon Area. National Research Council of Canada, Division of Building Research, Paper #178, 1981.

Ontario Ministry of Municipal Affairs and Housing. The Weatherize Project. Prepared by Sheltair Scientific Ltd., 1984.

Cogeneration Associates, Study of Apple Hill Energy Efficient Homes, under preparation for CMHC, 1983.

Beach, R.K. Relative Tightness of New Housing in the Ottawa Area. National Research Council of Canada, Division of Building Research, Paper #149, 1979.

Energy, Mines and Resources Canada. Airtightness Tests On 200 New Houses Across Canada: Summary of Results. Prepared by Saskatchewan Research Council, 1984.

Dumont (1981) measured the airtightness of 176 houses in Saskatoon using the fan depressurization test. In general he found that bungalows were tighter than multiple story or split level homes and that the age of the house had a tremendous effect on the "equivalent leakage area" (ELA) of the houses. Prior to 1945, houses in Saskatoon had no vapour barrier; between 1945 and 1960, waxed paper vapour barriers were common; and since that time, polyethylene has been used for vapour barriers.

Table 2.2 gives an indication of the range of airtightness that is found in the Canadian housing stock.

Table 2.2

Typical Level Of Airtightness In Canadian Houses

Age	SLA (cm^2/m^2)	ach (@ 50 Pa)
Pre-1945	4.5 - 10.0	8.0 - 30.0
1945 - 1960	2.5 - 4.5	4.0 - 5.0
1960 - 1980	1.5 - 2.5	3.0 - 4.0
Low Energy	1.5	0.5 - 2.0

(Sheltair Scientific Ltd.)

The Ontario Ministry of Municipal Affairs and Housing (1984) carried out fan depressurization tests of 65 houses in Ottawa, Peterborough, Cambridge and Sault Ste. Marie to the CGSB standard. The houses were selected to provide a representative sample based on age, type of construction (frame or masonry), design (bungalow, multiple story) and the presence or absence of a chimney. The results are presented in Table 2.3 as specific leakage areas in cm^2/m^2.

Table 2.3

Average Airtightness Measurements of Detached Houses in Ontario

	Ottawa		Cambridge		Peterborough		S.S. Marie	
	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)
Pre-1920	7	13.70	3	11.60	3	10.70	1	11.08
1921-1945	0		4	12.90	4	15.32	4	7.71
1946-1960	4	8.82	4	8.14	3	13.43	5	6.43
1961-1970	2	10.02	4	8.90	4	12.05	2	3.65
Post-1970	2	4.48	5	7.07	1	13.05	3	3.44
Tightest house		2.26		3.22		6.05		2.37
Leakiest house		41.24		18.58		18.76		11.08

While the sample size of the Ontario Weatherize Project is small it does appear that Ontario houses are generally leakier than the average level of airtightness found in Canadian houses (Table 2.2).

Thirty-five new "energy efficient" homes from the Apple Hill subdivision near Ottawa were tested for their level of airtightness (Cogeneration Associates, 1983). The average SLA for 31 gas heated homes was 3.2 cm^2/m^2, ranging from 0.97 cm^2/m^2 to 4.1 cm^2/m^2, and the average SLA for four electrically heated home› was 1.9 cm^2/m^2. It was noted that the furnace room in the gas heated houses appeared to be the major contributor to the air leakiness of those houses. The gas heated houses had enclosed furnace rooms that were essentially at outdoor temperatures so the flues of the furnace and hot water were not sealed for the airtightness tests, as is required by the CGSB standard when flues are located within the heated space of the house. When these and other intentional openings such as bathroom vents, dryer vents and fireplaces were sealed, the average SLA dropped to 1.8 cm^2/m^2.

The National Research Council of Canada carried out airtightness tests on 63 new houses built in Ottawa in 1978 (Beach, 1979). The tests were conducted with all chimneys and flues sealed (as per CGSB standard) and the average SLA was 3.25 cm^2/m^2 with a range of 1.8 to 5.3 cm^2/m^2. The houses were categorized by house type (bungalow, split level, etc.) but, unlike Dumont's findings, there appeared to be no significant difference in the various items that could be associated with house type.

One relationship that was evident was that each of the nine builders involved, produced houses with a characteristic range of relative tightness values. "There was a distinct impression that the relative tightness of a house varied with the quality of workmanship." (Beach, 1979).

The Saskatchewan Research Council measured the airtightness of 20 new homes in Saskatchewan as part of Energy, Mines and Resources Canada's program to test 200 recently constructed houses across the country (EMR, 1984). The SLA's ranged between 1.1 and 2.3 cm^2/m^2 when the flues were left open, and between 0.7 and 1.1 cm^2/m^2 when these intentional openings were sealed. In light of Beach's data, this suggests that houses are more tightly constructed in Saskatchewan than in Ontario. Common construction features such as framing details, fireplaces, and house type were recorded, but no common characteristics were found to distinguish tight houses from leaky houses.

What's remarkable about most of these airtightness studies is the tremendous variation in SLA. Even within the recently constructed housing stock, the level of tightness can vary by 100 to 400 percent. In some cases, new houses appear to be as leaky as those built prior to 1945 (Table 2.3). From an indoor air quality perspective, a salient question would be whether or not air sealing older houses can make them tighter than an average new home built to the Ontario Building Code.

2.4 AIR CHANGE IN NEW AND EXISTING HOUSING

As was noted in Section 2.2, the rate of air change in a single house will vary considerably over the course of a day and over the course of a heating season. Tracer gas analysis has fluctuations of more than 100 percent; from 0.25 ach to 0.58 ach over a heating season (National Research Council of Canada, 1982). It therefore is difficult to assign a "typical" air change rate to a house or sample of houses.

Both tracer gas decay tests using SF_6 and time-averaged measurements employing perfluorocarbon were carried out on newly constructed houses in the "energy efficient" Apple Hill subdivision in Kanata, Ontario (Cogeneration Associates, 1983). The results of the SF_6 tests showed that 31 gas heated houses averaged 0.35 ach during the winter with a range of 0.18 to 0.55 ach. Four electrically heated houses averaged 0.21 ach, with a range of 0.09 ach to 0.31 ach during the winter. Time-averaged measurements (2 weeks) of seven gas heated houses indicated that they had an average air change rate of 0.18 ach, with a range of 0.09 to 0.39 ach, although the authors note that these may be underestimates since basements were not included in the analysis.

The Apple Hill homes are tighter than most newly constructed houses. Twelve post-1970 electrically heated homes in the Toronto area were subjected to tracer gas analysis and measured air change rates varied between 0.21 and 0.60 ach (NRC, 1982).

Much of the literature fails to adequately account for the variables that can affect air change rates when reporting the results from tracer gas analyses, and with the exception of the Apple Hill study, the level of air circulation in the house is never considered. To clearly examine the relationship between the level of ventilation and indoor air quality, a "motion picture" of the rate of air change and pollutant concentrations is necessary. However, the literature provides "still photographs" which may say very little about the movie.

2.5 IMPACT OF OCCUPANT BEHAVIOUR ON VENTILATION

Tracer gas tests are carried out in houses with the windows and doors closed, exhaust fans switched off and occasionally with the furnace shut down. In reality, people open their windows during the heating season, open and shut outside doors and operate their furnaces, so measured air change rates would tend to underestimate the level of natural ventilation.

Shaw and Brown (1982) ran extensive tracer gas and airtightness tests in a house to examine the effect of a gas furnace on air leakage. They found that air leakage through the chimney accounted for 60 percent of the total air leakage out of the house. When winds were below 13 km/h, the rate of air change in the test house was 50 percent higher with the chimney open to the outside than it was when the chimney was capped. When the furnace burner was operating continuously, the air change rate in the house increased by 10 percent.

The significant impact that a gas furnace appears to have on air change in houses suggests that the current trend to convert to chimneyless high efficiency furnaces or electric heating systems may have a serious impact on ventilation. Perhaps the concerns that have been raised over the effect of air sealing activities on indoor air quality should be extended to oil substitution activities.

People generally use window opening as a means for regulating indoor temperature (Lyberg, 1981) so tracer gas analysis will always underestimate the air change rates of houses during the beginning and end of the heating season, and during mild spells at anytime over the winter. In fact, it is during these mild periods that the rate of air leakage in a house tends to be low.

Lee (1982) used tracer gas tests to measure the impact of window opening on air change. The results indicated that a window open just a few centimetres, can increase the rate of air change in a house by a factor of two to five. This depends on the location of the window (an upper story window will increase the stack effect), and the overall leakiness of the house.

It has been estimated that 50 percent of the air change that occurs over the heating season, in the United Kingdom, is due to window opening habits (Brundett and Poultney, 1982). In Sweden, Lyberg (1961) estimates that window opening behaviour accounts for approximately 30 percent of air leakage. In Ontario it has been estimated that less than 25 percent of the population leave windows open in the winter (Ontario Ministry of Municipal Affairs and Housing, 1984).

Lee (1982) found that window opening behaviour increased with the size of the family, with the amount of time the house was occupied and with the number of smokers. For every additional smoker, there was a 20 percent increase in window opening behaviour.

2.6 IMPACT OF AIR SEALING ON AIRTIGHTNESS AND VENTILATION

The trend in low energy new house construction is to seal the building envelope as tightly as possible to eliminate unintentional air leakage. Mechanical ventilation systems provide the occupants with direct control over the rate of air change in their homes instead of depending on wind and temperature difference to drive ventilation. The Division of Building Research of the National Research Council carried out airtightness tests on 14 airtight low energy houses in Saskatoon (Besant, 1981). The average fan-induced air change rate was 0.88 air changes per hour at 50 Pa. The range was from 0.37 ach to 2.19 ach at 50 Pa. If the average airtightness values measured by Dumont (1981) and Beach (1979), 3.57 ach and 4.41 ach (at 50 Pa) respectively, are typical of most new conventional house construction, Besant's results suggest that it's possible to improve the level of airtightness in new houses by 75 to 80 percent, if airtight construction techniques are employed. Current standards for R-2000 houses require the air change rate at 50 Pa to be less than 2.0 ach.

This level of airtightness cannot be achieved with conventional construction techniques unless an air barrier is included. Dumont (1983) reported on six retrofits in Saskatchewan where air barriers were installed in some of the houses during renovations. For the six houses, the median level of fan-induced air change was reduced from 5.5 ach to 1.6 ach at 50 Pa.

A total of 65 houses in Ontario, ranging in age from pre-1920 to post-1970, were tested for airtightness before and after they were air sealed by professional contractors (Ministry of Municipal Affairs and Housing, 1984). Four different contracting firms were used and they obtained average reductions of 30 percent, 41 percent, 26 percent and 38 percent in the ELA's of the houses they tightened. The results ranged from a minimum reduction of 9 percent to a maximum of 73 percent. There appeared to be no correlation between the percentage reduction in ELA that was obtained and the age of the house.

Two of the 65 houses that were air sealed became slightly tighter than what is attained in conventional new house construction. These two houses were post-1970 electrically heated houses with SLA's of 1.21 and 1.47 cm^2/m^2 respectively. As noted in Table 2.2 the typical range of SLA's for new construction is 1.5 to 2.5 cm^2/m^2.

Tracer gas analysis was carried out on 20 of these houses, after they were air sealed, to determine their rate of air changes under ambient conditions. The tracer gas test results reflect the same wide variation in air change that is found across the conventional housing stock. Three pre-1920 houses had an average air change of 1.2 ach, but the individual houses ranged between 0.38 ach and 1.92 ach. The post-1970 houses had an average air change of .52 ach but the results ranged from 0.11 ach to 1.08 ach. If the natural average seasonal air change rates across the Canadian housing stock are in the range of 0.4 to 0.7 ach (Moffat, 1984), then approximately 20 percent of the houses that were tested fell below this "typical" range and 20 percent exceeded it. One of the air sealed houses had air change rates below those measured in new electrically heated houses. It should be kept in mind that these results were based on single tracer gas tests carried out in mild April weather, and may not reflect the average air change rates in these houses, and certainly don't give any indication of the variation in air change rate that individual houses may experience.

The tracer gas test results from three of the houses that had been air sealed indicated air change rates lower than was measured in the Ministry of Municipal Affairs and Housing's Howland House demonstration project. This pre-1920, semi-detached house was completely gutted and refurbished with a continuous polyethylene air barrier. According to a single SF_6 test, Howland House had an air change rate of 0.31 ach (IEC Beak, 1983).

One of the most comprehensive investigations into the impact of air sealing houses was carried out as part of the Bonneville Power Administration's conservation program in central Washington state. The results are reported in:

> Dickinson, J.B., Grimsrud, D.T., Krinkel, D.L. and Lipschutz, R.D. Results of the Bonneville Power Administration Weatherization and Tightening Projects at the Midway Substation Residential Community. Lawrence Berkeley Laboratory, LBL-12742, 1982.

A total of 18 houses were retrofitted and monitored over a three year period. The houses were divided into three groups of six and retrofitted according to the schedule below.

	1978-1979	1979-1980	1980-1981
Group 1	Monitoring	Control Group	22 hours of air sealing
Group 2	Monitoring	Attic and crawl-space insulation, sill plate caulking	Control Group
Group 3	Monitoring	Insulation, sill plate caulking and storm windows	10 hours of air sealing

The majority of the houses were built either in 1943 or in 1951. All the houses were wood frame, single family, detached structures with floor areas ranging from 103 to 123 square metres. The energy consumption of the houses was monitored during the first heating season before any retrofit activity was undertaken. Fan depressurization tests were carried out before and after each phase of the retrofit.

It was found that insulation had little effect on the equivalent leakage areas of the houses but the addition of storm windows reduced the average ELA's by 14 percent. Twenty-two person-hours of air sealing managed to reduce the average ELA of Group 1 by 27 percent while 10 person-hours of air sealing in Group 3, reduced the average ELA's by 20 percent.

The Lawrence Berkeley Lab infiltration model (Sherman and Grimsrud, 1980) was applied to the airtightness test results to convert ELA into air changes per hour. After 22 hours of air sealing, Group 1 dropped from 0.44 ach to 0.32 ach. The average air change rate of Group 2 houses, after only 10 hours of air sealing, dropped from 0.35 ach to 0.28 ach. These results fall within the lower range of air change rates found in post-1970 electric houses in Toronto (NRC, 1982).

Dickinson suggests that the reductions in airtightness were less than had been expected because the Midway houses were relatively tight to begin with. The three groups had average specific leakage areas of 4.1, 3.4 and 3.5 cm^2/m^2 before they were tightened. This can be compared to the specific leakage areas of four groups of pre-1960 houses in Ontario which were 8.8, 8.1, 13.4 and 6.4 cm^2/m^2 (Table 2.3).

There were two major sources of error in the Midway house tightening project that may have affected the air sealing results. The first problem was that different air sealing measures were used in different homes. For instance in Group 3 homes, where 22 person-hours were spent on air sealing, baseboards were caulked in only one house, window and door frames were sealed in only four of the six houses and cracks in the attic were sealed in only half the houses. The other problem was that indoor temperatures were never recorded over the three year project (an input required for the LBL model), so the accuracy of the predicted air change rates is questionable.

A project, similar to that undertaken by the Bonneville Power Administration, was carried out by Pacific Gas and Electric in Walnut Creek, California (Dickinson, 1982). Twenty houses underwent 14 person-hours of air sealing. In ten houses the average equivalent leakage area was reduced by 15 percent while the remaining nine attained an average of a 33 percent reduction. The latter group received "additional contractor-installed measures" that were not described.

Based on the above-mentioned case studies it can be reasonably assumed that on average, professional air sealing can reduce the equivalent leakage area of a house by 20 to 40 percent. According to a number of air sealing contractors, reasonably knowledgeable do-it-yourselfers attain approximately half the reduction in air leakage that a professional job can accomplish.

Whether or not a corresponding reduction in air change rates is brought about by reductions in ELA's has not been well documented. The Lawrence Berkeley Laboratory infiltration model (Sherman and Grimsrud, 1981) has been used to predict such a reduction based on equivalent leakage area measurements, but this needs to be corroborated by tracer gas analysis.

The range of SLA's and air change rates that have been reported in the literature for houses that have been air sealed, appears to rarely drop below what has been measured in new houses that have been built to Ontario Building Code standards. This raises the question of whether there has been an over-reaction to the impact that air sealing has on the ventilation rates, and indoor air quality of existing housing.

Perhaps the important question is whether or not the accidental openings in the house shell can guarantee an adequate supply of air at all times of the year under all conditions, regardless of any air sealing measures that may have been implemented.

2.7 INDOOR AIR QUALITY IN AIR SEALED HOUSES

Concern about the quality of residential indoor air came to the public's attention in 1979, shortly after the nuclear accident at Three Mile Island, with the publishing of a number of papers warning against the health effects of radon in sealed houses. Cohen (1980) concluded that energy conservation by insulation of buildings would cause at least 10,000 extra fatal cancers per year in the U.S. (4 per 100,000 population) due to reduced ventilation. This is compared to the radiation hazards of nuclear power plants where the predicted fatalities amounted to between 0.1 and 6.0 percent of those caused by energy conservation activities.

> It seems reasonable to estimate that insulation efforts already executed have accomplished about 10 percent of the job and are therefore now causing about 1,000 fatalities per year.
>
> (Cohen, 1980)

A year after Three Mile Island and the resulting flurry of warnings about radon inside houses, urea formaldehyde foam insulation was banned in Canada because its "off-gassing" was causing health problems in a segment of the population and it had been found that formaldehyde caused nasal cancer in laboratory animals. Attention was once again focussed on residential indoor air quality and researchers began to investigate the impact of formaldehyde sources other than insulation.

During the 1981-1982 heating season in Ontario, indoor air quality once again became an issue when a Mississauga man died from carbon monoxide asphyxiation in his home. Initially blamed on energy conservation measures, it was found that a combination of a partially blocked chimney, improperly adjusted furnace, and closed furnace room caused a backdraft down the chimney, filling the house with carbon monoxide. This and similar incidents have precipitated an unprecedented amount of concern and activity with respect to indoor air quality. As a result, much of the research into indoor air quality in tighter houses that has been undertaken to date, has been a reaction to specific problems.

The most prominent concern of some energy utilities and government departments is whether the kinds of energy conservation activities they've been advocating have an adverse impact on health. Heating industry associations and government bodies that regulate fuel safety have become sensitive about the role that gas-fired combustion appliances may play in some indoor air quality problems. There are health researchers whose primary interest is the impact of any level of chemical contaminant on hypersensitive people. And there are air sealing and insulating contractors who in many instances, desire technical guidance and standards with respect to pollutant levels in houses.

There have been a number of major empirical studies on the impact of energy conservation activities, such as air sealing, on indoor air quality. These include:

Berk, J.V., Hollowell, C.D. et al. The Impact of Reduced Ventilation on Indoor Air Quality in Residential Buildings. Lawrence Berkeley Laboratory, LBL-10572, 1980.

Hollowell, C.D., Berk, J.V. Indoor Air Quality in New Energy Efficient Houses and Retrofitted House. Lawrence Berkeley Laboratory, 1982.

Offerman, F.J., Girman, J.R., and Hollowell, C.D. Midway House Tightening Project: A Study of Indoor Air Quality. Lawrence Berkeley Laboratory, LBL-12777, 1981.

Ontario Ministry of Municipal Affairs and Housing. Indoor Air Quality - Cambridge Sealed Homes. IEC Beak Consultants, 1983.

Offerman, F.J., Dickinson, J.B., Fisk, W.J., and Grimsrud, D.T. Residential Air Leakage and Indoor Air Quality in Rochester, New York. Lawrence Berkeley Laboratory, LBL-13100, 1982.

Cogeneration Associates. Study of Apple Hill Energy Efficient Homes, under preparation for Canada Mortgage and Housing Corporation, 1983.

The Berk et al (1980) study was one of the first to measure contaminant levels in buildings with low ventilation rates. Three energy-efficient research houses were monitored, with Lawrence Berkeley Laboratory's Energy-Efficient Buildings Mobile Laboratory, for carbon dioxide, carbon monoxide, nitrogen oxide, nitrogen dioxide, formaldehyde, other aldehydes (the class of compounds to which formaldehyde belongs), particulates, and ventilation rates (using tracer gas analysis).

The test houses were located in California, Iowa and Maryland, and they all had been designed to use approximately 50 percent less energy than conventional new houses. Unfortunately only the California house was actually occupied by a family, and it was monitored in the late summer. The two unoccupied houses were monitored during the winter and early spring, but their indoor environments could not possibly reflect the situation in a house that is actually lived in by people going about their daily routine. (The LBL staff was housed in the Maryland house but it was pointed out by the authors that they did little more than sleep in the house.) No control houses (conventional construction) were used in the study, so the effect of the energy conservation measures on ventilation and indoor air quality are unclear.

The air change rate in the California house ranged between 0.2 and 0.8 ach with an average of 0.4 ach. The Iowa house ranged between 0.1 and 0.4 ach with an average of 0.2 ach, and the Maryland house had an average air change rate of 0.05 to 0.3 ach with an average of 0.15 ach.

The indoor and outdoor levels of carbon monoxide were found to be comparable for all three houses. The California house had elevated levels of nitrogen oxide and nitrogen dioxide that sometimes exceeded the one hour Canadian ambient air quality objective of 0.21 ppm. These peaks were associated with cooking activity. The air was monitored for particulates in the Iowa and Maryland houses, and both experienced elevated levels of particulates. When welding and smoking was going on in the Iowa house, particulate levels exceeded those found outdoors. In the Maryland house, fine particle concentrations regularly exceeded outdoor concentrations. This was attributed to cleaning and cooking activities. Formaldehyde levels in the houses occasionally exceeded indoor air standards (0.1 ppm) while total aldehyde levels frequently exceeded this guideline. When furniture was added to one of the unoccupied houses, the formaldehyde concentration tripled. Table 2.4 illustrates the impact of furnishings and occupant behaviour on formaldehyde levels. Radon gas levels were found to be approximately 0.5 pCi/L in the California and Iowa houses, however the Maryland house had concentrations as high as 24 pCi/L, six times the upper limit set by the U.S. Environmental Protection Agency for houses constructed on reclaimed phosphate lands in Florida.

As a result of their study, Berk et al (1980) made the following recommendations:

1) Detailed measurements of a variety of housing types, including houses undergoing retrofits, under a range of occupancy conditions (such as presence of smokers) should be carried out.

2) The health effects of elevated levels of indoor contaminants need to be researched so that the impact of energy conservation measures on indoor air quality can be clearly documented.

3) Energy-efficient ventilation standards should not be established until these relationships are clearly understood.

Table 2.4

Summary of Indoor and Outdoor Formaldehyde and Total Aliphatic Aldehyde Concentrations Under Varying Conditions of Occupancy

Condition	Number of Measurements	Sampling Time (hours)	Formaldehyde (ppb)[a]
Unoccupied, without furniture	3	12	66 ± 9%
Unoccupied, with furniture	3	24	183 ± 7%
Occupied, day[c]	9	12	214 ± 10%
Occupied, night[d]	9	12	115 ± 31%

a Determined using pararosaniline method (100 ppb ≅ 120 ug/m^3). All outside concentrations <10 ppb.

c Air exchange rate ≅ 0.4 ach.

d Windows open part of time; air exchange rate significantly greater than 0.4 ach and variable.

Since Berk's study lacked any control houses, it doesn't shed any light on the relationship between air change rates and indoor levels of air pollutants. However this early study does point out the importance of pollutant source strengths. Elevated levels of nitrogen dioxide were associated with the use of a gas range, and the impact that furniture can have on formaldehyde levels was demonstrated.

Hollowell, Berk et al (1982) reported on the indoor air quality in five energy-efficient houses and three retrofitted houses. In the energy-efficient houses(air change rates lower than 0.4 ach) the indoor levels of radon, formaldehyde and particulates sometimes exceeded existing guidelines or standards for outdoor air, however air quality monitoring was not carried out on control houses with higher rates of air change. In many cases the elevated levels were explained in terms of the pollutant source strengths.

All five energy-efficient houses had air change rates that were considerably lower than the national average (0.75 ach in the U.S.), ranging from 0.1 to 0.4 ach. No carbon monoxide problems were detected in any of the houses despite the presence of smokers and gas-fired appliances. One house, located in Rio, Wisconsin, had very high levels of particulates. This house contained propane combustion appliances, a woodburning stove and an occupant that smoked, but Hollowell and Berk attributed the high levels of particulates to cigarette smoke alone. One house in Minnesota had high levels of nitric oxide, and this was attributed to the operation of an oil-fired furnace. Radon gas levels exceeded existing standards for indoor air in four out of five of the houses tested. The results are presented in Table 2.5.

Table 2.5

INDOOR AIR QUALITY MEASUREMENTS IN FIVE NEW ENERGY-EFFICIENT OCCUPIED HOUSES [a]

	Carroll County MD	Mission Viejo CA	Northfield MN	Dundas MN	Rio WI
Infiltration rate (ach)	0.15	0.4	0.1	0.1	0.3
CO (ppm)	1.2	1.4	0.5	0.7	2.2
CO_2 (ppm)	598	689	1175	1316	1125
NO_2 (ppb)	9	41	15	19	77
NO (ppb)	5	44	5	70	72
SO_2 (ppb)	3.2	0.9	1.0	-	9.0
O_3 (ppb)	4.3	15.6	1.7	9.0	15.0
Particulates--fine (ug/m^3)	7.0	32.6	6.8	19.5	92.4[b] 6.0[c]
Particulates--total (ug/m^3)	9.9	48.9	14.8	27.9	129.6[b] 23.5[c]
Formaldehyde (ppb)	98	214	69	80	53
Total aldehydes (ppb)	150	227	99	122	81
Radon (pCi/L)	22.0	5.0	7.5	1.7	6.5

a All values represent average concentrations during the monitoring period

b Smoking

c No smoking

(Hollowell, Berk *et al*, 1982)

The three retrofitted houses that Hollowell and Berk monitored provide some insight into the impact of reduced ventilation on indoor air quality. Two of the three retrofitted houses had been upgraded by Pacific Power and Light Company as part of its energy-conservation program in Medford, Oregon. The utility's program added storm windows and doors, door weatherstripping, attic and floor insulation, replaced sliding glass doors and insulated heating ducts, but involved no comprehensive air sealing. The air change rates in these two houses were reduced by 40 percent, to 0.20 ach. The third house that was monitored was a 100-year-old farmhouse in New Jersey that had previously been retrofitted but was super-retrofitted for the purposes of the study. No details about the specific measures undertaken were provided. The reduction in air change after the super-retrofit was 11 percent resulting in a measured air change rate of 0.39 ach. All air change rates and pollutant concentrations are presented as averages for the monitoring period. The length of the monitoring period and the weather conditions over that time were not described. Table 2.6 summarizes the results.

Table 2.6

INDOOR AIR QUALITY MEASUREMENTS
IN THREE RETROFITTED OCCUPED HOUSES [a]

	Medford, OR #1		Medford, OR #2		Cranbury, NJ	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit	Pre-[b] Retrofit	Post-[c] Retrofit
Infiltration rate (ach)	(Fan Off) 0.33	0.20	(Fan Off) 0.33	0.23	0.44	0.39
CO (ppm)	0.3	0.3	0.3	0.3	2.9	3.1
CO_2 (ppm)	670	847	593	656	767	703
NO_2 (ppb)	7	4	4	5	25	29
NO (ppb)	3	7	8	7	50	46
SO_2 (ppb)	-	-	-	-	3	3
O_3 (ppb)	4	4	5	14	-	-
Particulates-- fine (ug/m^3)	(Smoking) 31	36	12	10	12	8
	(No Smoking) 9	8				
Particulates-- total (ug/m^3)	(Smoking) 62	77	45	26	25	18
	(No Smoking) 31	35				
Formaldehyde (ppb)	55	53	68	51	22	19
Total aldehydes (ppb)	84	85	94	71	29	31
Radon (pCi/L)	1	1.2	1	1	3.6	3.8

a All values represent average concentrations during the monitoring period

b Previously weatherized by owner at time of measurement

c "Super" retrofit done by Princeton University house doctors

(Hollowell, Berk, et al, 1982)

None of the gaseous pollutants showed any appreciable increase after the retrofits, with the exception of carbon dioxide which increased in concentration by 10 to 30 percent in two houses and decreased in the third. The levels of particulates in one of the Minnesota houses increased by 20 percent as a result of the retrofit. This house had a smoker with a 20 to 40 cigarette-a-day habit. Radon levels were near the limits of detection in the Minnesota houses, while levels in the New Jersey farmhouse had increased by 5.5 percent to just below existing indoor standards for radon. According to Table 2.6, there was a decrease in the concentration of contaminants as frequently as there was an increase, but this was not dealt with in Hollowell and Berk's discussion of the results.

The only house that had combustion appliances (gas water heater, dryer and stove) had unusually low levels of gaseous pollutants. This was attributed to the fact that occupancy levels were low and almost no cooking was done during the monitoring period.

Hollowell and Berk concluded:

> The impact of residential retrofit programs on indoor air quality appears to be minimal based on this study of three retrofitted houses where no pollutants reached levels approaching health guidelines or standards. We can conclude that retrofit programs such as that of Pacific Power and Light Company improve the thermal integrity of houses and should continue without fear of significantly increasing indoor air pollution.

While Hollowell and Berk's conclusions sound encouraging, they are specific to the retrofit program that was carried out by Pacific Power and Light Company and cannot be generalized.

In contrast to the study of retrofitted houses by Hollowell and Berk (1982), Offerman, Girman and Hollowell (1981) carried out a rigorous study of the indoor air quality of 12 houses that were tightened as part of the Bonneville Power Administration's Midway house tightening project described in Section 2.6 (Dickinson and Grimsrud, 1982).

The houses, located near Richland, Washington, were monitored for radon, formaldehyde and nitrogen dioxide. According to the authors, carbon monoxide and particulates were not monitored because inexpensive instrumentation suitable for long-term sampling does not exist. Relative humidity was monitored because of its influence on people's comfort and its potential for creating condensation problems. The results are summarized in Table 2.7.

Air change rates were estimated from the equivalent leakage areas determined from fan depressurization tests (Sherman and Grimsrud, 1980). To account for ventilation resulting from window and door opening and fireplace use, 0.1 to 0.15 ach was added to the predicted air change rate.

Six of the houses received an average of 12 person-hours of air sealing (one day retrofit), and the other six received 22 person-hours of airtightening (two day retrofits). The average reductions in equivalent leakage area were 27 percent and 37 percent respectively, resulting in estimated average air change rates of .28 and .32 ach. The largest reduction in equivalent leakage area was 51 percent, while the smallest reduction was 9 percent.

After air sealing, a third of the houses showed elevated levels of radon, most of which were at the lower limit of the radon guideline (assuming 0.02 WL corresponds to 3 to 6 pCi/L of radon). Offerman and Girman (1981) pooled the data on radon and airtightness because they thought that it would provide a more statistically significant assessment of the impact of tightening the houses. The result was that there was an average increase in radon of 0.5 $\pm$ 0.5 pCi/L after air sealing, representing a 42 percent increase. However, with a standard deviation of 100 percent the reliability of this figure is suspect.

The average increase in formaldehyde concentrations, after air sealing, was 4 ppb, representing an increase of 24 percent (once again, pooling all the data). But in 50 percent of the houses there was a decrease in the levels of formaldehyde after air sealing.

Table 2.7

SUMMARY OF PRE- AND POST-RETROFIT LEAKAGE AND INDOOR AIR QUALITY MEASUREMENTS IN TWELVE HOUSES OF THE BPA MIDWAY SUBSTATION RESIDENTIAL COMMUNITY

House ID#	Sampling Period	Equivalent Leakage Area (cm^2)	(% Change)	Radon (pCi/l)	HCHO (ppb) Indoor/Outdoor	NO_2 (ppb) Indoor/Outdoor	Relative Humidity (%)
1	Pre-retrofit	426		<1	5/ 5	2/3	45
	Post-retrofit	266	38	1	21/ 5	2/3	44
2	Pre-retrofit	364		<1	5/ 5	4/3	41
	Post-retrofit	227	38	<1	17/ 5	3/2	46
3	Pre-retrofit	407		<1	28/ 5	3/2	42
	Post-retrofit	231	43	1	24/ 5	3/3	43
4	Pre-retrofit	288		1	12/ 5	1/3	38
	Post-retrofit	197	32	2	8/ 5	2/3	36
5	Pre-retrofit	374		1	34/ 5	4/1	52
	Post-retrofit	337	10	3	16/ 5	3/2	38
6	Pre-retrofit	433		2	15/ 5	3/2	42
	Post-retrofit	377	13	1	10/ 5	3/3	42
7	Pre-retrofit	276		-	5/ 5	$<1/3$	41
	Post-retrofit	200	28	3	69/ 5	3/4	62
8	Pre-retrofit	325		2	19/ 5	2/2	47
	Post-retrofit	204	37	3	31/ 5	2/3	52
9	Pre-retrofit	203		2	44/ 5	1/2	48
	Post-retrofit	185	9	2	49/ 5	2/2	54
10	Pre-retrofit	392		<1	5/ 5	3/2	46
	Post-retrofit	241	39	2	19/ 5	3/2	49
11	Pre-retrofit	338		1	79/ 5	2/2	48
	Post-retrofit	201	41	-	13/ 5	1/3	43
12	Pre-retrofit	364		3	5/ 5	2/3	39
	Post-retrofit	179	51	3	7/ 5	1/4	38

(Offerman, Girman and Hollowell, 1981)

The importance of a pollutant's source strength was underlined by the results of occupants moving from house #11 to house #7. The formaldehyde levels in the vacated house dropped from 79 ppb to 13 ppb, while the levels in the newly occupied house rose from less than 5 ppb to 69 ppb.

All the measured nitrogen dioxide levels were very near the detection limit of the monitoring equipment. Both pre- and post-retrofit concentrations were among the lowest that Offerman and Girman had ever measured. This was expected as there were no combustion appliances and the houses were in a rural area so the outdoor levels of pollutants were extremely low.

Only one house had a significant increase in relative humidity after airtightening so it was suggested that this was related to a change in occupancy. The houses in the study were relatively tight before they were retrofitted which may account for the minimal changes in relative humidity.

According to the authors, the results of monitoring the indoor air quality in the Midway houses are somewhat inconclusive because of the lack of information about the pollutant source strengths, and occupant behaviours; along with the short sampling periods (one to two weeks), and small size and homogeneity of the sample. To this list could be added, indoor air circulation and external weather conditions.

> Until a sufficiently large indoor air quality data base is established for the United States, it is strongly recommended that all house-tightening programs include an indoor air quality measurement to assure that the retrofits designed to reduce infiltration and thereby save energy do not have adverse effects on indoor air quality and human health. A suitable protocol for large-scale indoor air quality monitoring needs to be developed.
>
> (Offerman, Girman and Hollowell, 1981)

It has sometimes been assumed in the past that if humidity is not excessive inside a house then there is little concern about indoor air quality. The results from the Midway house tightening project appear to lend some credence to this informal rule of thumb. Table 2.7 clearly indicates that the three houses with the highest relative humidities, contain the highest formaldehyde concentrations and the highest levels of radon in two out of the three cases. However house #12 had a high level of radon and one of the lowest relative humidities.

While high levels of humidity can result from low air change rates, as with chemical contaminants, the source strength of the water vapour can play an important role. One of the significant sources of water vapour is the soil surrounding a house foundation. As was noted in Section 1.1, the soil is an important source of radon gas so there may exist a relationship between elevated levels of water vapour and radon gas, and leaky foundations. High levels of humidity are also known to increase the rate of formaldehyde emission from materials.

The only Canadian investigation of indoor air quality in existing houses that had received air sealing measures was carried out by the Ontario Ministry of Municipal Affairs and Housing (1983) on 20 homes in Cambridge, Ontario. Approximately 300 measurements of carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, formaldehyde and radon gas were taken over a two week period. Potential pollutant sources, occupancy patterns, the lifestyle of the occupants and air change rates were assessed. With the exception of radon, contaminants were monitored in a number of locations in the houses to examine the role that air circulation might play in creating local "hot spots." However, unlike the Midway house tightening project (Offerman, Girman and Hollowell, 1982), contaminant levels were not monitored prior to air sealing the houses and no control group of "unsealed" houses was monitored for comparison purposes.

The authors of this study established criteria levels, above which contaminant concentrations were considered excessive, by dividing limits that had been set for occupational hygiene by 20, unless indoor standards or guidelines already existed. The result was that 42 of the 300 measurements exceeded the study's criteria levels. These excesses represent less than 14 percent of the total number of measurements. The results are summarized in Table 2.8 below.

Table 2.8

Percentage of Measurements Exceeding Criteria
For Monitored Contaminants in Air Sealed Cambridge Houses

Contaminant	Criteria Level (ppm)	Percentage of Excesses
Carbon Monoxide	2.5	3%
Carbon Dioxide	600.0	23%
Nitric Oxide	0.5	7%
Nitrogen Dioxide	0.15	5%
Formaldehyde	0.05	27%
Radon	0.02 WL	40%

Because of their careful assessment of occupancy patterns, occupant lifestyles and pollutant sources, the authors were often able to show a correlation between these variables and high levels of contaminants. This lends support to concerns about the adequacy of simply relying on a specified rate of ventilation to guarantee acceptable indoor air quality (Coon, 1982).

Since there was no air quality testing before the houses were tightened, it's impossible to attempt any correlation between contaminant levels and ventilation rates.

The tightest house in the sample had an SLA of 2.8 cm^2/m^2 and a measured air change rate of less than 0.2 ach, yet the concentration of contaminants in the house never exceeded the study's criteria levels. Conversely, five out of the six houses, that had levels of pollutants that most regularly exceeded the criteria levels, had SLA's that fell within the range that is typical for houses built prior to 1960 (greater than 2.5 cm^2/m^2) and single SF_6 decay tests indicated that they experienced air change rates that were slightly above 0.5 ach. Despite their relatively high level of air change, these houses had experienced major moisture problems before and after air sealing (Ontario Ministry of Municipal Affairs and Housing, 1984).

There is some indication from the CO_2 measurements that at least some of the houses had poor air circulation. In some houses, levels of CO_2 exceeded 2500 ppm on the main floors while the measured concentrations of CO_2 in the basements and on the second floors never exceeded 450 ppm. High levels of CO_2 could also have been influenced by the concentration of occupancy and the use of gas ranges in main floor kitchens. The measured concentrations of formaldehyde did not exhibit any kind of stratification.

As with many of the indoor air quality studies that appear in the literature, the MOMAH report was based on short-term sampling of contaminants, so it's impossible to know whether the levels of contaminants that were measured reflect the long-term situation in the houses tested. In the Apple Hill Study of Energy Efficient Homes (Cogeneration Associates, 1983), indoor air contaminants were monitored over three distinct seasons.

The measured concentrations of carbon monoxide, nitrogen dioxide and nitric oxide suggested some seasonal variation, with higher levels in the winter. Attempts to correlate elevated levels with air change rates proved to be inconclusive.

In some of the Apple Hill houses, carbon dioxide and formaldehyde were found at levels exceeding existing guidelines. At least five houses frequently had basement radon concentrations that exceeded 6.0 pCi/L, the upper limit of indoor air quality guidelines for radon. It should be noted that the Kanata area of Ontario where the Apple Hill houses are located, has much higher background levels of radon than most other parts of Canada.

Two general recommendations were made by the authors of the indoor air quality component of the Apple Hill study:

> There is a fundamental need to continually evaluate and monitor residential air quality such that cost-effective control measures can be adequately defined.
>
> An awareness by both builders and homeowners about air quality is required, so that, unhealthy indoor air quality conditions are not imposed upon individuals without their knowledge or consent.
>
> (Cogeneration Associates, 1983)

Offerman, Dickinson et al (1982) monitored 10 houses in Rochester, New York for formaldehyde, aldehydes, nitrogen dioxide and radon and compared the results to an extremely leaky house.

Two of the ten houses were also monitored for particulates and gaseous pollutants that are associated with combustion. Three of the houses contained gas stoves and four had smokers. All but one of the houses were constructed with sealed polyethylene vapour barriers, and they had an average air change rate of 0.35 ach, ranging between 0.22 and 0.5 ach (an average specific leakage area of 2.4 ± 0.7 cm^2/m^2). The average rate of air change in this study was predicted from measured ELA's using the LBL infiltration model (Sherman and Grimsrud, 1980).

The leaky house that was monitored for comparison purposes had a predicted average air change rate of 1.17 ach with a high of 4.46 ach. The houses were monitored for one week periods during which tracer gas decay tests indicated that air change rates in the tight houses were relatively stable with an average standard deviation of 0.1 ach. The rate of air exchange in the leaky house varied considerably with a standard deviation of 0.65 ach.

The average radon concentrations ranged from below the detectable limit in the leaky house to 2.2 pCi/L in one of the tight houses. Several of the measurements approached the lower level (3 pCi/L) of existing guidelines for radon. Average formaldehyde levels ranged between .007 and 0.64 ppm, and all the measured levels were below the existing guideline for indoor air (0.1 ppm). It was noted that the houses with the highest aldehyde levels were also the only houses with any significant amount of new particleboard. Levels of nitrogen dioxide (NO_2) were consistently lower than outdoor concentrations in all but the one house with an unvented gas clothes dryer and range. The houses with gas stoves had average concentrations of 0.15 ppm, while houses with electric stoves had average NO_2 levels of .004 ppm. The two houses that were monitored for particulates, contained smokers and had 2-3 times the outdoor concentrations of respirable suspended particulates (RSP). There is no ambient standard for RSP's. The concentration of respirable particulates in one house slightly exceeded the ambient standard for total suspended particulates (some suspended particulates are removed in the upper respiratory tract and do not reach the lungs).

Because the concentrations of radon, formaldehyde and nitrogen dioxide were low in the tight houses they monitored, Offerman and

Dickinson (1982) concluded that the source strengths of these contaminants were low. They suggest that the key to having an energy-efficient house with both lower levels of ventilation and acceptable indoor air quality, is to construct and furnish it so that the pollutant sources are low.

> When designing houses to have low air-exchange rates, builders should be selective in choosing building materials that are not potential sources of indoor air pollution. Research has been initiated at Lawrence Berkeley Labs to study contaminant emission rates from various building materials. However, many sources of indoor air pollution are occupant-related and beyond the control of builders, such as tobacco smoking, use of unvented combustion appliances and toxic cleaning products, and selection of house furnishings constructed with urea formaldehyde based resins. Homeowners must accept responsibility for controlling these sources.
>
> (Offerman and Dickinson, 1982)

The only Canadian study examining air change and indoor air quality that has been published, monitored radon and formaldehyde in 12 relatively tight houses (NRC, 1982). The houses were monitored for four months, on a weekly basis, over a heating season and for two months during the summer. Air change rates were based on the 45 minute sampling period typical of the decay method of tracer gas analysis; formaldehyde concentrations were measured over one hour periods; 24 hour periods and seven days; while radon gas and radon daughters were measured on a daily basis.

The average air change rate for each house varied from 0.21 ach to 0.66 ach over the heating season, ranging from a low of .14 ach to a high of .78 ach. Unlike the results from the Apple Hill study (Cogeneration Associates, 1983), SF_6 tracer gas tests indicated that average monthly air change rates followed the changes in degree-day months (an indication of difference between inside and outside temperatures) and average monthly wind speed data. Average air change rates during the summer for those houses with air conditioning systems ranged from 0.12 ach to 0.40 ach while the two houses without air conditioning had average air change rates of 1.75 ach and 2.78 ach respectively. The rate of air change in the air conditioned houses was considerably lower in the summer than the winter, primarily because there is no temperature difference between inside and outside and little wind to drive infiltration during the summer months.

Average concentrations for formaldehyde ranged from 0.017 ppm to 0.058 ppm. The houses with the three highest levels of formaldehyde also had the largest variation. In the summer the average formaldehyde levels in these houses, all of which were kept closed up for the air conditioning, were well above the 0.1 ppm level recommended by Health and Welfare Canada. The authors suggest that the air change rates had a marked effect on formaldehyde concentrations but they initially failed to consider the differences in source strengths among the houses and, because of equipment failure, were unable to monitor outdoor levels of formaldehyde. In fact formaldehyde concentrations and air change showed poor correlations for individual houses. There was, however, a clear inverse relationship between the average monthly air change rates for all the houses and the formaldehyde gas concentration.

Before the summer monitoring commenced, occupancy patterns, home-owner habits and possible sources of formaldehyde were assessed. During the summer, outdoor formaldehyde levels were monitored as well. The three houses with the highest formaldehyde levels were all found to have significant sources. Each house was occupied by at least one smoker, two of the houses had installed new furniture during the monitoring period and one house had a new burglar alarm and new wallpaper installed, so there was extensive use of glue. In addition, all three houses were within less than 100 m of Highway 401 and were exposed to outdoor concentrations of formaldehyde that were almost 150 percent higher than the ambient levels near most of the other houses.

The average radon concentration over the heating season ranged from 0.3 pCi/L to 2.2 pCi/L with an overall average of 1.2 pCi/L. The average radon daughter concentration ranged from 0.0007 Working Levels (WL) to 0.0065 WL with an overall average of 0.0037 WL. The 0.02 WL limit established for housing in uranium mining and processing communities was exceeded once by a house that had the second highest average radon daughter concentration, the highest average radon gas concentration and, notably, the highest average air change rate.

During the summer months, on average, radon concentrations in the closed air-conditioned houses increased by 44 percent and radon daughter concentrations increased by 32 percent. In the two houses that utilized windows for summer cooling, concentration of radon gas and radon daughters dropped drastically in one case and actually increased slightly in the other. The house that exceeded .02 WL in the winter was not re-tested over the summer months.

The recommendations for future work made by the authors of the NRC report are similar to those made in other studies:

1) Survey a wider range of housing types.

2) Include houses with combustion appliances in the survey.

3) Monitor buildings of different tightnesses.

4) Sample houses in different geographical locations.

5) Carry out year-long monitoring.

6) Conduct a physical survey of the house, survey occupancy patterns and homeowner's habits.

7) Identify specific areas of air leakage and potential formaldehyde sources.

A careful survey of the literature failed to turn up a single case study whose design would satisfy the above recommendations. Indoor air quality monitoring programs are expensive, time consuming, technically complex, and require a tremendous amount of co-operation from the people living in the homes. It has been suggested that in order to adequately characterize the indoor air quality in Canadian houses, a total of 160 dwellings in four different locations should be monitored for a period of one year (NRC, 1982).

Since none of the indoor air quality case studies that were reviewed in this section accounted for all the important variables and provided for adequate controls, it's impossible to draw any firm conclusions about the relationship between low rates of air change and indoor air quality, but some trends were evident. At the level of air change that is typical of tighter new construction and air sealed existing housing, the pollutant source strength plays a crucial role in contributing to high levels of contaminants. This can become less important at high levels of ventilation such as occur in the summer with the windows open (NRC, 1982). Although, even under these conditions the NRC study found a slight increase in radon concentration in one house.

In general, elevated levels of radon and carbon dioxide seem to be common in some of the newer tighter houses and in some existing houses that have been air sealed. But the results do not seem to be consistent. The situation is even more unpredictable with formaldehyde. Sometimes air sealing reduces its concentration, sometimes it becomes elevated and in some cases its concentration doesn't change at all.

High levels of relative humidity tended to exist in the homes with the highest levels of radon and formaldehyde. It would be instructive to monitor some houses where careful attention has been paid to the airtightness of the basement area, as well as the above ground area of the building shell. Research is also needed to investigate the relationship between indoor air circulation and the contaminant concentration in different rooms of a house. Better air circulation may eliminate chemical "hot spots" in some houses.

A number of researchers have attempted to predict the effects of reduced air leakage in houses on indoor pollutant levels using mathematical models (Silberstein, 1978; GEOMET, 1981). However, the usefulness of these models is severely limited by the gaps in our knowledge with respect to air change in housing, the source strength of pollutants and ultimately by the uniqueness of individual houses.

Many of those who have examined the indoor air quality in tighter houses have understandably recommended that more detailed research be undertaken. However a recommendation for education, made by the authors of the Apple Hill study (Cogeneration Associates, 1983), would appear to have the greatest pay-off in the near term. If both builders and homeowners were made aware of indoor air quality issues they, as Offerman and Dickinson (1982) suggest, could accept responsibility for controlling pollutant sources. And ultimately the informed homeowner can decide on the kind of air quality that he is willing to tolerate or deem acceptable.

2.8 SUMMARY

There is a tremendous variation in the airtightness of Canadian houses which appears to be related to the quality of workmanship rather than simply house style or age. Within a single house there is significant variation in the level of ventilation over the course of a heating season, since the rate of air exchange is dependent on such variables as wind speed and direction, inside/outside temperature difference and frequency of furnace operation. Two houses can have the same level of airtightness (identical specific leakage areas) but widely different air change rates at any given time. If the rate of air change in a typical new house can vary from 0.2 to 0.6 air changes per hour over the same heating season, then the accidental openings in a building envelope may not be able to guarantee an adequate supply of air under all conditions.

The tracer gas decay test method that is commonly used to quantify air change rates, can only provide a glimpse of what the level of ventilation in a house is at any given time, which may not be representative of the average situation. Concerns have also been raised about the accuracy of this test method over the short-term. It appears that under some conditions the tracer gas stratifies instead of mixing evenly with house air. A tracer gas technique that employs perfluorocarbon emitters and samplers may overcome many of the disadvantages of the decay method.

A number of attempts have been made to use the equivalent leakage area of a house, as determined by fan depressurization, to predict its level of ventilation. The large number of variables that affect the rate of air change in a house make this a complex task, and to date, the results have not been reliable.

The problems associated with quantifying ventilation rates has severely limited our ability to clearly characterize the impacts of air sealing on air exchange. However,there is a general consensus in the literature that professional air sealing techniques can improve the airtightness of existing houses by 20 to 40 percent, reducing their average natural air change rates to between 0.3 and 0.6 ach.

Air sealing existing houses does not appear to reduce their rate of air change below that of conventional new houses with one possible exception. Electrically heated houses that had been built subsequent to 1970, in some cases, were tighter than new houses after air sealing. (It should be noted that air sealing work tends to be carried out in older homes, where it may be difficult to even attain the level of tightness found in modern houses.)

There is a distinct lack of information in the literature about the effects of reduced ventilation on indoor air quality. Much of the monitoring of indoor air quality to date has been carried out in conventional houses to assess the impact of specific pollutant sources, such as gas stoves. The research that has been directed at tight houses has been very cursory and narrow in its focus. Pollutant levels have been measured in relatively tight houses without monitoring any control houses with which to compare the results. Existing houses have sometimes been monitored only after airtightening. In the few studies where adequate controls were provided, the results were inconclusive. Either the sample size was too small, the houses were not representative of existing housing stock, the occupants' behaviour was not characterized adequately, the adequacy of air circulation within the house was not addressed, and/or no inventory of pollutant sources as made.

It is apparent from the literature that air sealing a house does not necessarily elevate indoor pollution levels. Indoor air quality is determined by the rate at which contaminants are emitted into the house air, the extent to which they mix with house air, the rate at which they are removed from the house, and the sensitivity of the occupants - these factors vary widely from house to house and within the same house over time. In some reported cases, air sealing did raise the level of indoor air contaminants where there was a reduction in the rate of air change and no corresponding reduction in the source strength of indoor pollutants. However, the concentration of contaminants, such as radon and formaldehyde, were decreased in some houses after air sealing; presumably because their access points to the living spaces had been sealed.

A review of the literature demonstrated repeatedly that houses with high concentrations of a particular contaminant, were often ones with a strong pollutant source. Houses with unvented gas stoves, a significant amount of new particleboard, new furniture, smokers or high levels of outdoor pollutants were often the ones with elevated levels of indoor contaminants - not simply the tightest houses. Some houses with measured air change rates of less than 0.2 ach had low concentrations of indoor air contaminants, while some houses with air change rates that exceed 0.5 ach had levels of a number of contaminants that exceed existing standards and guidelines.

There is a need to provide homeowners, builders and air sealing contractors with information that will help them identify existing or potential air quality problems that might be affected by air sealing or low ventilation rates. High levels of indoor air contaminants are often associated with high levels of relative humidity and moisture problems, but the absence of humidity problems does not guarantee acceptable air quality, as is commonly assumed.

A separate concern which overlaps the air quality issue, is the need for an adequate air supply for combustion appliances. This is an air quantity problem and was not dealt with in this section of the report. The introduction to Part 1 of this report lists some useful references in this area.

In reviewing the existing indoor air quality literature, it appeared as though a significant amount of work has been interpreted to coincide with the self-interests of the sponsor. For those who intend to do further reading on indoor air quality issues, it is important that papers be read critically with the interests of the sponsoring body in mind.

Natural gas associations may tend to shy away from conclusions that suggest unvented gas appliances contribute to air quality problems (Little, 1981). An association of electrical utilities, on the other hand, might be interested in demonstrating such a connection (GEOMET, 1981). Engineering professionals allied with the nuclear industry may be interested in associating energy conservation activities with increased frequency of radiation-induced lung cancers (Runnals, 1982). And energy conservation firms, after spending years promoting air sealing to reduce energy consumption, are not likely to raise an alarm about poor indoor air quality in tight houses.

Part 3 of this report will investigate measures to improve indoor air quality in both airtight and conventional houses.

PART 3: MEASURES TO IMPROVE INDOOR AIR QUALITY

If it is assumed that low rates of ventilation are responsible for indoor air quality problems, the logical solution is to increase the rate of ventilation. However, as much of the literature reviewed in Part 2 demonstrated, a tight house does not necessarily have poor indoor air quality.

To date, the majority of the research into controlling the levels of contaminants in indoor air has centered around controlled ventilation strategies. Similarly, the common regulatory approach to insuring acceptable indoor air quality has been to set minimum standards of air change. However, as it has become more apparent that the source strength of pollutants plays a major role in determining the quality of indoor air, the literature has begun to focus on the control of the pollutant sources themselves.

Part 3 provides an overview of what is known about reducing indoor air pollution and reviews existing ventilation standards for residential buildings. For a comprehensive survey of indoor air pollution control and low pollution construction techniques, consult:

> Canada Mortgage and Housing Corporation. Indoor Air Pollution and Housing Technology. Bruce Small and Associates, 1983.

3.1 IDENTIFYING PROBLEM HOUSES

To meet both objectives of conserving energy and improving indoor air quality it would be useful to be able to identify problem houses without resorting to an expensive monitoring program. The literature is relatively limited in this area but there are a few reports that are relevant; for example:

> Girman, J.R. et al, Pollutant Emissions Rates From Indoor Combustion Appliances and Sidestream Cigarette Smoke. Lawrence Berkeley Laboratory, 1982.

Silberstein, S., Energy Conservation and Indoor Pollution. Energy and Buildings, Vol. 2: 185-189, 1979.

Traynor, A.V. et al, Exclusion List Methodology For Weatherization Program in the Pacific Northwest. Lawrence Berkeley Laboratory, LBL-14467, 1982.

Silberstein (1979) developed a model to predict the effects of tighter building envelopes on indoor pollution levels, that considers the lower pollution production from the heating system resulting from the lower heating demand. The model suggests that if there is a 75 percent reduction in air change, the carbon monoxide levels contributed by furnace and stove pilot lights would quadruple. Assuming a ventilation rate of 0.25 ach, the model predicts that it would take 4.5 hours for carbon monoxide levels to fall below the Environmental Protection Agency ambient standard after one hour of oven (gas-fired) use. The author suggests that pilot lights should be eliminated and kitchens should be ventilated before airtightening a house.

Girman et al (1982) measured the emission rates of a gas-fired stove, gas-fired unvented space heater, kerosene-fired unvented space heater and sidestream cigarette smoke in a specially constructed environmental chamber where ventilation could be precisely controlled. They concluded that the emission rates of nitric oxides from all four combustion appliances and tobacco smoking were high enough to be of concern, in both single rooms and entire houses, when ventilation is reduced. The authors went as far as to suggest that because the emissions from the unvented space heaters were so high, even under relatively high rates of ventilation, serious consideration should be given to restricting their use.

Traynor (1981) recommends that any residential energy conservation program should include an indoor air quality audit in order to protect the occupants from elevated levels of pollutants. Pollutant sources with a narrow range of emission rates would be inventoried by way of a questionnaire or visual inspection. For example, a questionnaire could assess:

1) the amount and age of indoor particleboard
2) the amount of smoking
3) the amount of concrete and other building materials known to emit radon or formaldehyde
4) the number, location, and ventilation schemes of all combustion appliances.

Those pollutant sources with unknown source strengths, such as radon (source strength can vary by factors of 1,000 from house to house), carbon monoxide, and combustion products from appliances, such as forced-air furnaces and woodburning stoves, would have to be quantified by on-site measurements. Nitrogen dioxide and radon concentrations can be measured quite simply and cheaply with passive monitors (require no external power), but it's expensive and time consuming to measure carbon monoxide, formaldehyde and particulates. A source list of readily available monitoring devices is included in Appendix B.

The Bonneville Power Administration was concerned about the effect that its weatherization program might have on people's health, so it developed an exclusion list which was intended to limit airtightening activities to those houses that lacked major sources of pollutants (Nero, 1982). The power company was primarily concerned about carcinogens such as radon and suspected carcinogens such as formaldehyde and benzo(a)pyrene (a by-product of wood and tobacco combustion), so its exclusion list ruled out airtightening in 70 percent of the eligible homes. Air quality monitoring was not carried out so this list was by necessity, overly conservative.

Homes lacking major sources of indoor air pollutants were defined as having the following characteristics:

1) a full crawl space with cross ventilation and a ground cover vapour barrier (uncommon in eastern Canada)

2) no woodstoves or unvented combustion appliances

3) municipal water supply or a surface water source

4) wood frame construction

5) no urea formaldehyde foam insulation.

The list ignores indoor air pollutants such as cigarette smoke and particleboard.

Nero recommended that more houses could be airtightened if radon levels were quantified by monitoring the houses or by characterizing the source strength in the area. If levels were high, then the power company could offer to undertake remedial measures before air sealing. Similarly, air sealing could be carried out in houses with gas ranges which had ventilation hoods and in houses with UFFI, if the measured levels were low.

The Bonneville Power Administration recently filed an Environmental Impact Statement on the effects of expanding their weatherization program to all houses, as it proposes to meet future demands for electricity through energy conservation (Bonneville Power Administration, 1983).

3.2 INDOOR POLLUTION CONTROL STRATEGIES

The literature on indoor air pollution control strategies, aside from controlled ventilation, is minimal. Control strategies are sometimes incorporated as part of a report on a specific pollutant. Two examples are:

Budnitz, R.J. et al. Human Disease from Radon Exposure: The Impact of Energy Conservation in Residential Buildings. Energy and Buildings, Vol. 2: 209-215, 1979.

Bowen, R.P., Shirtliffe, C.J. and Chown, G.A. Urea Formaldehyde Foam Insulation: Problem Identification and Remedial Measures for Wood-Frame Construction. National Research Council of Canada, Division of Building Research, Building Practice Note #23, 1981.

Budnitz suggests that the best approach to passive radon control is to eliminate the pathways into the building. Radon enters houses through the floor/wall joints, the basement floor drain, around loose fitting pipes, and through cracks in the concrete. Auxier et al (1974) tested a number of sealants and found sealing the foundation walls and floor with epoxy paint reduced the concentration of radon daughters in the air by 75 percent. Aside from actively ventilating a house, Budnitz notes that an electrostatic precipitator or other particle filters could reduce the concentrations of radon daughters in the air, although radon gas would continue to flow into the house at the same rate. Radon control continues to be under active research, particularly in the Scandinavian countries. One of the methods currently being tested is direct ventilation of the radon source in much the same way that a septic tank or sewer is vented.

Bowen et al (1981) lists a series of remedial measures to reduce the concentrations of formaldehyde in homes with UFFI. Since the pollutant source is outside the living space of the house, like radon, the rate at which formaldehyde enters the house air can be slowed by sealing the inside surface of the interior walls. In this situation, the rate of air change would be reduced and formaldehyde levels would drop at the same time. At the other end of the spectrum, the pollutant source can be eliminated by removing the insulation from the walls and ceiling.

There are three papers that provide a useful summary of potential control strategies. These include:

Lord, D. Controlling Indoor Air Pollution in Energy Efficient Environments. National Research Council, Washington, D.C., 1982.

Nero, A.V. et al. Exclusion List Methodology For Weatherization Program in the Pacific Northwest. Lawrence Berkeley Laboratory, LBL-14467, 1982.

Canada Mortgage and Housing Corporation (CMHC). Indoor Air Pollution and Housing Technology. Bruce Small, 1983.

Lord divides pollution control strategies into three major categories: source control, dilution and ventilation, and removal.

Source Control

1) Isolate the pollutant source from the indoor environment. (For example, make occupants who smoke, do so outdoors.)

2) Contain the pollutant source by using paints or films. (Seal the basement walls and floor against radon, for example.)

3) Exhaust the pollutant near its source. (A vent hood over a gas range would be an example.)

Dilution and Ventilation

1) Uncontrolled air exchange through openings in the building envelope.

2) Natural ventilation through open windows, vents or chimneys.

3) Mechanical ventilation.

Removal

1) Mechanical filters and electrostatic air cleaners.

2) Devices that remove gas and vapour.

Bruce Small (CMHC, 1983) lists 16 factors which can help reduce indoor air pollution. They include:

1) Increased Ventilation

2) Decreased Ventilation
   - where outdoor sources are significant

3) Adsorption on Interior Surfaces
   - some pollutants attach themselves to the surface materials in the house

4) Gassing-out Time
   - source strength of some pollutants diminishes with time

5) Low Emission Materials
   - materials can be selected with low rates of pollution emission

6) Source Removal

7) Modified Combustion Processes
   - maintenance, adjustment or redesign of combustion appliances

8) Changes in Design
   - change house design and construction practices to lower pollution

9) Changes in Maintenance Practices
   - reduce reliance on volatile chemical cleaning products

10) Air Filtration

11) Use of Sealants

12) Adjustment of Product Formulation
   - modify the constituents of building materials and furnishings that pollute

13) Treatment of Final Product
   - treat product at factory to reduce out-gassing

14) Ventilation at Source

15) Human Factor Control
   - deliberate reduction of polluting activities

16) Warning Devices and Controls.

Nero et al (1982) lists a series of control techniques that the authors felt were most promising for use in utility sponsored weatherization programs. These include removal of unvented combustion appliances and installation of range hoods for gas stoves; a combination of electrostatic air cleaning and mechanical filtration to remove particulates and lower the concentration of radon daughters; "scrubbing" the air for formaldehyde by passing the gas through water where it would be absorbed, or by passing it over a solid surface where it would be adsorbed (attached); and improved air circulation to increase the rate at which radon daughters and other "reactive" contaminants would attach to indoor surfaces. Reactive contaminants are those compounds, like radon daughters and nitrogen dioxide, that readily attach themselves to indoor surfaces.

The Ontario Ministry of Municipal Affairs and Housing is currently preparing a paper that will outline new ideas and practical guidelines for householders interested in maintaining or improving the quality of their indoor air.

Of all the indoor air pollution control strategies presented in the literature, constant or automatic mechanical ventilation has received an inordinate amount of attention. Many researchers assume that if some minimum level or air change is guaranteed by a mechanical system then concerns about indoor air quality should be alleviated.

3.3 VENTILATION

According to Berk et al (1980) adequate air change is required in all occupied buildings to:

1) Establish a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) released into the environment by human activities.

2) Remove excess heat and moisture from internal sources.

3) Dilute human and non-human odours to acceptable levels.

4) Remove contaminants produced by activities, furnishings, construction materials, etc. in occupied spaces.

Mechanical ventilation systems consisting of a fan driven exhaust system, sometimes balanced with a fan driven fresh air supply, are commonplace in commercial, industrial and even farm buildings. Until recently little consideration has been given to forced ventilation in single-family dwellings. It's always been assumed that wind and temperature differences between inside and outside of a house would be sufficient to move air through the unintentional openings in the building's envelope. Mechanical ventilation provides the occupants with the ability to directly control the ventilation rate to meet their needs. Mechanical ventilation systems are a necessity in air-tight low energy houses where natural infiltration has been reduced to a minimum.

The impact of mechanical ventilation on indoor air quality in relatively tight houses in Rochester, New York was studied by Offerman (1982). When mechanical ventilation (with heat reclamation) was used, the average air change rate increased by 80 percent, from an average of 0.35 ach to 0.63 ach. This resulted in a 50 percent decrease in radon gas concentrations from 1.0 pCi/L to 0.5 pCi/L, a 21 percent decrease in formaldehyde, a 30 percent decrease in respirable particulates, and the relative humidity decreased from 39 percent to 35 percent. The average indoor concentration of nitrogen dioxide increased because the ambient levels outdoor exceeded the indoor levels. Lebret et al (1982) monitored 286 kitchens for nitrogen dioxide and found that ventilation hoods over gas ranges reduced the average NO_2 concentration by 15 percent.

Hollowell et al (1982) monitored the effect of mechanical ventilation in two new energy efficient houses. Air change rates increased from 0.1 ach to 0.3 ach. This resulted in a dramatic drop in levels of carbon dioxide, radon gas and nitric oxide. However the change in air change had little effect on nitrogen dioxide, sulphur dioxide, formaldehyde and ozone.

Formaldehyde, nitrogen dioxide, suspended particulates and radon daughters (not radon gas) are considered to be reactive contaminants. They readily combine with indoor surfaces by absorption or adsorption so that an increase in ventilation rate will not result in an equivalent decrease in the levels of these contaminants. Offerman (1982) suggests that if the reactivity of a contaminant is particularly high, relative to the air exchange rate in a well-mixed space, neither increasing or decreasing ventilation would have a significant effect on its indoor concentration.

A mechanical ventilation system was installed in a house in Maryland that had radon levels well above the existing standard (Nazaroff et al, 1980). The rate of air exchange was systematically increased over two weeks from the natural ventilation rate of 0.2 ach to 0.6 ach. It was only at 0.6 ach that the radon levels dropped below the existing guidelines. No attempt was made to seal the pathways through which the radon gas was entering the house.

3.3.1 Mechanical Ventilation Strategies

Mechanical ventilation strategies break down into two broad categories: unbalanced mechanical exhaust systems and balanced ventilation systems. The former approach uses a fan to exhaust stale air from the house and depends on the unintentional openings in the building envelope to supply the fresh make-up air. The latter strategy employs two fans, one to exhaust stale air and the other to draw in fresh air from outside. Both approaches require a distribution system to effectively ventilate the entire house. Mechanical ventilation systems usually operate at a predetermined speed, but in some cases can be pre-set to speed up when indoor humidity levels increase. Centralized mechanical ventilation systems provide the opportunity to reclaim some of the heat that is normally carried out of the house by exfiltrating air.

Sherman and Grimsrud (1982) examined the impact of a mechanical exhaust system, a mechanical exhaust system with heat recovery, and a balanced system with heat recovery (commonly called an air-to-air heat exchanger) on the total ventilation and energy load of a house. Their results demonstrated that the effectiveness of the ventilation system is critically dependent on the leakiness of the building envelope. An exhaust system with heat recovery appeared to be the most appropriate system for a relatively leaky house because it created a very small additional ventilation and heating load. Exhaust systems increase the rate of infiltration through the building envelope but decrease the amount of natural exfiltration, significantly reducing the naturally driven part of ventilation.

A balanced ventilation system, such as an air-to-air heat exchanger, appeared to be most appropriate for tight houses since it's impact on total ventilation is heavily influenced by the rate of natural ventilation. In a leaky house, natural ventilation through the unintentional openings in the building envelope will combine with the additional ventilation supplied by a balanced system, such that the total ventilation will be greater than would exist with an unbalanced exhaust system (which diminishes the effect of naturally driven ventilation).

The Housing and Urban Development Association of Canada (HUDAC) has drafted guidelines for the design and installation of residential controlled ventilation systems in Canada (HUDAC, 1983). The draft guidelines recommend that a fan induced exhaust system should operate continuously at a low speed to remove moisture and pollutants. To balance the system, an intake is supposed to be provided to supply air for ventilation and for combustion appliances. The exhaust system draws air from all bathrooms and the kitchen, through ducts which ultimately vent the stale air to the outdoors at a centralized location. The intake system uses the furnace fan and the existing forced-air distribution system to draw air into the house and distribute it to the rooms. For houses with hydronic, electric baseboard or radiant heating systems, an intake fan would be required.

HUDAC suggests that the intake equipment should be sized to provide make-up air for all the house's exhausting devices, including furnace and hot water heater flues. According to the Ontario Research Foundation (EMR[b], 1983), the demands of some combustion appliances are important enough to warrant their own air supply without relying on the house's ventilation system.

Balanced ventilation systems with heat recovery provide the opportunity to reduce the energy losses associated with ventilation because warm exhaust air can be used to pre-heat incoming fresh air. A number of researchers have tested the ability of air-to-air heat exchangers to reclaim heat. Their results are reported in the following papers:

> Hamlin, T., and Besant, R.W. Air-to-Air Heat Exchanger Performance Evaluation for Low Energy Houses in Saskatoon, Saskatchewan. Dept. of Mechanical Engineering, University of Saskatchewan, 1982.

Fisk, W.J., Roseme, G.D. and Hollowell C.D. Test Results and Methods: Residential Air-to-Air Heat Exchangers for Maintaining Indoor Air Quality and Saving Energy. Lawrence Berkeley Laboratory, LBL-12280, 1981.

Fisk, W.J. and Turiel, I. Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics. Lawrence Berkeley Laboratory, LBL-13843, 1982.

Offerman F.J. et al. Residential Air Leakage and Indoor Air Quality in Rochester, New York. Lawrence Berkeley Laboratory, LBL-13100, 1982.

Fisk (1981) (1982) tested several heat exchangers in the laboratory and found that the least efficient model reclaimed 43 percent of the heat from the exhaust air stream, while the most efficient model reclaimed 84 percent of the heat that was potentially available from the exhausting air. Hamlin and Besant (1982) tested 13 heat exchangers under operating conditions during a typical Saskatchewan winter. They found that the heat transfer effectiveness of the heat exchangers ranged from 18 percent, when the unit had frosted up, to 60 percent. The most significant finding they reported was that most of the heat exchangers were installed or operated improperly.

Offerman (1982) monitored nine heat exchangers in the field, including two units that were designed to transfer both heat and water vapour. While these heat exchangers would be useless in cold climates where the objective is to exhaust water vapour to the outside, Offerman's results suggest that they may be ineffectual in controlling contaminants that are water soluble, such as formaldehyde.

Fisk (1982) estimates that the operation of an air-to-air heat exchanger can reduce a house's ventilation heating load by 5.3 to 18 gigajoules ($63 to $213 worth of heating oil). This potential for energy saving has precipitated a number of economic analyses of air-to-air heat exchangers (Fisk, 1981, 1982 and Offerman, 1982, Roseme, 1980). Not surprisingly, it's sometimes difficult to justify the installation of a $1,000 heat exchanger, strictly from an investment perspective. Considering the utilitarian role of mechanical ventilation in helping to control indoor air quality and humidity, the value of such cost-benefit analyses is questionable.

Mechanical ventilation systems are already the principle means for ventilating Swedish homes. Approximately 50 percent of the installed mechanical ventilation systems are exhaust systems and 50 percent are air-to-air heat exchangers (Harryssen, 1982). In France, 40 percent of the single-family dwellings and 80 percent of the multi-story flats have mechanical ventilation (Bates and Jardinier, 1982). In Canada, whole house ventilation is a relatively new phenomenon even though there already are 10,000 operating air-to-air heat exchangers installed in single-family dwellings (Allen, 1983).

At what point does one install a centralized mechanical ventilation system? Hamlin and Besant (1982) suggest that air-to-air heat exchangers are only warranted when the house has an airtight vapour barrier or when there are serious humidity or indoor pollution problems. However, some governments have taken the guesswork out of ventilation by passing air-tightness standards that, in most cases, make controlled ventilation practical.

3.3.2 Ventilation Standards

Harryssen (1982) lists 0.2 ach as the minimum air change rate that is required in a typical house to control moisture. The Swedish Building Code stipulates that occupied buildings must be mechanically ventilated at a rate of 0.5 ach. The maximum airtightness value of a building's envelope is required to be 3 ach at a 50 Pa pressure difference.

Proposed revisions to the Code will set a maximum airtightness value of 1.0 ach at a 50 Pa pressure difference, and will require heat recovery from exhaust airstream of the ventilation system.

The Danes have also set a standard of 0.5 ach to maintain acceptable air quality and conserve energy at the same time (Fangar, 1979). In Finland the current airtightness standard is 4 ach at 50 Pa, however, it has been proposed that this eventually be reduced to 2 ach at 50 Pa once the building industry had adopted airtightness as a goal. The standard on which many regulatory bodies in North America and Europe are basing their ventilation standard is ASHRAE 62-1981.

Ventilation for Acceptable Indoor Air Quality

ASHRAE 62-1981 is intended to ensure that buildings have an acceptable level of indoor air quality. This is defined as air that doesn't contain contaminants that exceed concentrations known to impair health or cause discomfort to the occupants.

To ensure acceptable air quality, ASHRAE establishes minimum rates of air change. For residential occupancy, outside air must be supplied at a rate of 5 litres/second (L/s) per habitable room. An additional 25 L/s and 50 L/s must be available on an intermittent basis for bathrooms and kitchens respectively. In commercial buildings ASHRAE specifies higher ventilation rates for spaces where smoking is permitted. As noted in Section 1.3, this standard is currently under revision and may be requiring higher air change rates in the future.

Recognizing that ventilation is only an indirect solution to the control of indoor contaminants, the ASHRAE standard provides for an alternative approach that sets maximum concentration guidelines for certain contaminants. These include the following:

Carbon Dioxide	2500 ppm
Formaldehyde	0.1 ppm
Radon	0.01 WL

Ontario has not yet adopted ASHRAE 62-1981, but it has been recommended that the standard form the basis of the Canadian Standards Association ventilation standard (EMR, 1984). The draft HUDAC ventilation system guidelines uses the ASHRAE standard's ventilation procedure for ensuring acceptable air quality.

The Canadian Standards Association recently sponsored a review of the basic precepts, practices and problems associated with whole house ventilation with a view to identifying the potential for standards (Canadian Standards Association, 1983). The author found no reason to recommend that new ventilation standards or airtightness standards be established until we fill the serious gaps in our knowledge with respect to airtightness, air change rates, safe levels of contaminants and the effectiveness and reliability of mechanical ventilation systems.

It was recommended that a "practice manual" on home ventilation be prepared to assist homeowners and contractors in understanding the problem of maintaining acceptable indoor air quality and to guide them in selecting an appropriate ventilation system. The author also identified eight major studies that must be undertaken, in his opinion, before any kind of ventilation standards can be established.

3.4 SUMMARY

Twelve years ago the prevailing attitude was that, "the solution to pollution depends on dilution." While that approach to outdoor air pollution control solved some localized problems, it caused problems elsewhere. Just as we now attempt to control outdoor pollutants at their sources, the source strengths of indoor pollutants must be reduced. Pollutants like radon can be reduced by sealing the cracks in the basement to keep the radioactive gas from infiltrating into the house. Other pollutants, such as nitrogen dioxide, can be kept at low levels by venting the gas to the outside from the area where it is produced. Still other pollutants, such as formaldehyde, could be minimized by selectively choosing building materials and furnishings for their low pollution characteristics. Houses that lack significant sources of pollutants can be tightened with the least risk of compromising the indoor air quality. If pollution control measures are carried out during energy conservation activities, the indoor air might be of better quality after tightening than before.

Unintentional air leakage cannot provide a house with a constant source of adequate ventilation. Mechanical ventilation provides the occupants with direct control over their fresh air requirements and the opportunity for heat reclamation from exhausting air. Extremely airtight houses can have good air quality if mechanical ventilation is used in combination with pollution control measures. The air supply requirements of combustion appliances should be dealt with separately.

It is often mentioned in the literature that a ventilation rate of 0.5 ach will maintain an acceptable level of air quality, if there are no significant pollutant sources. This, however, is an over-simplification and is not well supported by experimental data. The American Society of Heating, Refrigeration and Air Conditioning Engineers has set a ventilation standard based on the number of habitable rooms in a house. And for the first time in a ventilation standard, ASHRAE is making an attempt to address the sources of indoor air quality problems by setting maximum indoor standards for specific contaminants.

CONCLUSION

Over the past five years there has been a growing concern over the quality of indoor air and its potential impact on human health. The issues involved are not simple or readily resolved, but like the concerns over low levels of chemical contaminants in the food we eat and the water we drink, they are often controversial. This literature review has presented an overview of the existing body of knowledge on the effects of air sealing on indoor air quality; an increasingly popular energy conservation measure that can influence the level of pollutants in indoor air.

In the introduction to this report it was suggested that the salient question was: how tight is too tight? The answer is that it depends. It depends on the type and strength of the pollutant sources in the house, on how well those pollutants mix with the indoor air, and on whether and how much you deliberately ventilate a tight home.

It is evident from the literature that simply air sealing a house does not necessarily elevate indoor pollution levels. It is clearly not the villain that some people understand it to be. The level of indoor air pollution is determined by the rate at which pollutants are emitted into house air, the extent they mix with house air and the rate at which they are removed from the house. It is the combination of these factors that should be of concern.

Air sealing a house can reduce indoor air pollution levels from pollutant sources that are outside of the living space, such as radon from surrounding soil and formaldehyde from urea formaldehyde foam insulation. Air sealing can increase indoor pollution levels if it reduces the level of ventilation, and there is no corresponding reduction made in the source strength of the indoor pollutants.

The work reviewed in this report suggests that air sealing measures rarely reduce the level of ventilation in existing houses to below what is characteristic of conventionally constructed new houses. The one consistent exception are those electrically heated houses that were constructed after 1970. However, ventilation in both the new and old housing stock is uncontrolled and highly variable. The unintentional openings through which air change takes place may not be able to guarantee an adequate supply of air under all conditions. This lends support to the desirability of providing mechanical ventilation for houses to guarantee a minimum level of ventilation, but this is no more the solution to indoor air quality problems than air sealing is the cause.

There are significant gaps in our knowledge about the emission rate of indoor pollutants, their rate of diffusion through the house, the actual concentrations of contaminants that occupants ingest, the sensitivity of different individuals, and the health risks of extended exposure to low concentrations of pollutants. It is easy to point to the need for more and better research to fill those gaps, but in the short-term it is critical that people are made aware of what is known about the sources of indoor air pollution, the associated health risks, pollution control strategies, the conditions where air sealing will reduce indoor air quality, and the conditions where air sealing will enhance it.

TECHNICAL INFORMATION RESOURCES

Lawrence Berkeley Laboratory

A surprising amount of indoor air quality literature has been generated by researchers at the Lawrence Berkeley Laboratory in California. Since 1978, LBL has had a Building Ventilation and Indoor Air Quality Program. For those interested in reviewing their recent work, the mailing address is:

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Air Infiltration Centre

The Air Infiltration Centre (AIC) was established in 1979 by the International Energy Agency to provide technical support for active research in air infiltration in buildings. The AIC publishes a quarterly newsletter: the Air Infiltration Review, sponsors an annual international conference, and publishes AIRBASE: a bibliographic database which includes short abstracts. The AIC can be contacted at:

Air Infiltration Centre
Old Bracknell Lane
Bracknell
Berkshire RG124AH
Great Britain

Canada's national representative is:

Robert Dumont
Division of Building Research
National Research Council
Saskatoon, Saskatchewan
S7N OW9

ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AECB	Atomic Energy Control Board (CANADA)
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
EPA	Environmental Protection Agency (U.S.A.)
CMHC	Canada Mortgage and Housing Corporation
EMR	Energy, Mines and Resources Canada
HUDAC	Housing and Urban Development Association of Canada
MOL	Ontario Ministry of Labour
NAAQS	National Ambient Air Quality Standards (U.S.A.)
NCRP	National Council on Radiation Protection (U.S.A.)
NRC	National Research Council of Canada
OMMH	Ontario Ministry of Municipal Affairs and Housing
OSHA	Occupational Safety and Health Administration (U.S.A.)
SRC	Saskatchewan Research Council
TLV	Threshold Limit Values

GLOSSARY

Acute--When referring to the health effects of air pollutants, acute means those effects that immediately follow the exposure and disappear with the removal of the air pollution.

Air Barrier--A carefully installed covering of the interior of a structure to minimize the uncontrolled passage of air into and out of a dwelling; most commonly a continuously sealed 6 ml polyethylene sheet.

Air Change Per Hour (ach)--A unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour.

Air Infiltration--This is the process by which outside air enters a building through cracks, joints, and other nonintentional openings. The air-infiltration process allows the trading of outside air for inside air (see 'tightening').

Airtightness--The degree to which unintentional openings have been avoided in a building's structure.

Ambient Air--That portion of the atmosphere, external to buildings, to which the general public has access.

ASHRAE--American Society of Heating, Refrigeration, and Air Conditioning Engineers.

Benzo-(a)-Pyrene (BaP)--A tarry, organic material composed of five aromatic rings. BaP has been shown to induce cancers in animals.

Building Code--A legal instrument that is in effect in a province, administered by local government, the provisions of which must be adhered to if a building is to be considered to be in conformance with law and to be suitable for occupancy and use.

Building Envelope--The enclosure created by the components of a house that physically separate the heated living space from outdoors.

Carbon Dioxide (CO_2)--A colourless, odourless gas, heavier than air that arises from the complete combustion of carbon. Carbon Dioxide is a normal constituent of air, amounting to 0.03% by volume.

Carbon Monoxide (CO)--A colourless, odourless toxic gas of approximately neutral density relative to air arising as a result of the incomplete combustion of carbon-bearing materials.

Carcinogen--A material capable of causing cancer.

Chronic--When referring to the health effects of air pollutants, chronic means those effects that are delayed and are exhibited after one or repeated exposures.

EPA--Environmental Protection Agency

Epidemiological--As used here, epidemiological refers to statistical studies that attempt to relate health effects due to small exposures to pollutants by observing human populations exposed naturally or in employment.

Equivalent Leakage Area (ELA)--The total area of all the unintentional openings in a building's envelope, often expressed in square centimetres (cm^2).

Fan Depressurization--A large fan is used to exhaust air from a building in order to create a pressure difference across the building envelope; an analysis of the flow rate through the fan at different pressure differences provides a measure of air-tightness.

Formaldehyde (HCHO)--An organic chemical widely used to link one molecule to another. Formaldehyde-based glues and binders are widely used, in plywood, particleboard, and furniture, for example.

Guidelines--Criteria recommended by government agencies, professional organization, or other groups. Guidelines are not legally binding.

Hemoglobin--The molecule in the blood responsible for oxygen transport. The globin molecule has sites on which oxygen can bind. In this way oxygen is carried from the oxygen-rich lung tissue to the remainder of the body. Carbon monoxide (CO) can also bind to the hemoglobin. Because CO binds to the hemoglobin better than oxygen, this can interfere with the transport of oxygen to the tissue.

Infiltration--The act of permeating with a liquid or a gas by passing through interstices; as used here, the introduction of air to the building from the outside through cracks or other openings.

Micro--A prefix meaning one millionth, abbreviated as μ . For instance, a microgram (ug) is one millionth of a gram.

Milli--A prefix meaning one thousandth, abbreviated as m. For instance, a milligram (mg) is one thousandth of a gram.

Million Electron Volts (MeV)--This is a measure of energy suitable for atomic particles. A MeV is the energy gained by one electronic charge in passing through a potential of one million volts. One MeV is approximately 4.4 x 10-20 kWh.

NAAQS--National Ambient Air Quality Standards

Nano--A prefix meaning one billionth, abbreviated as n. For instance, a nanogram (ng) is one billionth of a gram.

NIOSH--National Institute of Occupational Safety and Health

Nitrogen Oxides (or Oxides of Nitrogen) (NO_x)--All oxides of nitrogen except nitrous oxide as measured by test methods prescribed by EPA.

Normalized Equivalent Leakage Area--Also called the Specific Leakage Area (SLA), this is determined by dividing the ELA of a house by the surface area of its above ground envelope in order to compare the relative airtightness of different size hours.

NRC--National Research Council

Organics--A general term for compounds containing carbon.

OSHA--Occupational Safety and Health Administration

Pico--A prefix meaning one trillionth, abbreviated as p. For instance, a picogram (pg) is one trillionth of a gram.

Pico Curie (pCi)--10^{-12} Curie. The Curie is a measure of radioactivity. A curie is 3.7×10^{10} disintegrations per second.

ppm--Parts per million; when used applying to air pollutants, refers to litres of pollutant per million litres of air.

Radon (Rn)--A colourless, radioactive, inert, gaseous element formed by the disintegration of radium.

Radon Daughters--Product of the radioactive decay of radon. Radon decays by emission of a particle (charged helium nucleus) to polonium (Po). Subsequent decays through the release of a - and b - particles (electrons) result in lead (Pb), bismuth (Bi), and polonium nuclei. The radon daughters discussed in this document are the short-lived daughters through polonium-214. The decay of the radon leaves a charged metal atom that can attach to dust. If the dust is lodged in the lung, the a- and b- particles emitted by the radioactive nuclei damage the tissue. This damage can result in cancer.

Reactive--Some contaminants, such as radon daughters, nitrogen dioxide and ozone, readily attach themselves to surfaces instead of remaining mixed with air.

Retrofit--The thermal improvement of an existing house or structure.

Respirable Suspended Particulate (RSP) Matter--RSP are particles less than 3.5 microns in diameter. RSP tends to be carried to and lodge in the deepest part of the lungs during breathing action.

Standards--Criteria enacted by statute or regulation and are legally binding.

Threshold--As used here, refers to a concentration or exposure below which no health effects occur.

Tightening (also air sealing) - see air infiltration-- Tightening is the process of sealing cracks, joints, and other nonintentional paths by which outside air may enter a residence.

Time-Averaged--Refers to concentration levels averaged over time.

Total Suspended Particulate (TSP) Matter--The quantity of all suspended particles. See Respirable Suspended Particulate Matter.

Working Level--A quantity of short-lived radon daughters that will result in 130 thousand million electron volts (MeV) of potential alpha (a) particle activity per litre of air (see: Million Electron Volt, Radon Daughters).

CONVERSION FACTORS

1 ppm CO	=	1150 ug/m^3
1 ppm CO_2	=	1800 ug/m^3
1 ppm NO_2	=	1880 ug/m^3
1 ppm HCHO	=	1230 ug/m^3

NOTE: Values at 25^oC and 1 atm. pressure (760 mm Hg)

(Ministry of Consumer and Commercial Relations, 1981)

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APPENDIX A

Standards For Carbon Dioxide

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3 (ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act		no standard	
	Ontario Environmental Protection Act a) Ambient Air Quality Criteria b) Emission Standards		no criterion	
	NAAQS a) Primary U.S. EPA b) Secondary		no standard	
INDOOR	ASHRAE 62-73 Standards		9.0×10^5 (500)	TLV/10[2]
	Submarine Environment Standards U.S. Navy	90 d	0.8% 0.5% for Trident and later class submarines	average reading, levels not to exceec 1%, tactical situation permitting
		24 h	1.0%	limit
		1 h	2.5%	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	9.0×10^6 (5000)	
	NIOSH Recommendations (Status OCT. 1978)	10 h	18 000 (10,000)	TWA[1]
		10 m	54 000 (30,000)	Ceiling limit
	OSHA Standards (Status OCT. 1978)	8 h	9.0×10^6	TWA

NOTE: 1 Time Weighted Average

2 As specified in Sec. 3.3., ASHRAE Standard 62-73

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Carbon Monoxide

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act	8 h	6 000	(5.22)	max. desirable[1]
			15 000	(13.04)	max. acceptable[2]
			20 000	(17.39)	max. tolerable[3]
		1 h	15 000	(13.04)	max. desirable
			35 000	(30.43)	max. acceptable
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria	8 h	15 700	(13.00)	
		1 h	36 200	(30.00)	
	b) Maximum Concentration	0.5 h	6 000	(5.22)	at point of impingement (defined in Reg.308)
	NAAQS U.S. EPA Primary & Secondary	8 h	10 000	(9.00)	max. standards based on other than annual ave. not to be exceeded more than once a year
		1 h	40 000	(35.00)	
INDOOR	ASHRAE 62-73 Standards	1 y	20 000	(17.39)	
		8 h	30 000	(26.09)	not to be exceeded more than once per year
	Submarine Environment Standards U.S. Navy	90 d	17 250	(15.00)	limit
		24 h	230 000	(200.)	limit
		1 h	230 000	(200.)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	57 500	(50.00)	accepted by Canadian federal and provincial authorities for occupational standard
	NIOSH Recommendations (Status OCT. 1978)	10 h	40 000	(35.00)	TWA[4]
		15 m	30 000	(10.00)	Ceiling limit
	OSHA Standard (Status OCT. 1978)	8 h	57 500	(50.00)	TWA

NOTE:
1 For new industry in non-industrialized areas
2 Secondary objectives for established industrial areas
3 Objectives for heavily industrialized areas
4 Time Weighted Average

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Oxides of Nitrogen

(All Standards Given For Nitrogen Dioxide)

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m³	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act	1 y	60	(0.03)	max. desirable [1]
			100	(0.05)	max. acceptable [2]
		24 h	200	(0.11)	max. acceptable
			300	(0.16)	max. tolerable [3]
		1 h	400	(0.21)	max. acceptable
			1 000	(0.53)	max. tolerable
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria	24 h	200	(0.10)	
		1 h	400	(0.20)	
	b) Maximum Concentration	0.5 h	500	(0.26)	at point of impingement (defined in Reg. 308)
	NAAQS U.S. EPA Primary & Secondary	1 y	100	(0.05)	
INDOOR	ASHRAE 62-73 Standards	1 y	200	(0.11)	
		24 h	500	(0.26)	not to be exceeded more than once per year
	Submarine Environment Standards U.S. Navy	90 d	940	(0.50)	limit
		24 h	1 880	(1.00)	limit
		1 h	18 800	(10.00)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	9 400	(5.0)	MAC[4], accepted by Canadian federal and provincial authorities for occupation stnd.
	NIOSH Recommendation (Status OCT. 1978)	15 m	18 000	(1.00)	Ceiling limit
	OSHA Standard (Status COT. 1978)	8 h	9 400	(5.00)	TWA [5]

NOTE:
1 For new industry in non-industrialized regions
2 Secondary objectives for established industrial areas
3 Objectives for heavily industrialized areas
4 Maximum Acceptable Concentration
5 Time Weighted Average

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Formaldehyde

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act		no standard		
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria		no criterion		
	b) Maximum Concentration	0.5 h	65	(0.05)	at point of impingement (defined in Reg. 308)
	NAAQS a) Primary U.S. EPA b) Secondary		no standard		
INDOOR	ASHRAE 62-73 Standards		300	(0.20)	TLV/10[3]
	Submarine Environment	90 d	615	(0.50)	limit
		24 h	1 230	(1.00)	limit
		1 h	3 690	(3.00)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	2 460	(2.00)	MAC[1]
	NIOSH Recommendations (Status OCT. 1978)	30 m	1 200	(1.00)	Ceiling limit
	OSHA Standards (Status OCT. 1978)	8 h	3 690	(3.00)	TWA[2]
			6 150	(5.00)	Acceptable Ceiling
		30 m	12 300	(10.00)	Maximum Ceiling

INDOOR
RESIDENTIAL OTHER COUNTRIES

Sweden and Czechosovakia 1979	Maximum allowable indoor air quality standard 100 ug/m^3 (0.08 ppm) (Ref. 48)
Netherlands 1978	Maximum permissible concentration indoors 120 ug/m^3 (0.01 ppm) (Ref. 48, 20)

Denmark and West Germany considering 120 ug/m^3 (0.1 ppm) for indoor air quality (Ref. 20). Germany's occupational limit is 1200 ug/m^3 and 30 ug/m^3 for continuous exposure in outdoor air (1975) (Ref. 4)

NOTE: 1 Maximum Acceptable Concentration
2 Time Weighted Average
3 As specified in Sec.

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Radon Daughters

AIR TYPE	STANDARD	Averaging Period	Concentration	COMMENT
AMBIENT	--	--	--	None available
INDOOR	AECB Primary Criterion - remedial action	1 y	0.02 WL	Prompt interim action 0.15 WL investigational level 0.01 WL
	Ontario Ministry of Labour - new homes		0.02 WL	
	EPA Recommendations Florida - remedial	1 y	0.02 WL/ALARA[1]	Remedial action recommended for greater than 0.02 WL, and ALARA for 0.005 to 0.02 WL
	- new homes		0.005 WL above BG[2] or ALARA	
	Dec. 1980 Draft		0.015 WL	
	U.S. Surgeon General Grand Junction	1 y	0.01 WL above BG	Remedial action recommended for greater than 0.05 WL, and perhaps suggested for 0.01 to 0.05 WL
	Sweden - remedial - major renovations - new homes	1 y	400 Bq (0.11 WL) 200 Bq (0.50 WL) 70 Bq (0.019 WL)	No exposure to exceed 2000 Bq.y/m^3 over 5 year trial period
WORK PLACE	U.S. Secretary of Labour	1 y	4 WLM	) No more than) 2 WLM in any) 3 month period
	Canada - AECB Regulation as of Jan. 1978	1 y	4 WLM	)

NOTE: 1 ALARA as low as reasonably achievable
2 BG implies normal background for the area.

(Ministry of Consumer and Commercial Relations, 1981)

APPENDIX B

Detection and Monitoring Equipment for Indoor Air Pollutants

Carbon Monoxide		General Electric Co. Wilmington, MA Energetics Science Elmsford, NY
Formaldehyde	PRO-TEK BADGE	E.I. duPont de Nemours & Co. Inc. Wilmington, Delaware 19898
Nitrogen Dioxide	PALMES SAMPLER	MDA Scientific Inc. Glenview, IL
Radon	TRACK ETCH DETECTOR	Terradex Corp. Walnut Creek, CA
Furnace Flue Malfunctions	GAS-TRAC DETECTOR	J & N Enterprises Wheeler, IN

INDOOR AIR QUALITY IN TIGHT HOUSES: A LITERATURE REVIEW

PREPARED FOR:

HOUSING CONSERVATION UNIT

ONTARIO MINISTRY OF MUNICIPAL AFFAIRS AND HOUSING

BY:

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of the Ministry of Municipal Affairs and Housing

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the views or the opinions of the Ministry
of Municipal Affairs and Housing

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INTRODUCTION

In order to reduce heating costs and increase comfort levels there has been a move towards building more tightly sealed houses and reducing air leakage in existing dwellings. This trend has raised questions regarding the possible adverse effects of lower ventilation rates on indoor air quality and on the health of occupants.

The salient question that needs to be answered would appear to be: how tight is too tight? Or how much air leakage can be eliminated without compromising health, safety and comfort? But the air in most homes already contains a host of chemicals that are present in low concentrations. Outdoor air pollution, combustion appliances, building materials, furnishings, and human activities such as smoking, all contribute noxious gases to the indoor environment. So a better question might be: how does air sealing affect indoor pollutant levels?

If there are existing indoor air quality problems, are these a result of inadequate ventilation or do the emission rates of the pollutants themselves play a more significant role? Perhaps pollutants simply accumulate in those areas of a house where there is poor circulation, creating local "hot spots."

We are exposed to a plethora of chemicals everyday in the food we eat, the water we drink and in the air we breathe; at work, outdoors and inside our homes. Perhaps current concerns over the quality of indoor air are simply a reaction to the effect of low levels of contaminants on a few hypersensitive people, or to some of the sensationalized media coverage the subject has received. Headlines such as: "Energy Conservers Nearly Lose Lives In Insulated House," "Homes So Airtight They Make People Sick" and "A Snug, Warm House May

Be A Health Hazard" don't instill a lot of confidence in the benefits of air sealing and other energy conservation measures.

Air sealing and controlled ventilation are strategies that are being used to improve air quality inside homes that have been insulated with urea formaldehyde insulation. Perhaps air sealing is part of the solution to other indoor air quality problems. For example, much of the radon gas that is found indoors, enters the house from outside.

The objectives of this literature review are to provide an overview of the existing body of knowledge on the effects of air sealing on indoor air quality, to identify the gaps in our knowledge and make suggestions regarding possible research efforts in the future. While it is recognized that other energy conservation activities, such as the installation of urea formaldehyde insulation, can affect the air quality in houses, an examination of these measures is beyond the scope of this paper.

Low ventilation rates can contribute to furnace backdrafting, particularly where fireplaces, exhaust fans and clothes dryers lack a sufficient supply of air, so that carbon monoxide and other noxious products of combustion are drawn down the furnace flue and into the house. This kind of acute indoor air quality problem will not be addressed in this paper. Rather, the emphasis will be on the build-up of contaminants which, over time, can lead to chronic health problems. The following papers provide a good overview of the air requirements of fuel burning appliances and the backdrafting problem:

B.C. Research. A Study of Residential Combustion-Air Requirements and Air Supplies, prepared for Gas Safety Branch, Ministry of Labour, British Columbia, 1983.

Hatch Associates Ltd. Hazardous Heating and Ventilation Conditions In Housing, prepared for Canada Mortgage and Housing Corporation, 1983.

Moffat, S. Evaluation Of A Residential Chimney Backdraft Checklist, under preparation for Canada Mortgage and Housing Corporation, 1984.

Part 1 of this review will briefly examine the nature and sources of contaminants found in indoor air, and their effects on human health and comfort. The levels or air pollutants that have been measured in conventional housing stock will be summarized, and the existing guidelines and standards for indoor air pollutants will be described.

The second section will review the methods of determining the airtightness of a house's structure and its air change rate. Empirical data on the airtightness and air change rates of conventional housing stock will be described. Case studies that assess the actual impact of air sealing on air leakage will be presented, along with the effects of lower air change rates on contaminant levels in both new and existing housing.

Finally, this paper will review the literature pertaining to those measures that can be taken to improve indoor air quality. The effectiveness and desirability of such remedial measures as reducing the source strength of pollutants, adding controlled mechanical ventilation and installing air cleaning equipment, will be described and evaluated.

An emphasis has been placed on incorporating Canadian literature into this review. To make this paper as relevant as possible, an issues-oriented format has been used.

PART 1: INDOOR AIR QUALITY IN CONVENTIONAL HOUSING STOCK

In order to assess the impact of air sealing measures on indoor air quality, it's necessary to characterize the quality of the air in conventional housing stock.

In his exhaustive review of the indoor air quality literature, Bruce Small (CMHC[a], 1983) concluded that indoor air pollution is, in fact, a problem in Canada. He reviewed hundreds of research reports which clearly established that indoor air is typically more polluted than outdoor air.

> Typical indoor air in most buildings is like a thin chemical soup. Most dwellings contain many air contaminants at relatively low concentrations, below present industrial and outdoor exposure limits. (However) these levels of exposure can pose a health problem at least for certain high-risk groups. The long term risk to the general population is unknown.
> (CMHC[a], 1983)

What follows is a brief summary of the nature of the contaminants, their sources, possible health effects, average and maximum levels of contaminants measured in the housing stock, and existing or proposed indoor standards.

1.1 NATURE OF THE CONTAMINANTS AND THEIR SOURCES

Indoor air contains trace amounts of hundreds of chemicals but few have been investigated with respect to home environments. The indoor air contaminants that have received most of the attention in the literature are those chemicals that have already created health problems, such as carbon monoxide and formaldehyde, and those that have been frequently measured at levels that exceed either existing outdoor standards or occupational exposure limits, such as carbon dioxide, the oxides of nitrogen and radon. The health effects that have been attributed to these chemicals range from feelings of uneasiness due to exposure to formaldehyde, to cancer induced by radon.

Table 1.1 summarizes the major sources of indoor air contaminants.

What follows is a brief summary of the nature of the contaminants that are currently recognized as being important, their sources, possible health effects, average and maximum levels measured in the housing stock, and existing or proposed standards (for quick reference, consult Table 1.2). This topic area has recently been reviewed in two comprehensive publications. Readers are encouraged to consult:

C.M.H.C. Indoor Air Pollution and Housing Technology. Prepared by Bruce Small and Associates, 1983.

National Research Council (U.S.) Committee on Indoor Pollutants. Indoor Pollutants. National Academy Press, Washington, D.C. 1981 NTIS Report PB82180563.

Table 1.1

Major Sources of Indoor Air Contaminants

SOURCES	MAJOR POLLUTANT TYPES
OUTDOOR	
Automobile Exhaust	Carbon Monoxide
Soil and Groundwater	Radon Gas - Radon Daughters
INDOOR	
Gas Ranges Kerosene Heaters Gas Clothes Dryers	Carbon Monoxide, Nitrogen Dioxide, Carbon Dioxide
Malfunctioning Fossil Fuel Furnaces	Carbon Monoxide, Nitrogen Dioxide
Wood Stoves, Fireplaces	Carbon Monoxide, Nitrogen Dioxide, Benzo(a)pyrene
Particleboard, Plywood	Formaldehyde
Furnishings	Formaldehyde
Urea Formaldehyde Foam Insulation	Formaldehyde
Concrete	Radon Gas - Radon Daughters

Table 1.1 (cont'd)

Tobacco Smoke	Carbon Monoxide, Nitrogen Dioxide, Benzo(a)pyrene, Formaldehyde
Human/Animal Metabolic Activity	Carbon Dioxide

1.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is a gaseous by-product of combustion and animal metabolism. The major outdoor sources of CO_2 are related to the combustion of fossil fuels and industrial processes. Significant indoor sources include humans, pets and unvented gas appliances such as ranges, clothes dryers and space heaters. High levels of CO_2 are generally found in the areas of a house where the occupants spend most of their time, and appears to be directly related to the occupant density (IEC Beak, 1983).

CO_2 reduces the flow of oxygen to the brain and can cause headaches, dizziness and nausea at high concentrations above 30,000 parts per million (ppm). In occupied houses, CO_2 concentrations range between 300 and 2,000 ppm (NRC (U.S.), 1981). The long-term health effects of exposure to moderate concentrations (1,000 - 5,000 ppm) of CO_2 are not well documented. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has stated that levels of indoor CO_2 should not exceed 2,500 ppm in residences. The Ontario Ministry of Labour uses an average 8 hour concentration of 600 ppm as its guideline for CO_2 in office buildings.

1.1.2 Carbon Monoxide

Carbon monoxide (CO) is a product of the incomplete combustion of fossil fuels. This occurs when insufficient oxygen is mixed with the fuel during combustion. The largest outdoor source of carbon monoxide is the automobile, followed by power plants and industrial processes (Gas Research Institute, 1981). Major indoor sources include cigarette smoking, gas ranges, malfunctioning gas-fired heating systems, unvented kerosene space heaters, fireplaces, misfiring oil furnaces, and idling cars in attached garages (Traynor et al, 1981). Unvented gas or kerosene space heaters appear to be the most significant indoor source of CO in the housing stock although gas ranges are the predominant source in houses that contain them (Sitwell, 1982).

CO combines with hemoglobin in the blood and inhibits oxygen uptake. Symptoms of CO poisoning include impaired vision, headache and nausea; coma and death can result at levels above 400 parts per million (ppm) depending on the duration of exposure and concentration of CO (Kent, 1979). As reported by Small (CMHC[a], 1983), CO levels above 35 ppm have been found, in some studies, to decrease the amount of oxygen taken up by the blood during exercise, resulting in a reduction in endurance. The long-term effects of exposure to CO are not well established, but studies of children whose mothers were heavy smokers during pregnancy, have found indications that these children lag a few months behind children of non-smokers in general reading and mathematical ability (Butler and Goldstein, 1973).

Indoor levels of CO can exceed 100 ppm in kitchens where unvented gas stoves are used (Sitwell, 1983). Sterling et al (1981) reported that indoor levels are between 6 and 7 ppm near medium-sized thoroughfares. Indoor levels of CO typically vary from 0.5 to 5 ppm as an average (Yocum et al, 1970). Outdoor levels in Toronto, for example, range between 10 and 50 ppm (Sitwell, 1983).

There are currently no residential indoor air standards for CO. The Ontario Ministry of Consumer and Commercial Relations (1981) review of air quality standards reports that the U.S. Navy has a 90 day average of 15 ppm as the allowable limit in submarine environments. Ontario has an eight hour average ambient air quality criteria of 13 ppm for outdoor air.

1.1.3 Oxides of Nitrogen

Nitric oxide (NO) and smaller amounts of nitrogen dioxide (NO_2) are produced during combustion. After mixing with air, the nitric oxide combines with oxygen to produce nitrogen dioxide. The principle outdoor sources are automobiles and industrial furnaces, while indoor sources include unvented fuel burning appliances such as gas ranges and kerosene space heaters, and tobacco smoking.

The short-term health effects of exposure to NO_2 include irritation of the mucous membranes of the respiratory tract, changes in sensory perception at levels as low as 0.1 ppm, and aggravation of respiratory illnesses at concentrations of 13 ppm or more (CMHC[a], 1983).

The long-term health effects of NO_2 have been the subject of vigorous debate. Melia et al (1977) (as reported in Hollowell and Traynor, 1978) found that children living in homes with gas cooking had significantly more respiratory illnesses than did children from homes where electric ranges were used. This study has been widely quoted in the literature as evidence of a link between exposure to NO_2 and respiratory ailments but as Young (Gas Research Institute, 1981) noted, the smoking habits of the parents and the room temperatures in the houses were not considered in Melia's analysis. Young also noted that the authors themselves felt their results were inconsistent and that any association between the indoor levels of NO_2 and the health of the children had been exaggerated and misinterpreted. There is no doubt that homes with gas ranges have higher levels of NO_2 than homes with electric ranges but the evidence of an association between respiratory illness and gas cooking remains inconclusive (Dockery, 1981).

In typical houses the indoor concentrations of NO_2 range from 100 to 530 parts per billion (ppb) with reported peaks of 900 ppb (CMHC[a], 1983). The Canadian Ambient Air Quality Standards for NO_2 are a one hour average of 0 to 20 ppb and a 24 hour average of 1 - 110 ppb. There are no standards for NO_2 in residential indoor air.

1.1.4 Benzo(a)pyrene

Benzo(a)pyrene (BaP) is a gaseous compound that is formed during the combustion of organic materials. BaP is just one of a number of polycyclic aromatic hydrocarbons (PAH) that result from combustion, but it is the most commonly measured compound from this group and is used as an indicator for the presence of these compounds. Wood burning and tobacco smoke are the major indoor sources of BaP, while unvented gas appliances and kerosene space heaters are less important sources. The most important outdoor sources of BaP include coal-fired industrial processes and electrical power plants. BaP, like many of the PAH compounds, is known to be a potent carcinogen. Some of the risk of developing lung cancer from smoking may come from exposure to BaP (Bonneville Power Administration, 1983).

BaP has been measured in urban locations at .002 micrograms per cubic metre (ug/m^3), at .002 to .004 ug/m^3 in a medium-sized room with three smoking occupants, and in a restaurant at levels ranging between 0.3 to 0.14 ug/m^3 (as reported in CMHC[a], 1983). There are no standards or guidelines for exposure to BaP.

BaP readily attaches itself to particulates which are also a by-product of combustion. Particulates are either classified as respirable suspended particulates (RSP) or total suspended particulates (TSP). Respirable suspended particulates are thought to be more damaging to the lungs than TSP because they are small enough to become trapped in the lungs. There are no standards for RSP. The U. S. Environmental Protection Agency's standard for maximum allowable levels of TSP in outdoor air is 75 ug/m^3 on an annual basis (time-averaged) and 240 ug/m^3 for a single 24-hour period (NRC, 1981).

1.1.5 Formaldehyde

Formaldehyde (HCHO) is a colourless gas with a pungent odour. It is commonly used in the manufacture of urea formaldehyde resins which are used as adhesives in particleboard, plywood, carpet backing, furnishings, and are major components of urea formaldehyde foam insulation (UFFI). These materials release the gas into the air at a variable rate, depending on their age, surrounding humidity and temperature. It has been reported that the rate of formaldehyde released from most materials decreases by 50 percent within five years of their manufacture (NRC (U.S.), 1981). Formaldehyde is also a by-product of combustion, with gas stoves and tobacco smoking as the major indoor sources.

Eye, nose and throat irritation, coughing and asthma-like symptoms, headaches, dizziness, nausea, vomiting, and nose bleeds have all been reported by people living in houses with elevated formaldehyde levels (Chown, 1981). Most of the known short-term health effects related to formaldehyde exposure are transitory in nature and disappear when the pollutant is eliminated, however, repeated or long-term exposure may increase a person's sensitivity to the gas, and to allergens such as dust. Chronic exposure to formaldehyde may cause changes in the structure and performance of the respiratory system (Bonneville Power

Administration, 1983). Formaldehyde is a suspected carcinogen since animal studies have shown that it can produce nasal cancer.

Average indoor levels of formaldehyde in homes with UFFI or a significant amount of particleboard, range from 0.01 ppm to 1.0 ppm. This is the range in which health effects have occurred (NRC (U.S.), 1981). Most people can smell formaldehyde gas at concentrations of less than 1.0 ppm. Canada, Norway, Denmark and West Germany have established 0.1 ppm as the acceptable level of formaldehyde in residential indoor air while Sweden and Czechoslovakia have set a standard of 0.08 ppm (CMHC[a], 1983 and Consumer and Commercial Relations, 1981).

For a comprehensive review of the literature pertaining to formaldehyde and other organic (carbon-containing) compounds that can have adverse health effects in indoor environments see:

Lepman, S.R., Miksch, R.R., Hollowell, C.D. Organic Contaminants: A Bibliography. Lawrence Berkeley Laboratory, LBL-12199, 1981.

1.1.6 Radon

Radon is a radioactive gas that is released by the decay of radium, which itself is a decay product of uranium. Radium is a naturally occurring trace element found in soil, rock and groundwater, and to a lesser extent, in building materials such as concrete and brick. Radon gas enters houses by diffusing through the basement floor slab and foundation walls, by leaking through cracks in the basement, around loose fitting pipes and floor drains, and via tap water taken from wells (Budnitz, 1979). Radon can also be released by radium-containing building materials.

Radon gas in itself doesn't pose a significant health threat but its decay products, or radon daughters, can cause lung cancer. Radon gas has four daughters, which can attach themselves to dust or other airborne particles. When inhaled, these particles may become trapped in the lung, irradiating the surrounding tissue (Budnitz, 1979). Since radon gas usually enters the house from outdoors, a careful sealing job in the basement should reduce the flow of radon into the house. Also because radon daughters readily attach themselves to dust particles, electrostatic air cleaners or particle filters could be effective in reducing the concentrations of radon daughters.

Harley (1980) suggests that the lung cancer which appears to be spontaneously induced (not related to smoking or known carcinogens in the work environment) may be the result of exposure to radon daughters in the environment. He developed a model which predicts an upper limit of 30 to 60 lung cancers per year per million persons resulting from exposure to radon. The Bonneville Power Administration (1983) has estimated that between 22 and 257 radon-induced lung cancers occur in the Pacific Northwest (Washington, Oregon, western Montana) each year.

Concentrations of radon gas are conventionally expressed in pico-Curies per litre of air (pCi/L). (The Curie is a measure of radio-activity and pico is simply a prefix meaning one trillionth.) Radon daughter concentrations are expressed in working levels (WL), a unit designed to indicate the relative health hazard of the radon daughters. The concentration of radon gas in a house is not a good indication of the health hazard associated with its daughters.

McGregor (1980) measured the concentrations of radon gas and radon daughters in the basements of 9,999 homes in 14 Canadian cities. Approximately 64 percent of all homes measured had radon gas concentrations of 1 pCi/L or less and about 95 percent had radon daughter concentrations of 0.2 WL or less. The highest concentration of radon gas was 75 pCi/L in St. Lawrence, Newfoundland and the highest concentration of radon daughters was 0.233 WL in Sherbrooke, Quebec. Of the 14 cities sampled, Sudbury had the highest average level of radon daughters, with Thunder Bay ranking fourth and Toronto in seventh position.

The Atomic Energy Control Board (AECB) and the Ontario Ministry of Labour have adopted an average annual concentration of 0.02 WL as the level above which remedial measures must be taken in housing in uranium mining and processing communities (Primary Criterion). AECB has also adopted two single measurement criteria: 0.15 WL to identify houses that require immediate attention and 0.01 WL to identify houses that warrant further investigation. Based on an "equilibrium factor" that was selected by AECB, the corresponding concentrations of radon gas are 7 pCi/L, 50 pCi/L and 3 pCi/L (IEC Beak, 1983). Most of the literature assumes a range of 3 to 6 pCi/L corresponds to 0.02 WL, depending on the source strength of the radon and the household rate of air change that were assumed.

For a comprehensive review of the radon literature see:

Lepman, S.R., Doegel, M.L., Hollowell, C.D. Radon: A Bibliography, Lawrence Berkeley Laboratory, LBL 12200, 1981.

Table 1.2

Standard, Reported Data and Typical Sources

Contaminant	Outdoor Standards Time Span	Outdoor Standards Level (ppm)	Reported Outdoor Levels Time Span	Reported Outdoor Levels Range (ppm)	Reported Outdoor Levels Average (ppm)	Indoor Guidelines Time Span	Indoor Guidelines Level (ppm)	Reported Indoor Level Range (ppm)	Reported Indoor Level Maximum (ppm)	Typical Sources
Carbon Monoxide	Canada -8 hour -1 hour U.S. -8 hour -1 hour	5.5-14 14-32 9 25	Annual 8 hour 1 hour	0.8-3.2 0-17 0-31	1.7 NA NA	ACGIH -8 hour -STEL	50 400	0.05-5 Kitchens 34.5-120	100 -	Unvented kerosene heater gas ranges, automobiles, tobacco smoking, mal-functioning furnaces
Carbon Dioxide	NA	NA	1 hour	NA	400	ACGIH -8 hour STEL ASHRAE MOL (8hr)	5000 15000 2500 600	1 hour 0-3000	NA	Human metabolic activity unvented fuel burning appliances
Nitric Oxide	NA	NA	NA	NA	0.002	ACGIH -8 hour -STEL	25 35	1 hour -.03-0.3	0.5	Unvented fuel burning appliances, tobacco smoking, automobile exhaust
Nitrogen Dioxide	Canada -Annual -24 hour -1 hour	0.032 0.110 0.220	Annual -24 hour -1 hour	0.01-0.0 NA NA	0.026 0.011 0.530	-8 hour -STEL	3.0 5.0	0.1-0.53 0.05-0.5 (1hr)	0.9	
Formaldehyde	NA	NA	-2 hour	0.01-0.05	NA	UFFI/ICC -7 day Health & Welfare ACGIH (8 hr)	0.05 0.1 2.0	0.02-0.4	0.4	Urea Formaldehyde Foam Insulation, particle-board, plywood, furnishings
Radon	NA	NA	-30 days	0.01-1.0 pCi/L		-Annual AECB -Single Measure	0.02WL (3-6pCi/L) 0.15WL-Prompt Action (50 pCi/L 0.01WL-Investigate (3 pCi/L)	0.1-1140 pCi/L	?	Soil, rock, groundwater

ACGIH - American Conference of Governmental Industrial Hygienists
STEL - Short Term Exposure Limit - 15 minutes maximum
ASHRAE - American Society of Heating, Refrigeration & Air Conditioning Engineers
MOL - Ontario Ministry of Labour
UFFI/ICC - Urea Formaldehyde Foam Insulation/Information-Coordination Centre
AECB - Atomic Energy Control Board

(Ontario Ministry of Municipal Affairs and Housing, 1983)

1.2 HEALTH EFFECTS OF LOW LEVEL EXPOSURE TO INDOOR AIR CONTAMINANTS

One of the objectives of Small's review of the indoor air quality literature for CMHC (CMHC[a], 1983) was to comment on the significance of the indoor air pollution problem in Canada. While he concluded that a problem existed, he found that there was not enough information available to know the extent of health damage associated with indoor air pollution.

The technology is readily available to measure the concentration of contaminants in indoor air but little is known about the emission rates of indoor pollutant sources, the rate of diffusion of the pollutants through the home, the actual contaminant concentrations that the occupants ingest, the sensitivity of different occupants, and the long-term health effects of extended exposure to low concentrations of pollutants.

There is a significant body of knowledge surrounding the risk of health effects of exposure to high levels of some of the contaminants commonly found in indoor air, and this has been used to estimate risk at lower concentrations. For example in one study, the Bonneville Power Administration in the U.S. (BPA, 1983) used occupational health data for exposure to radon, formaldehyde and Benzo(a)pyrene, in an attempt to estimate the health effects of exposure to lower concentrations of these chemicals. This was done through a downward linear extrapolation from known risks at high levels of exposure, to lower levels of exposure. It was assumed that there was no threshold below which health was not threatened and that the level of risk decreased in direct proportion to the decrease in concentration of contaminants. Residences were assumed to have a range of pollutant emission rates, volumes, and air exchange rates. On this basis it was estimated that between 1 and 18 formaldehyde-induced cancers, between 22 and 257 radon-induced cancers and 9 to 487 BaP-induced cancers occur in the Pacific Northwest of the U.S. (pop. 3.3 million) each year due to exposure in the home.

The Bonneville Power Administration notes in its report that these estimates are highly speculative because of the high degree of uncertainty in the technique used for assessing the risk. The assessment of health risk is extrapolated from occupational study groups which primarily include healthy adult males who may also be exposed to high levels of other pollutants in their work environments.

In a 1979 report to the Canadian Environmental Advisory Council, Ross Hall and Donald Chant examined some of the current limits to our knowledge of the health effects of chemicals (Hall and Chant, 1979). Toxicology conventionally deals with chemical contamination by studying a single chemical at a time, by establishing acute short-term effects, under carefully controlled laboratory conditions, with relatively high levels of substances. However the reality of chemical contamination is that humans are exposed to thousands of chemicals in their food, water and air, often at very low levels, under widely variable conditions.

It has been estimated by the U.S. Environmental Protection Agency that there are approximately 63,000 commercial chemicals in use, most of which didn't exist 25 years ago (Maugh, 1978). Paints, sealants, household fabric and furnishings contain a host of chemical additives, and the use of glue-laden particleboard and plywood in building materials and furnishings is now commonplace. This trend has contributed to a higher likelihood of increased indoor air pollution levels in houses today (CMHC[a], 1983).

Since it's difficult to quantify the risks associated with exposure to low levels of those contaminants whose health effects are known and impossible to identify the long-term health effects of other contaminants given the current state of toxicology, there is no adequate yardstick that can be used to set indoor air pollution standards or guidelines that would establish acceptably "safe" levels of contaminants. However, much of the air quality literature relies heavily on "acceptable levels" of a few standard indoor air pollutants as proof that there is or is not an indoor air quality problem.

1.3 INDOOR AIR QUALITY STANDARDS AND GUIDELINES

In 1981 the Ontario Ministry of Consumer and Commercial Relations undertook a survey of existing indoor air quality standards.

Consumer and Commercial Relations Indoor Air Quality Standards Literature Survey, Report No. 1184/1154. DSMA ATCON LTD., 1981.

Its review surveyed ambient (outdoor) air, occupation and residential indoor air quality standards in Canada, the U.S. and other countries for a variety of contaminants including nitrogen dioxide, carbon monoxide, carbon dioxide, formaldehyde and radon daughters (see Appendix A for a summary). The review found that specific residential indoor air guidelines and standards exist only for formaldehyde and radon daughters.

The report cautions against applying occupational standards set for the workplace to the residential environment. Occupational standards permit higher levels of contaminants than ambient standards because they are primarily concerned with immediate health of the workers. These standards assume a uniformly healthy, adult population, working at a moderate rate, that is exposed to the pollutants in question for only 8 to 10 hours a day, five days a week. Some occupational standards also take into account the short-term releases of contaminants that routinely occur in some work environments. In the residential environment, the population includes the very young, the elderly, people in poor health, people who are sensitized (individuals who react to contaminants at levels far below the general population), and those who suffer from allergies. The exposure time to residential indoor air pollutants may be 24 hours a day, all year long.

It is suggested in the review that the U.S. Navy's standards for submarine environments might have some relevance to residential environments, since submarines could be compared to very tight houses with low ventilation rates. This comparison, however, has a number of pitfalls. Submarines lack many of the pollutant sources commonly found in homes, the submariners are not particularly representative of the general population, and when submarines are submerged, the occupants breathe recirculated air.

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) usually recommends that acceptable levels of contaminants in the residential environment should be one-tenth the standard or Threshold Level Value (TLV) set for the workplace (ASHRAE 62-81). It is assumed, quite arbitrarily, that the population in residential environments is 10 times as susceptible to health effects from exposure to indoor air contaminants, as the population in the workplace, because the general population may be continually exposed to chemicals in the home environment on a 24 hour basis and it is characterized by a greater variation in age and in health status.

ASHRAE Standard 62-81 is currently under review and it's expected that there will be significant revisions to the acceptable levels of indoor air contaminants that it promulgates.

1.3.1 Federal Provincial Working Group on Indoor Air Quality

In 1981 the provincial Deputy Ministers of Health from across the country approved a recommendation by the Federal Provincial Advisory

Committee on Environmental and Occupational Health to establish a Federal Provincial Working Group on Indoor Air Quality with the following objectives:

1. To develop guidelines for concentrations of selected contaminants of residential indoor air, taking into account such factors as sensitivity of groups at special risk and the sources and mechanisms of action of the contaminants.

2. To develop guidelines for ventilation requirements for domestic premises that reflect the indoor air quality guidelines in order to preserve and improve air environments.

(Armstrong, 1983)

At the time of writing, the working group has identified twelve types of contaminants that, in its opinion, warrant priority consideration. These include:

Carbon Monoxide	Nitrogen Dioxide
Formaldehyde	Aldehydes
Carbon Dioxide	Moisture
Oxides of Sulphur	Ozone
Particulates	Polycyclic Aromatic Hydrocarbons
Radon and Radon Daughters	Microbiological Hazards.

Criteria reviews to support guidelines for exposure limits are currently being prepared by the staff of Health and Welfare Canada's Bureau of Chemical Hazards.

In light of the significant gaps in our knowledge about the health effects of exposure to the low levels of contaminants found in indoor air, it may be impossible to set meaningful standards in the near future. If there is no real threshold level below which there are no health effects, as most researchers agree is the case with carcinogenic chemicals, it is impossible to establish "safe" levels of exposure. The best approach may be for people to simply minimize their exposure to environmental contaminants where possible. This could be facilitated in the indoor environment by standards that are directed at the major pollutant sources, to restrict the rate at which they emit contaminants.

1.4 SUMMARY

Air in the residential environment contains a variety of chemicals including some proven and suspected carcinogens. Some of these contaminants, such as radon, enter the house from outside the building; others, such as benzo(a)pyrene and formaldehyde, are generated indoors by combustion or are "off-gassed" by building materials and furnishings; while pollutants such as tobacco smoke are added to the air by occupants.

There are significant gaps in our knowledge about the long-term health effects of relatively continuous exposure to low levels of chemicals. The traditional methods for determining the health effects of chemicals, and consequently "safe" levels, are limited to identifying the effects of large concentrations of a single chemical on laboratory animals and extrapolating from the incidence of health problems in the workplace where the population is exposed to relatively high levels of contaminants. Serious questions have been raised about the validity of these techniques for establishing the risk of chemically-induced health problems in the general population at low levels of exposure.

Until more is known about the risks associated with long-term exposure to low levels of indoor air pollutants, meaningful residential indoor air quality standards cannot be formulated. "Safe" levels of exposure, a concentration below which no health effects occur, may not even exist for many chemicals. Often situations where health problems have been associated with exposure to indoor air pollutants have involved complex mixes of gases and particles, all at levels well below the accepted standards or guidelines. Yet,there is still a heavy reliance on "acceptable levels" of pollutants as proof that there is or is not an indoor air quality problem. Until more is known about the risks associated with exposure to low levels of chemicals, the only recourse for people at this time is to minimize their exposure to chemical contaminants wherever possible.

Smoking can be eliminated from the indoor environment, unvented and poorly maintained combustion equipment can be avoided, and building materials and furnishings can be selected to avoid pollution.

The second part of this report will examine the impact of air sealing measures, such as caulking and weatherstripping, on the levels of contaminants in indoor air.

PART 2: IMPACT OF AIR SEALING ON INDOOR AIR QUALITY

In an effort to reduce home heating bills and make the indoors more comfortable in the winter, people have been tightening their houses to reduce the uncontrolled air leakage that occurs through the cracks and holes in the building envelope. This also prevents water vapour, generated indoors, from being carried into the walls or ceiling by exfiltrating air where it can condense and reduce the effectiveness of insulation, and create conditions where dry rot (a fungus that feeds on wood) can thrive. Air sealing has also been used as a measure to improve indoor air quality by preventing contaminants, such as formaldehyde, from leaking into a house's living space.

Airtightening activities may be restricted to caulking and weatherstripping in existing homes, or may include the installation of a continuous plastic air barrier on the warm side of insulated wall and ceiling cavities during renovations or new construction. Both measures can result in less ventilation, elevated levels of indoor humidity, and presumably, higher levels of those pollutants that originate from inside the house and lower concentrations of those contaminants that originate outside the living space.

The first part of this paper pointed out that while there exists an indoor air quality problem in Canada, it's impossible to determine the extent of the associated health problems. Part 2 presents literature that has examined the extent to which air sealing and reduced rates of ventilation aggravate the indoor air quality problem. The present range of ventilation rates in new and existing buildings is surveyed, and case studies that have evaluated effects of various energy conservation measures on ventilation rates and air quality are presented.

2.1 SOURCES OF UNCONTROLLED AIR LEAKAGE

> Although the importance of air tightness has been stressed for the past 25 years in the technical literature dealing with the design of building enclosures, we still construct buildings that provide their owners with excessive energy costs, that make the occupants uncomfortable because of drafts and the infiltration of contaminated air, and that suffer from problems of condensation and the deterioration of their components and materials, which require high costs for repair and maintenance. Air tightness, accordingly, should be the primary objective in the design and construction of walls, windows, floors and roofs of buildings.
>
> (National Research Council, 1980)

The significant heat loss and condensation problems associated with uncontrolled air leakage have only generally been recognized outside the building sciences community since 1979. Consequently many homeowners and insulating contractors are still unfamiliar with the various sources of air leakage in a house.

Between 20 and 50 percent of the heat loss in typical housing can be attributed to the uncontrolled leakage of air through the building's shell (Caffey, 1979, Offerman, 1982 and EMR, 1983). Tamura (1975) tested six homes, built in Ottawa in the 1950's, to determine their air leakage characteristics. His results revealed a tremendous variation in the importance of various sources of air leakage. Air leakage through the ceilings accounted for 8 to 67 percent of the total, penetrations through walls contributed 15 to 77 percent, windows and doors accounted for 15 to 23 percent and fireplaces were responsible for 3 to 4 percent of the total air leakage in the houses. Clearly there is no "typical" house with respect to the importance of various air leakage points in a building. The Energy, Mines and Resources air sealing handbook (EMR, 1983) stresses that the relative importance of the various leakage openings in a house will vary with its design, age, quality of construction and component materials. Table 2.1 lists the locations of openings that can play a significant role in contributing to the overall air leakage in a house.

It has been suggested that there are significant differences between pre-war and post-war houses with respect to the distribution of air leakage (Moffat, 1984). As an example, Moffat suggests that in a pre-war house: 30 percent of the air leakage occurs around the sill plate, floor joist, ducts, pipes and wires in the basement; 30 percent of the leakage occurs through the attic around plumbing, wiring, partition walls and chimney flues; a further 20 percent through the walls, through cracks in the plaster, around electrical outlets, baseboard trim, window and door trim and vents; and the remaining 20 percent is accounted for by windows and doors.

In a post-war house, 20 percent of the air leakage may occur through the electrical outlets alone; 25 percent might be accounted for by the wall sill plate; 40 percent through the attic and 15 percent through windows and doors.

Table 2.1

Typical Locations of Air Leakage Points

WALLS:	WINDOWS:
Switch Covers	Sashes
Outlet Covers	Frames
Baseboards	Moulding
Wall Cracks	Weatherstripping
Fireplace/Wall Joint	
TV Cable	**EXTERIOR DOORS:**
Bathtub/Shower	Frames
Medicine Cabinet	Moulding
Exhaust Fans	Weatherstripping
Plumbing Penetrations	Leaks Through Doors
Dryer Vent	
Service Entrances	**CEILINGS:**
Wiring to Outside Outlets	Attic Hatch
Top of Foundation Wall	Chimney
	Ceiling Fixtures
MISCELLANEOUS:	Partition Walls
Fireplace Damper	Exterior Walls
Stair Risers	Plumbing Stack
Basement Floor Drains	Wiring
Floors Over Unheated Spaces	Ducts
	Exhaust Fans
	Ceiling Cracks
	Dropped Ceiling

(Energy, Mines and Resources Canada, 1983)

2.1.1 Measuring Airtightness

A method to determine the airtightness of a building, that is the degree to which unintentional openings in the building structure have been avoided, was developed by researchers at the National Research Council of Canada's Division of Building Research.

> Orr, H.W. and Figley, D.W. An Exhaust Fan Apparatus For Assessing the Air Leakage Characteristics of Houses. Building Research Note #156, National Research Council of Canada, 1980.

A large fan, temporarily installed into an outside door opening, is used to exhaust air from a building to create pressure differences across the building envelope. The rate at which air is exhausted by the fan is measured for a series of pressure differences and an analysis of the relationship between these two parameters provides a measure of what's called the equivalent leakage area (ELA). Often expressed in square centimetres (cm^2), the ELA represents the total area of all the unintentional openings in the building envelope.

This fan depressurization test is an inexpensive, fast and straightforward technique for rating the airtightness of buildings. The Canadian General Standards Board (CGSB) has established a standard procedure for testing homes with the fan or "blower door."

> Canadian General Standards Board. Determination of Airtightness of Buildings by the Fan Depressurization Method, Standard #149-GP-10M, 1983.

To compare the relative airtightness of two houses, the ELA for each house is simply normalized by dividing by the total above ground surface areas of the respective building envelopes. This is referred to as the normalized ELA or specific leakage area (SLA) and expressed as cm^2/m^2.

Airtightness tests are not always presented in a standardized fashion in the literature. At times the ELA or rate of air flow through the fan is presented with no accounting for house size. If the ELA's are normalized, the volume or even floor area of the houses is sometimes used, instead of the surface area of the above ground building envelope. To complicate matters further, the CGSB standard is new, so fan test results in the literature have not all been obtained under similar test conditions. These inconsistencies can make it difficult to compare the results obtained by different researchers.

The major limitation of the fan depressurization test is that it provides no information about air change. Houses exposed to identical conditions, with the same SLA may experience quite different air change rates depending on the location and distribution of the air leakage points.

2.2 AIRTIGHTNESS AND NATURAL VENTILATION

In order to assess the impact of air sealing on indoor air quality, the ventilation rate of a house must be quantifiable. Determining this rate of air change is not as straightforward as might be expected.

The amount of ventilation in a house is dependent on the rate at which air flows through the accidental gaps and holes in the house shell. This rate of air exchange is dependent on wind speed and direction, the difference in temperature between indoors and outdoors, the frequency of exhaust fan and furnace operation, and the window and door opening habits of occupants. The influence of wind on air change is dependent on the shape of the building, the location and size of surrounding buildings and vegetation, the local terrain, the size and distribution of the air leakage points around the house; as well as on wind speed and direction.

The temperature difference between indoors and outdoors creates a stack effect in houses where heated air rises up through the house, leaking outside through cracks and gaps in the upper part of the house.

This creates a negative pressure in the lower part of the house so cold outside air flows into the building to replace the exhausting heated air. The greater the temperature difference and the taller the building, the stronger the stack effect (NRC, 1980).

The number of variables that influence household ventilation rates make it difficult to draw an accurate picture of a house's rate of air change. Ventilation rates will vary over the course of a year, over the course of a heating season, and even over the course of a day. Conventional techniques for assessing air change measure only what is happening at the time of the test and don't give any indication of how this changes over time. In order to analyze the relationship between ventilation rates and indoor air quality, any testing of contaminant concentrations must be done in conjunction with an assessment of the rate of air exchange.

2.2.1 Measuring Air Change

The rate of air change in houses is usually determined by mixing a tracer gas, such as sulphur hexafluoride (SF_6), with the house air and monitoring the rate at which its concentration changes. Theoretically the SF_6 serves as a tag for the indoor air so that the rate at which its concentration changes mimics the rate of air change in the house. Historically there have been three basic approaches to using tracer gases for determining air change rates. They are:

Decay Method (Dilution Method) - a known amount of tracer gas is injected into the air of a building and distributed by the furnace fan or by fans temporarily placed around the house for that purpose. The decay in concentration of the gas is then measured as a function of time.

Constant Flow Method - the tracer gas is injected continuously at a specified rate and its decay is measured as a function of time.

Constant Concentration Method - air infiltration rate is determined by measuring the rate at which the tracer gas has to be injected into the air of each room to maintain a constant concentration of gas in the air.

There are two useful reviews of these techniques:

Harrje, D.T., Grot, R.A., and Grimsrud, D.T. Air Infiltration Site Measurement Techniques. Proceedings of the 2nd Air Infiltration Centre Conference, Building Design for Minimum Air Infiltration, Stockholm, Sweden. Paper 10, p. 115, 1981.

Sherman, M.H. Air Infiltration in Buildings. Lawrence Berkeley Laboratory, Report LBL-10712, 1980.

The constant flow technique is costly, cannot run unattended and has had little application in residential buildings (Sherman, 1980). The constant concentration method (Orr, 1963) is useful for long-term unattended measurements but the technique for controlling the flow of the tracer gas and the measuring apparatus are complicated (Kumar, 1979). In fact the major drawback to this technique is that it's virtually impossible to maintain a constant concentration of tracer gas in a house (Harrje, 1981).

The decay method of tracer gas analysis has been the most popular approach to measuring air change rates because it is the least expensive and simplest of the three approaches. However it can only determine the air change rate that exists during the 45 minutes to an hour that the test takes, which as discussed in Section 4.1, may have little relevance to the "average" air change rate in the house. Serious doubts have also been raised about the reliability of the test method itself.

The SF_6 tracer gas decay technique was used to determine the air change rates in 35 houses in the Ottawa area (Cogeneration Associates, 1983). Four sets of air change tests were conducted to coincide with the four seasons, however there was no clear correlation between the measured air change rates and the measured wind speed and temperature difference between indoors and outdoors. While the overall average results reflected a tendency for changes in wind conditions and stack effect to coincide with the changes in air change, the results from many of the individual houses did not indicate any such relationship, calling into question the reliability of the testing technique.

Tracer gas analysis assumes that there is perfect mixing of the gas with the air throughout the building. SF_6 is denser than air so it has a tendency to sink and accumulate in the basement area. This stratification of SF_6 may be compounded by the inadequacy of household air circulation. Rooms at the ends of heating duct lines, the absence of cold air returns and unbalanced registers may help isolate sections of the house (Cogeneration Associates, 1983).

The furnace fan is usually used to distribute the tracer gas around the house, but operating the fan can increase the level of air change when the furnace is in a leaky furnace room or when fresh air intakes are present.

A new time-averaged technique for determining natural rates of air change that uses perfluorocarbon tracer gas sources (PFT) and passive samples (cappillary absorption tube complex - CAT) may be the most promising approach (Moffat, 1984). The PFT's emit perfluorocarbon at a known rate over a long period of time, and the CAT's absorb the gas at a rate proportional to its concentration. The average concentration of tracer gas is determined by a laboratory analysis of the CAT's and this is compared to the known emission rates of the PFT's. This time-average air change test determines the average air change rate of a house over a period of two weeks to two months, under typical operating conditions. The technique is not sensitive to sudden or short-term changes in air change so the results may be as representative of the "typical" air change rate as possible.

To overcome the problems associated with conventional tracer gas analysis, researchers have been attempting to develop a mathematical model of air change that would use the results of a fan depressurization test to predict the natural rate of air change.

2.2.2 Correlating Airtightness with Air Change Rates

To use the data from fan depressurization tests in a mathematical model to predict air change rates, information about the site location, building details and weather data are necessary and must be quantifiable. Such theoretical models have to account for wind speed and direction, and the nature of the terrain, shape of the building, size, shape and location of surrounding buildings and vegetation, and the temperature difference between inside and outside, the size and distribution of points of air leakage throughout the house, the height of the building, the location of the neutral plane (where air neither moves in or out of openings in the building envelope), and the frequency of operation of exhausting devices, including vented heating systems. Creating a mathematical model to account for all these variables is a complicated task, but numerous models have been developed to predict air change rates from fan tests.

Wilson (1983) suggests that there are as many models as there are investigators, but recent work tends to break down into two basic models:

Shaw, C.Y. A Correlation Between Air Infiltration and Air Tightness for Houses in a Developed Residential Area. ASHRAE Transactions, V. 87, Pt. 2, 1981.

Sherman, M.H., Grimsrud, D.T. Measurement of Infiltration Using Fan Depressurization and Weather Data. Lawrence Berkeley Laboratory, LBL-10852, 1980.

Air exchange can be caused by the stack effect alone, or by wind acting alone, or by the combined action of the two. Shaw found that when the wind speed is less than 12.6 km/hr, the air change rate (measured by tracer gas test) was primarily dependent on the inside/outside temperature difference. When the temperature difference was less than $20^{o}C$ and the wind speed was greater than 12.6 km/hr, then wind was the dominant force driving air change. When the temperature difference was between $20^{o}C$ and $40^{o}C$, and the wind speed was greater than 12.5 km/hr but less than 25.2 km/hr, Shaw found no direct relationship between the rate of air change and wind speed or temperature difference. He developed three equations to predict air change rates to account for the relative importance of wind and temperature difference in driving ventilation.

Temperature Caused Infiltration

$$I = 0.32\ (A/v)\ C\ (t)^{n}$$

where

I = natural infiltration rate in air changes per hour (ach)
v = volume, m^3
A = area of building envelope calculated for fan test
C = flow coefficient as calculated from fan test results
n = flow exponent as calculated for fan test results.

Wind Induced Infiltration

$$I = a\ (A/v)\ C\ \ V^{bn}$$

where

V = on-site wind speed, m/s
a = a constant
b = a constant that depends on whether the building is shielded or not.

Wind and Temperature Caused Infiltration

$$I = 4.31\ (A/v)\ C$$

Shaw used his model to predict the air change rates of 25 houses whose air change rates and ELA's had been reported in the literature.

The infiltration rates predicted by this model were within $\pm$ 25 percent of the measured rates. He suggested that if the effect of furnace operation, house shape, distribution of the leakage openings and the height of the neutral plane could be accounted for, the accuracy of the model would be improved, at the expense of the simplicity of the correlation. Shaw's model has been field tested on three identical houses in one subdivision to date (Moffat, 1984).

Sherman and Grimsrud (1980) developed an infiltration model, that uses the equivalent leakage area (ELA) determined by a fan depressurization test, that accounts for many more variables than Shaw's model. The model considers the terrain, shielding from local sources, the leakage area that is directly exposed to the wind (assumed to be located in the walls) versus the leakage area that is inaccessible to the wind (assumed to be located in the floors and ceiling), the height of the building, the height at which wind speed is recorded, and the height of the neutral plane.

The infiltration due to the temperature difference and the infiltration rate induced by wind are calculated separately and then combined in the following manner: $Q_{total} = \sqrt{Q^2\ stack + Q^2\ wind}$.

The model was used to predict the air change rates of 15 houses that had previously been subjected to fan tests and tracer gas analysis. In most cases the predicted change rate came within $\pm$ 35 percent of the measured results although in a few houses the rate of air change was drastically over or under predicted.

Sherman and Grimsrud noted that the accuracy of their model could be improved by including parameters to account for more local shielding, leakage through vents and flues running out the roof, the effect of wind direction and furnace operation. They also noted that the model did not account for occupant effects such as opening windows, but concluded that the need to incorporate this into the model was minimal since, in the author's opinion, people are most likely to open windows when the outside temperature is in the comfort range.

Blomsterberg (1982) used Sherman and Grimsrud's infiltration model to predict the rate of air change in three houses. The predicted air change was overestimated in one house by 47 percent, underestimated in a second house by 42 percent and coincided with the measured rate of air change in the remaining house.

Of the two models, the Sherman model has been used more widely because it accounts for more variables. However it still neglects to account for wind direction and furnace operation; two variables that can have significant impact on air leakage. Most studies of air change rates in housing continue to rely on tracer gas analysis.

2.3 AIRTIGHTNESS OF NEW AND EXISTING HOUSING STOCK

A number of studies have been carried out to characterize the airtightness of the Canadian housing stock. The results are generally expressed as specific leakage areas (SLA) that have been adjusted for differences in house size by dividing their equivalent leakage areas (ELA) by the above ground surface area of the building envelope to yield units of cm^2/m^2. Airtightness test results are also expressed as air changes per hour (ach) at a fan-induced pressure differential of 50 Pascals (Pa). This is the number of times in one hour that the entire volume of air in a house is replaced with outside air under the conditions of a fan depressurization test. The major airtightness studies that have been carried out in Canada are:

Dumont, R.S., Orr, H.W., Figley, D.A. Airtightness Measurements of Detached Houses in the Saskatoon Area. National Research Council of Canada, Division of Building Research, Paper #178, 1981.

Ontario Ministry of Municipal Affairs and Housing. The Weatherize Project. Prepared by Sheltair Scientific Ltd., 1984.

Cogeneration Associates, Study of Apple Hill Energy Efficient Homes, under preparation for CMHC, 1983.

Beach, R.K. Relative Tightness of New Housing in the Ottawa Area. National Research Council of Canada, Division of Building Research, Paper #149, 1979.

Energy, Mines and Resources Canada. Airtightness Tests On 200 New Houses Across Canada: Summary of Results. Prepared by Saskatchewan Research Council, 1984.

Dumont (1981) measured the airtightness of 176 houses in Saskatoon using the fan depressurization test. In general he found that bungalows were tighter than multiple story or split level homes and that the age of the house had a tremendous effect on the "equivalent leakage area" (ELA) of the houses. Prior to 1945, houses in Saskatoon had no vapour barrier; between 1945 and 1960, waxed paper vapour barriers were common; and since that time, polyethylene has been used for vapour barriers.

Table 2.2 gives an indication of the range of airtightness that is found in the Canadian housing stock.

Table 2.2

Typical Level Of Airtightness In Canadian Houses

Age	SLA (cm^2/m^2)	ach (@ 50 Pa)
Pre-1945	4.5 - 10.0	8.0 - 30.0
1945 - 1960	2.5 - 4.5	4.0 - 5.0
1960 - 1980	1.5 - 2.5	3.0 - 4.0
Low Energy	1.5	0.5 - 2.0

(Sheltair Scientific Ltd.)

The Ontario Ministry of Municipal Affairs and Housing (1984) carried out fan depressurization tests of 65 houses in Ottawa, Peterborough, Cambridge and Sault Ste. Marie to the CGSB standard. The houses were selected to provide a representative sample based on age, type of construction (frame or masonry), design (bungalow, multiple story) and the presence or absence of a chimney. The results are presented in Table 2.3 as specific leakage areas in cm^2/m^2.

Table 2.3

Average Airtightness Measurements of Detached Houses in Ontario

	Ottawa		Cambridge		Peterborough		S.S. Marie	
	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)	#Houses Tested	SLA (cm^2/m^2)
Pre-1920	7	13.70	3	11.60	3	10.70	1	11.08
1921-1945	0		4	12.90	4	15.32	4	7.71
1946-1960	4	8.82	4	8.14	3	13.43	5	6.43
1961-1970	2	10.02	4	8.90	4	12.05	2	3.65
Post-1970	2	4.48	5	7.07	1	13.05	3	3.44
Tightest house		2.26		3.22		6.05		2.37
Leakiest house		41.24		18.58		18.76		11.08

While the sample size of the Ontario Weatherize Project is small it does appear that Ontario houses are generally leakier than the average level of airtightness found in Canadian houses (Table 2.2).

Thirty-five new "energy efficient" homes from the Apple Hill subdivision near Ottawa were tested for their level of airtightness (Cogeneration Associates, 1983). The average SLA for 31 gas heated homes was 3.2 cm^2/m^2, ranging from 0.97 cm^2/m^2 to 4.1 cm^2/m^2, and the average SLA for four electrically heated homes was 1.9 cm^2/m^2. It was noted that the furnace room in the gas heated houses appeared to be the major contributor to the air leakiness of those houses. The gas heated houses had enclosed furnace rooms that were essentially at outdoor temperatures so the flues of the furnace and hot water were not sealed for the airtightness tests, as is required by the CGSB standard when flues are located within the heated space of the house. When these and other intentional openings such as bathroom vents, dryer vents and fireplaces were sealed, the average SLA dropped to 1.8 cm^2/m^2.

The National Research Council of Canada carried out airtightness tests on 63 new houses built in Ottawa in 1978 (Beach, 1979). The tests were conducted with all chimneys and flues sealed (as per CGSB standard) and the average SLA was 3.25 cm^2/m^2 with a range of 1.8 to 5.3 cm^2/m^2. The houses were categorized by house type (bungalow, split level, etc.) but, unlike Dumont's findings, there appeared to be no significant difference in the various items that could be associated with house type.

One relationship that was evident was that each of the nine builders involved, produced houses with a characteristic range of relative tightness values. "There was a distinct impression that the relative tightness of a house varied with the quality of workmanship." (Beach, 1979).

The Saskatchewan Research Council measured the airtightness of 20 new homes in Saskatchewan as part of Energy, Mines and Resources Canada's program to test 200 recently constructed houses across the country (EMR, 1984). The SLA's ranged between 1.1 and 2.3 cm^2/m^2 when the flues were left open, and between 0.7 and 1.1 cm^2/m^2 when these intentional openings were sealed. In light of Beach's data, this suggests that houses are more tightly constructed in Saskatchewan than in Ontario. Common construction features such as framing details, fireplaces, and house type were recorded, but no common characteristics were found to distinguish tight houses from leaky houses.

What's remarkable about most of these airtightness studies is the tremendous variation in SLA. Even within the recently constructed housing stock, the level of tightness can vary by 100 to 400 percent. In some cases, new houses appear to be as leaky as those built prior to 1945 (Table 2.3). From an indoor air quality perspective, a salient question would be whether or not air sealing older houses can make them tighter than an average new home built to the Ontario Building Code.

2.4 AIR CHANGE IN NEW AND EXISTING HOUSING

As was noted in Section 2.2, the rate of air change in a single house will vary considerably over the course of a day and over the course of a heating season. Tracer gas analysis has fluctuations of more than 100 percent; from 0.25 ach to 0.58 ach over a heating season (National Research Council of Canada, 1982). It therefore is difficult to assign a "typical" air change rate to a house or sample of houses.

Both tracer gas decay tests using SF_6 and time-averaged measurements employing perfluorocarbon were carried out on newly constructed houses in the "energy efficient" Apple Hill subdivision in Kanata, Ontario (Cogeneration Associates, 1983). The results of the SF_6 tests showed that 31 gas heated houses averaged 0.35 ach during the winter with a range of 0.18 to 0.55 ach. Four electrically heated houses averaged 0.21 ach, with a range of 0.09 ach to 0.31 ach during the winter. Time-averaged measurements (2 weeks) of seven gas heated houses indicated that they had an average air change rate of 0.18 ach, with a range of 0.09 to 0.39 ach, although the authors note that these may be underestimates since basements were not included in the analysis.

The Apple Hill homes are tighter than most newly constructed houses. Twelve post-1970 electrically heated homes in the Toronto area were subjected to tracer gas analysis and measured air change rates varied between 0.21 and 0.60 ach (NRC, 1982).

Much of the literature fails to adequately account for the variables that can affect air change rates when reporting the results from tracer gas analyses, and with the exception of the Apple Hill study, the level of air circulation in the house is never considered. To clearly examine the relationship between the level of ventilation and indoor air quality, a "motion picture" of the rate of air change and pollutant concentrations is necessary. However, the literature provides "still photographs" which may say very little about the movie.

2.5 IMPACT OF OCCUPANT BEHAVIOUR ON VENTILATION

Tracer gas tests are carried out in houses with the windows and doors closed, exhaust fans switched off and occasionally with the furnace shut down. In reality, people open their windows during the heating season, open and shut outside doors and operate their furnaces, so measured air change rates would tend to underestimate the level of natural ventilation.

Shaw and Brown (1982) ran extensive tracer gas and airtightness tests in a house to examine the effect of a gas furnace on air leakage. They found that air leakage through the chimney accounted for 60 percent of the total air leakage out of the house. When winds were below 13 km/h, the rate of air change in the test house was 50 percent higher with the chimney open to the outside than it was when the chimney was capped. When the furnace burner was operating continuously, the air change rate in the house increased by 10 percent.

The significant impact that a gas furnace appears to have on air change in houses suggests that the current trend to convert to chimneyless high efficiency furnaces or electric heating systems may have a serious impact on ventilation. Perhaps the concerns that have been raised over the effect of air sealing activities on indoor air quality should be extended to oil substitution activities.

People generally use window opening as a means for regulating indoor temperature (Lyberg, 1981) so tracer gas analysis will always underestimate the air change rates of houses during the beginning and end of the heating season, and during mild spells at anytime over the winter. In fact, it is during these mild periods that the rate of air leakage in a house tends to be low.

Lee (1982) used tracer gas tests to measure the impact of window opening on air change. The results indicated that a window open just a few centimetres, can increase the rate of air change in a house by a factor of two to five. This depends on the location of the window (an upper story window will increase the stack effect), and the overall leakiness of the house.

It has been estimated that 50 percent of the air change that occurs over the heating season, in the United Kingdom, is due to window opening habits (Brundett and Poultney, 1982). In Sweden, Lyberg (1961) estimates that window opening behaviour accounts for approximately 30 percent of air leakage. In Ontario it has been estimated that less than 25 percent of the population leave windows open in the winter (Ontario Ministry of Municipal Affairs and Housing, 1984).

Lee (1982) found that window opening behaviour increased with the size of the family, with the amount of time the house was occupied and with the number of smokers. For every additional smoker, there was a 20 percent increase in window opening behaviour.

2.6 IMPACT OF AIR SEALING ON AIRTIGHTNESS AND VENTILATION

The trend in low energy new house construction is to seal the building envelope as tightly as possible to eliminate unintentional air leakage. Mechanical ventilation systems provide the occupants with direct control over the rate of air change in their homes instead of depending on wind and temperature difference to drive ventilation. The Division of Building Research of the National Research Council carried out airtightness tests on 14 airtight low energy houses in Saskatoon (Besant, 1981). The average fan-induced air change rate was 0.88 air changes per hour at 50 Pa. The range was from 0.37 ach to 2.19 ach at 50 Pa. If the average airtightness values measured by Dumont (1981) and Beach (1979), 3.57 ach and 4.41 ach (at 50 Pa) respectively, are typical of most new conventional house construction, Besant's results suggest that it's possible to improve the level of airtightness in new houses by 75 to 80 percent, if airtight construction techniques are employed. Current standards for R-2000 houses require the air change rate at 50 Pa to be less than 2.0 ach.

This level of airtightness cannot be achieved with conventional construction techniques unless an air barrier is included. Dumont (1983) reported on six retrofits in Saskatchewan where air barriers were installed in some of the houses during renovations. For the six houses, the median level of fan-induced air change was reduced from 5.5 ach to 1.6 ach at 50 Pa.

A total of 65 houses in Ontario, ranging in age from pre-1920 to post-1970, were tested for airtightness before and after they were air sealed by professional contractors (Ministry of Municipal Affairs and Housing, 1984). Four different contracting firms were used and they obtained average reductions of 30 percent, 41 percent, 26 percent and 38 percent in the ELA's of the houses they tightened. The results ranged from a minimum reduction of 9 percent to a maximum of 73 percent. There appeared to be no correlation between the percentage reduction in ELA that was obtained and the age of the house.

Two of the 65 houses that were air sealed became slightly tighter than what is attained in conventional new house construction. These two houses were post-1970 electrically heated houses with SLA's of 1.21 and 1.47 cm^2/m^2 respectively. As noted in Table 2.2 the typical range of SLA's for new construction is 1.5 to 2.5 cm^2/m^2.

Tracer gas analysis was carried out on 20 of these houses, after they were air sealed, to determine their rate of air changes under ambient conditions. The tracer gas test results reflect the same wide variation in air change that is found across the conventional housing stock. Three pre-1920 houses had an average air change of 1.2 ach, but the individual houses ranged between 0.38 ach and 1.92 ach. The post-1970 houses had an average air change of .52 ach but the results ranged from 0.11 ach to 1.08 ach. If the natural average seasonal air change rates across the Canadian housing stock are in the range of 0.4 to 0.7 ach (Moffat, 1984), then approximately 20 percent of the houses that were tested fell below this "typical" range and 20 percent exceeded it. One of the air sealed houses had air change rates below those measured in new electrically heated houses. It should be kept in mind that these results were based on single tracer gas tests carried out in mild April weather, and may not reflect the average air change rates in these houses, and certainly don't give any indication of the variation in air change rate that individual houses may experience.

The tracer gas test results from three of the houses that had been air sealed indicated air change rates lower than was measured in the Ministry of Municipal Affairs and Housing's Howland House demonstration project. This pre-1920, semi-detached house was completely gutted and refurbished with a continuous polyethylene air barrier. According to a single SF_6 test, Howland House had an air change rate of 0.31 ach (IEC Beak, 1983).

One of the most comprehensive investigations into the impact of air sealing houses was carried out as part of the Bonneville Power Administration's conservation program in central Washington state. The results are reported in:

Dickinson, J.B., Grimsrud, D.T., Krinkel, D.L. and Lipschutz, R.D. Results of the Bonneville Power Administration Weatherization and Tightening Projects at the Midway Substation Residential Community. Lawrence Berkeley Laboratory, LBL-12742, 1982.

A total of 18 houses were retrofitted and monitored over a three year period. The houses were divided into three groups of six and retrofitted according to the schedule below.

	1978-1979	1979-1980	1980-1981
Group 1	Monitoring	Control Group	22 hours of air sealing
Group 2	Monitoring	Attic and crawl-space insulation, sill plate caulking	Control Group
Group 3	Monitoring	Insulation, sill plate caulking and storm windows	10 hours of air sealing

The majority of the houses were built either in 1943 or in 1951. All the houses were wood frame, single family, detached structures with floor areas ranging from 103 to 123 square metres. The energy consumption of the houses was monitored during the first heating season before any retrofit activity was undertaken. Fan depressurization tests were carried out before and after each phase of the retrofit.

It was found that insulation had little effect on the equivalent leakage areas of the houses but the addition of storm windows reduced the average ELA's by 14 percent. Twenty-two person-hours of air sealing managed to reduce the average ELA of Group 1 by 27 percent while 10 person-hours of air sealing in Group 3, reduced the average ELA's by 20 percent.

The Lawrence Berkeley Lab infiltration model (Sherman and Grimsrud, 1980) was applied to the airtightness test results to convert ELA into air changes per hour. After 22 hours of air sealing, Group 1 dropped from 0.44 ach to 0.32 ach. The average air change rate of Group 2 houses, after only 10 hours of air sealing, dropped from 0.35 ach to 0.28 ach. These results fall within the lower range of air change rates found in post-1970 electric houses in Toronto (NRC, 1982).

Dickinson suggests that the reductions in airtightness were less than had been expected because the Midway houses were relatively tight to begin with. The three groups had average specific leakage areas of 4.1, 3.4 and 3.5 cm^2/m^2 before they were tightened. This can be compared to the specific leakage areas of four groups of pre-1960 houses in Ontario which were 8.8, 8.1, 13.4 and 6.4 cm^2/m^2 (Table 2.3).

There were two major sources of error in the Midway house tightening project that may have affected the air sealing results. The first problem was that different air sealing measures were used in different homes. For instance in Group 3 homes, where 22 person-hours were spent on air sealing, baseboards were caulked in only one house, window and door frames were sealed in only four of the six houses and cracks in the attic were sealed in only half the houses. The other problem was that indoor temperatures were never recorded over the three year project (an input required for the LBL model), so the accuracy of the predicted air change rates is questionable.

A project, similar to that undertaken by the Bonneville Power Administration, was carried out by Pacific Gas and Electric in Walnut Creek, California (Dickinson, 1982). Twenty houses underwent 14 person-hours of air sealing. In ten houses the average equivalent leakage area was reduced by 15 percent while the remaining nine attained an average of a 33 percent reduction. The latter group received "additional contractor-installed measures" that were not described.

Based on the above-mentioned case studies it can be reasonably assumed that on average, professional air sealing can reduce the equivalent leakage area of a house by 20 to 40 percent. According to a number of air sealing contractors, reasonably knowledgeable do-it-yourselfers attain approximately half the reduction in air leakage that a professional job can accomplish.

Whether or not a corresponding reduction in air change rates is brought about by reductions in ELA's has not been well documented. The Lawrence Berkeley Laboratory infiltration model (Sherman and Grimsrud, 1981) has been used to predict such a reduction based on equivalent leakage area measurements, but this needs to be corroborated by tracer gas analysis.

The range of SLA's and air change rates that have been reported in the literature for houses that have been air sealed, appears to rarely drop below what has been measured in new houses that have been built to Ontario Building Code standards. This raises the question of whether there has been an over-reaction to the impact that air sealing has on the ventilation rates, and indoor air quality of existing housing.

Perhaps the important question is whether or not the accidental openings in the house shell can guarantee an adequate supply of air at all times of the year under all conditions, regardless of any air sealing measures that may have been implemented.

2.7 INDOOR AIR QUALITY IN AIR SEALED HOUSES

Concern about the quality of residential indoor air came to the public's attention in 1979, shortly after the nuclear accident at Three Mile Island, with the publishing of a number of papers warning against the health effects of radon in sealed houses. Cohen (1980) concluded that energy conservation by insulation of buildings would cause at least 10,000 extra fatal cancers per year in the U.S. (4 per 100,000 population) due to reduced ventilation. This is compared to the radiation hazards of nuclear power plants where the predicted fatalities amounted to between 0.1 and 6.0 percent of those caused by energy conservation activities.

> It seems reasonable to estimate that insulation efforts already executed have accomplished about 10 percent of the job and are therefore now causing about 1,000 fatalities per year.
>
> (Cohen, 1980)

A year after Three Mile Island and the resulting flurry of warnings about radon inside houses, urea formaldehyde foam insulation was banned in Canada because its "off-gassing" was causing health problems in a segment of the population and it had been found that formaldehyde caused nasal cancer in laboratory animals. Attention was once again focussed on residential indoor air quality and researchers began to investigate the impact of formaldehyde sources other than insulation.

During the 1981-1982 heating season in Ontario, indoor air quality once again became an issue when a Mississauga man died from carbon monoxide asphyxiation in his home. Initially blamed on energy conservation measures, it was found that a combination of a partially blocked chimney, improperly adjusted furnace, and closed furnace room caused a backdraft down the chimney, filling the house with carbon monoxide. This and similar incidents have precipitated an unprecedented amount of concern and activity with respect to indoor air quality. As a result, much of the research into indoor air quality in tighter houses that has been undertaken to date, has been a reaction to specific problems.

The most prominent concern of some energy utilities and government departments is whether the kinds of energy conservation activities they've been advocating have an adverse impact on health. Heating industry associations and government bodies that regulate fuel safety have become sensitive about the role that gas-fired combustion appliances may play in some indoor air quality problems. There are health researchers whose primary interest is the impact of any level of chemical contaminant on hypersensitive people. And there are air sealing and insulating contractors who in many instances, desire technical guidance and standards with respect to pollutant levels in houses.

There have been a number of major empirical studies on the impact of energy conservation activities, such as air sealing, on indoor air quality. These include:

Berk, J.V., Hollowell, C.D. et al. The Impact of Reduced Ventilation on Indoor Air Quality in Residential Buildings. Lawrence Berkeley Laboratory, LBL-10572, 1980.

Hollowell, C.D., Berk, J.V. Indoor Air Quality in New Energy Efficient Houses and Retrofitted House. Lawrence Berkeley Laboratory, 1982.

Offerman, F.J., Girman, J.R., and Hollowell, C.D. Midway House Tightening Project: A Study of Indoor Air Quality. Lawrence Berkeley Laboratory, LBL-12777, 1981.

Ontario Ministry of Municipal Affairs and Housing. Indoor Air Quality - Cambridge Sealed Homes. IEC Beak Consultants, 1983.

Offerman, F.J., Dickinson, J.B., Fisk, W.J., and Grimsrud, D.T. Residential Air Leakage and Indoor Air Quality in Rochester, New York. . Lawrence Berkeley Laboratory, LBL-13100, 1982.

Cogeneration Associates. Study of Apple Hill Energy Efficient Homes, under preparation for Canada Mortgage and Housing Corporation, 1983.

The Berk et al (1980) study was one of the first to measure contaminant levels in buildings with low ventilation rates. Three energy-efficient research houses were monitored, with Lawrence Berkeley Laboratory's Energy-Efficient Buildings Mobile Laboratory, for carbon dioxide, carbon monoxide, nitrogen oxide, nitrogen dioxide, formaldehyde, other aldehydes (the class of compounds to which formaldehyde belongs), particulates, and ventilation rates (using tracer gas analysis).

The test houses were located in California, Iowa and Maryland, and they all had been designed to use approximately 50 percent less energy than conventional new houses. Unfortunately only the California house was actually occupied by a family, and it was monitored in the late summer. The two unoccupied houses were monitored during the winter and early spring, but their indoor environments could not possibly reflect the situation in a house that is actually lived in by people going about their daily routine. (The LBL staff was housed in the Maryland house but it was pointed out by the authors that they did little more than sleep in the house.) No control houses (conventional construction) were used in the study, so the effect of the energy conservation measures on ventilation and indoor air quality are unclear.

The air change rate in the California house ranged between 0.2 and 0.8 ach with an average of 0.4 ach. The Iowa house ranged between 0.1 and 0.4 ach with an average of 0.2 ach, and the Maryland house had an average air change rate of 0.05 to 0.3 ach with an average of 0.15 ach.

The indoor and outdoor levels of carbon monoxide were found to be comparable for all three houses. The California house had elevated levels of nitrogen oxide and nitrogen dioxide that sometimes exceeded the one hour Canadian ambient air quality objective of 0.21 ppm. These peaks were associated with cooking activity. The air was monitored for particulates in the Iowa and Maryland houses, and both experienced elevated levels of particulates. When welding and smoking was going on in the Iowa house, particulate levels exceeded those found outdoors. In the Maryland house, fine particle concentrations regularly exceeded outdoor concentrations. This was attributed to cleaning and cooking activities. Formaldehyde levels in the houses occasionally exceeded indoor air standards (0.1 ppm) while total aldehyde levels frequently exceeded this guideline. When furniture was added to one of the unoccupied houses, the formaldehyde concentration tripled. Table 2.4 illustrates the impact of furnishings and occupant behaviour on formaldehyde levels. Radon gas levels were found to be approximately 0.5 pCi/L in the California and Iowa houses, however the Maryland house had concentrations as high as 24 pCi/L, six times the upper limit set by the U.S. Environmental Protection Agency for houses constructed on reclaimed phosphate lands in Florida.

As a result of their study, Berk et al (1980) made the following recommendations:

1) Detailed measurements of a variety of housing types, including houses undergoing retrofits, under a range of occupancy conditions (such as presence of smokers) should be carried out.

2) The health effects of elevated levels of indoor contaminants need to be researched so that the impact of energy conservation measures on indoor air quality can be clearly documented.

3) Energy-efficient ventilation standards should not be established until these relationships are clearly understood.

Table 2.4

Summary of Indoor and Outdoor Formaldehyde and Total Aliphatic Aldehyde Concentrations Under Varying Conditions of Occupancy

Condition	Number of Measurements	Sampling Time (hours)	Formaldehyde (ppb)[a]
Unoccupied, without furniture	3	12	66 ± 9%
Unoccupied, with furniture	3	24	183 ± 7%
Occupied, day[c]	9	12	214 ± 10%
Occupied, night[d]	9	12	115 ± 31%

a Determined using pararosaniline method (100 ppb $\cong$ 120 ug/m^3). All outside concentrations $<$10 ppb.

c Air exchange rate $\cong$ 0.4 ach.

d Windows open part of time; air exchange rate significantly greater than 0.4 ach and variable.

Since Berk's study lacked any control houses, it doesn't shed any light on the relationship between air change rates and indoor levels of air pollutants. However this early study does point out the importance of pollutant source strengths. Elevated levels of nitrogen dioxide were associated with the use of a gas range, and the impact that furniture can have on formaldehyde levels was demonstrated.

Hollowell, Berk et al (1982) reported on the indoor air quality in five energy-efficient houses and three retrofitted houses. In the energy-efficient houses(air change rates lower than 0.4 ach) the indoor levels of radon, formaldehyde and particulates sometimes exceeded existing guidelines or standards for outdoor air, however air quality monitoring was not carried out on control houses with higher rates of air change. In many cases the elevated levels were explained in terms of the pollutant source strengths.

All five energy-efficient houses had air change rates that were considerably lower than the national average (0.75 ach in the U.S.), ranging from 0.1 to 0.4 ach. No carbon monoxide problems were detected in any of the houses despite the presence of smokers and gas-fired appliances. One house, located in Rio, Wisconsin, had very high levels of particulates. This house contained propane combustion appliances, a woodburning stove and an occupant that smoked, but Hollowell and Berk attributed the high levels of particulates to cigarette smoke alone. One house in Minnesota had high levels of nitric oxide, and this was attributed to the operation of an oil-fired furnace. Radon gas levels exceeded existing standards for indoor air in four out of five of the houses tested. The results are presented in Table 2.5.

Standards For Radon Daughters

AIR TYPE	STANDARD	Averaging Period	Concentration	COMMENT
AMBIENT	--	--	--	None available
INDOOR	AECB Primary Criterion			
	- remedial action	1 y	0.02 WL	Prompt interim action 0.15 WL investigational level 0.01 WL
	Ontario Ministry of Labour			
	- new homes		0.02 WL	
	EPA Recommendations			
	Florida - remedial	1 y	0.02 WL/ALARA[1]	Remedial action recommended for greater than 0.02 WL, and ALARA for 0.005 to 0.02 WL
	- new homes		0.005 WL above BG[2] or ALARA	
	Dec. 1980 Draft		0.015 WL	
	U.S. Surgeon General Grand Junction	1 y	0.01 WL above BG	Remedial action recommended for greater than 0.05 WL, and perhaps suggested for 0.01 to 0.05 WL
	Sweden			
	- remedial	1 y	400 Bq (0.11 WL)	No exposure to exceed
	- major renovations		200 Bq (0.50 WL)	2000 Bq.y/m^3 over
	- new homes		70 Bq (0.019 WL)	5 year trial period
WORK PLACE	U.S. Secretary of Labour	1 y	4 WLM	) No more than) 2 WLM in any) 3 month period
	Canada - AECB Regulation as of Jan. 1978	1 y	4 WLM	)

NOTE: 1 ALARA as low as reasonably achievable
2 BG implies normal background for the area.

(Ministry of Consumer and Commercial Relations, 1981)

APPENDIX B

Detection and Monitoring Equipment for Indoor Air Pollutants

Carbon Monoxide		General Electric Co. Wilmington, MA
		Energetics Science Elmsford, NY
Formaldehyde	PRO-TEK BADGE	E.I. duPont de Nemours & Co. Inc. Wilmington, Delaware 19898
Nitrogen Dioxide	PALMES SAMPLER	MDA Scientific Inc. Glenview, IL
Radon	TRACK ETCH DETECTOR	Terradex Corp. Walnut Creek, CA
Furnace Flue Malfunctions	GAS-TRAC DETECTOR	J & N Enterprises Wheeler, IN

Table 2.5

INDOOR AIR QUALITY MEASUREMENTS
IN FIVE NEW ENERGY-EFFICIENT OCCUPIED HOUSES [a]

	Carroll County MD	Mission Viejo CA	Northfield MN	Dundas MN	Rio WI
Infiltration rate (ach)	0.15	0.4	0.1	0.1	0.3
CO (ppm)	1.2	1.4	0.5	0.7	2.2
CO_2 (ppm)	598	689	1175	1316	1125
NO_2 (ppb)	9	41	15	19	77
NO (ppb)	5	44	5	70	72
SO_2 (ppb)	3.2	0.9	1.0	-	9.0
O_3 (ppb)	4.3	15.6	1.7	9.0	15.0
Particulates--fine (ug/m^3)	7.0	32.6	6.8	19.5	92.4[b] 6.0[c]
Particulates--total (ug/m^3)	9.9	48.9	14.8	27.9	129.6[b] 23.5[c]
Formaldehyde (ppb)	98	214	69	80	53
Total aldehydes (ppb)	150	227	99	122	81
Radon (pCi/L)	22.0	5.0	7.5	1.7	6.5

a All values represent average concentrations during the monitoring period

b Smoking

c No smoking

(Hollowell, Berk *et al*, 1982)

The three retrofitted houses that Hollowell and Berk monitored provide some insight into the impact of reduced ventilation on indoor air quality. Two of the three retrofitted houses had been upgraded by Pacific Power and Light Company as part of its energy-conservation program in Medford, Oregon. The utility's program added storm windows and doors, door weatherstripping, attic and floor insulation, replaced sliding glass doors and insulated heating ducts, but involved no comprehensive air sealing. The air change rates in these two houses were reduced by 40 percent, to 0.20 ach. The third house that was monitored was a 100-year-old farmhouse in New Jersey that had previously been retrofitted but was super-retrofitted for the purposes of the study. No details about the specific measures undertaken were provided. The reduction in air change after the super-retrofit was 11 percent resulting in a measured air change rate of 0.39 ach. All air change rates and pollutant concentrations are presented as averages for the monitoring period. The length of the monitoring period and the weather conditions over that time were not described. Table 2.6 summarizes the results.

Table 2.6

INDOOR AIR QUALITY MEASUREMENTS
IN THREE RETROFITTED OCCUPED HOUSES [a]

	Medford, OR #1		Medford, OR #2		Cranbury, NJ	
	Pre- Retrofit	Post- Retrofit	Pre- Retrofit	Post- Retrofit	Pre-[b] Retrofit	Post-[c] Retrofit
Infiltration rate (ach)	(Fan Off) 0.33	0.20	(Fan Off) 0.33	0.23	0.44	0.39
CO (ppm)	0.3	0.3	0.3	0.3	2.9	3.1
CO_2 (ppm)	670	847	593	656	767	703
NO_2 (ppb)	7	4	4	5	25	29
NO (ppb)	3	7	8	7	50	46
SO_2 (ppb)	-	-	-	-	3	3
O_3 (ppb)	4	4	5	14	-	-
Particulates-- fine (ug/m^3)	(Smoking) 31	36	12	10	12	8
	(No Smoking) 9	8				
Particulates-- total (ug/m^3)	(Smoking) 62	77	45	26	25	18
	(No Smoking) 31					
Formaldehyde (ppb)	55	53	68	51	22	19
Total aldehydes (ppb)	84	85	94	71	29	31
Radon (pCi/L)	1	1.2	1	1	3.6	3.8

a All values represent average concentrations during the monitoring period

b Previously weatherized by owner at time of measurement

c "Super" retrofit done by Princeton University house doctors

(Hollowell, Berk, et al, 1982)

None of the gaseous pollutants showed any appreciable increase after the retrofits, with the exception of carbon dioxide which increased in concentration by 10 to 30 percent in two houses and decreased in the third. The levels of particulates in one of the Minnesota houses increased by 20 percent as a result of the retrofit. This house had a smoker with a 20 to 40 cigarette-a-day habit. Radon levels were near the limits of detection in the Minnesota houses, while levels in the New Jersey farmhouse had increased by 5.5 percent to just below existing indoor standards for radon. According to Table 2.6, there was a decrease in the concentration of contaminants as frequently as there was an increase, but this was not dealt with in Hollowell and Berk's discussion of the results.

The only house that had combustion appliances (gas water heater, dryer and stove) had unusually low levels of gaseous pollutants. This was attributed to the fact that occupancy levels were low and almost no cooking was done during the monitoring period.

Hollowell and Berk concluded:

> The impact of residential retrofit programs on indoor air quality appears to be minimal based on this study of three retrofitted houses where no pollutants reached levels approaching health guidelines or standards. We can conclude that retrofit programs such as that of Pacific Power and Light Company improve the thermal integrity of houses and should continue without fear of significantly increasing indoor air pollution.

While Hollowell and Berk's conclusions sound encouraging, they are specific to the retrofit program that was carried out by Pacific Power and Light Company and cannot be generalized.

In contrast to the study of retrofitted houses by Hollowell and Berk (1982), Offerman, Girman and Hollowell (1981) carried out a rigorous study of the indoor air quality of 12 houses that were tightened as part of the Bonneville Power Administration's Midway house tightening project described in Section 2.6 (Dickinson and Grimsrud, 1982).

The houses, located near Richland, Washington, were monitored for radon, formaldehyde and nitrogen dioxide. According to the authors, carbon monoxide and particulates were not monitored because inexpensive instrumentation suitable for long-term sampling does not exist. Relative humidity was monitored because of its influence on people's comfort and its potential for creating condensation problems. The results are summarized in Table 2.7.

Air change rates were estimated from the equivalent leakage areas determined from fan depressurization tests (Sherman and Grimsrud, 1980). To account for ventilation resulting from window and door opening and fireplace use, 0.1 to 0.15 ach was added to the predicted air change rate.

Six of the houses received an average of 12 person-hours of air sealing (one day retrofit), and the other six received 22 person-hours of airtightening (two day retrofits). The average reductions in equivalent leakage area were 27 percent and 37 percent respectively, resulting in estimated average air change rates of .28 and .32 ach. The largest reduction in equivalent leakage area was 51 percent, while the smallest reduction was 9 percent.

After air sealing, a third of the houses showed elevated levels of radon, most of which were at the lower limit of the radon guideline (assuming 0.02 WL corresponds to 3 to 6 pCi/L of radon). Offerman and Girman (1981) pooled the data on radon and airtightness because they thought that it would provide a more statistically significant assessment of the impact of tightening the houses. The result was that there was an average increase in radon of 0.5 $\pm$ 0.5 pCi/L after air sealing, representing a 42 percent increase. However, with a standard deviation of 100 percent the reliability of this figure is suspect.

The average increase in formaldehyde concentrations, after air sealing, was 4 ppb, representing an increase of 24 percent (once again, pooling all the data). But in 50 percent of the houses there was a decrease in the levels of formaldehyde after air sealing.

Table 2.7

SUMMARY OF PRE- AND POST-RETROFIT LEAKAGE AND INDOOR AIR QUALITY MEASUREMENTS IN TWELVE HOUSES OF THE BPA MIDWAY SUBSTATION RESIDENTIAL COMMUNITY

House ID#	Sampling Period	Equivalent Leakage Area (cm^2)	(% Change)	Radon (pCi/l)	HCHO (ppb) Indoor/Outdoor	NO_2 (ppb) Indoor/Outdoor	Relative Humidity (%)
1	Pre-retrofit	426		<1	5/ 5	2/3	45
	Post-retrofit	266	38	1	21/ 5	2/3	44
2	Pre-retrofit	364		<1	5/ 5	4/3	41
	Post-retrofit	227	38	<1	17/ 5	3/2	46
3	Pre-retrofit	407		<1	28/ 5	3/2	42
	Post-retrofit	231	43	1	24/ 5	3/3	43
4	Pre-retrofit	288		1	12/ 5	1/3	38
	Post-retrofit	197	32	2	8/ 5	2/3	36
5	Pre-retrofit	374		1	34/ 5	4/1	52
	Post-retrofit	337	10	3	16/ 5	3/2	38
6	Pre-retrofit	433		2	15/ 5	3/2	42
	Post-retrofit	377	13	1	10/ 5	3/3	42
7	Pre-retrofit	276		-	5/ 5	<1/3	41
	Post-retrofit	200	28	3	69/ 5	3/4	62
8	Pre-retrofit	325		2	19/ 5	2/2	47
	Post-retrofit	204	37	3	31/ 5	2/3	52
9	Pre-retrofit	203		2	44/ 5	1/2	48
	Post-retrofit	185	9	2	49/ 5	2/2	54
10	Pre-retrofit	392		<1	5/ 5	3/2	46
	Post-retrofit	241	39	2	19/ 5	3/2	49
11	Pre-retrofit	338		1	79/ 5	2/2	48
	Post-retrofit	201	41	-	13/ 5	1/3	43
12	Pre-retrofit	364		3	5/ 5	2/3	39
	Post-retrofit	179	51	3	7/ 5	1/4	38

(Offerman, Girman and Hollowell, 1981)

The importance of a pollutant's source strength was underlined by the results of occupants moving from house #11 to house #7. The formaldehyde levels in the vacated house dropped from 79 ppb to 13 ppb, while the levels in the newly occupied house rose from less than 5 ppb to 69 ppb.

All the measured nitrogen dioxide levels were very near the detection limit of the monitoring equipment. Both pre- and post-retrofit concentrations were among the lowest that Offerman and Girman had ever measured. This was expected as there were no combustion appliances and the houses were in a rural area so the outdoor levels of pollutants were extremely low.

Only one house had a significant increase in relative humidity after airtightening so it was suggested that this was related to a change in occupancy. The houses in the study were relatively tight before they were retrofitted which may account for the minimal changes in relative humidity.

According to the authors, the results of monitoring the indoor air quality in the Midway houses are somewhat inconclusive because of the lack of information about the pollutant source strengths, and occupant behaviours; along with the short sampling periods (one to two weeks), and small size and homogeneity of the sample. To this list could be added, indoor air circulation and external weather conditions.

> Until a sufficiently large indoor air quality data base is established for the United States, it is strongly recommended that all house-tightening programs include an indoor air quality measurement to assure that the retrofits designed to reduce infiltration and thereby save energy do not have adverse effects on indoor air quality and human health. A suitable protocol for large-scale indoor air quality monitoring needs to be developed.
>
> (Offerman, Girman and Hollowell, 1981)

It has sometimes been assumed in the past that if humidity is not excessive inside a house then there is little concern about indoor air quality. The results from the Midway house tightening project appear to lend some credence to this informal rule of thumb. Table 2.7 clearly indicates that the three houses with the highest relative humidities, contain the highest formaldehyde concentrations and the highest levels of radon in two out of the three cases. However house #12 had a high level of radon and one of the lowest relative humidities.

While high levels of humidity can result from low air change rates, as with chemical contaminants, the source strength of the water vapour can play an important role. One of the significant sources of water vapour is the soil surrounding a house foundation. As was noted in Section 1.1, the soil is an important source of radon gas so there may exist a relationship between elevated levels of water vapour and radon gas, and leaky foundations. High levels of humidity are also known to increase the rate of formaldehyde emission from materials.

The only Canadian investigation of indoor air quality in existing houses that had received air sealing measures was carried out by the Ontario Ministry of Municipal Affairs and Housing (1983) on 20 homes in Cambridge, Ontario. Approximately 300 measurements of carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, formaldehyde and radon gas were taken over a two week period. Potential pollutant sources, occupancy patterns, the lifestyle of the occupants and air change rates were assessed. With the exception of radon, contaminants were monitored in a number of locations in the houses to examine the role that air circulation might play in creating local "hot spots." However, unlike the Midway house tightening project (Offerman, Girman and Hollowell, 1982), contaminant levels were not monitored prior to air sealing the houses and no control group of "unsealed" houses was monitored for comparison purposes.

The authors of this study established criteria levels, above which contaminant concentrations were considered excessive, by dividing limits that had been set for occupational hygiene by 20, unless indoor standards or guidelines already existed. The result was that 42 of the 300 measurements exceeded the study's criteria levels. These excesses represent less than 14 percent of the total number of measurements. The results are summarized in Table 2.8 below.

Table 2.8

Percentage of Measurements Exceeding Criteria
For Monitored Contaminants in Air Sealed Cambridge Houses

Contaminant	Criteria Level (ppm)	Percentage of Excesses
Carbon Monoxide	2.5	3%
Carbon Dioxide	600.0	23%
Nitric Oxide	0.5	7%
Nitrogen Dioxide	0.15	5%
Formaldehyde	0.05	27%
Radon	0.02 WL	40%

Because of their careful assessment of occupancy patterns, occupant lifestyles and pollutant sources, the authors were often able to show a correlation between these variables and high levels of contaminants. This lends support to concerns about the adequacy of simply relying on a specified rate of ventilation to guarantee acceptable indoor air quality (Coon, 1982).

Since there was no air quality testing before the houses were tightened, it's impossible to attempt any correlation between contaminant levels and ventilation rates.

The tightest house in the sample had an SLA of 2.8 cm^2/m^2 and a measured air change rate of less than 0.2 ach, yet the concentration of contaminants in the house never exceeded the study's criteria levels. Conversely, five out of the six houses, that had levels of pollutants that most regularly exceeded the criteria levels, had SLA's that fell within the range that is typical for houses built prior to 1960 (greater than 2.5 cm^2/m^2) and single SF_6 decay tests indicated that they experienced air change rates that were slightly above 0.5 ach. Despite their relatively high level of air change, these houses had experienced major moisture problems before and after air sealing (Ontario Ministry of Municipal Affairs and Housing, 1984).

There is some indication from the CO_2 measurements that at least some of the houses had poor air circulation. In some houses, levels of CO_2 exceeded 2500 ppm on the main floors while the measured concentrations of CO_2 in the basements and on the second floors never exceeded 450 ppm. High levels of CO_2 could also have been influenced by the concentration of occupancy and the use of gas ranges in main floor kitchens. The measured concentrations of formaldehyde did not exhibit any kind of stratification.

As with many of the indoor air quality studies that appear in the literature, the MOMAH report was based on short-term sampling of contaminants, so it's impossible to know whether the levels of contaminants that were measured reflect the long-term situation in the houses tested. In the Apple Hill Study of Energy Efficient Homes (Cogeneration Associates, 1983), indoor air contaminants were monitored over three distinct seasons.

The measured concentrations of carbon monoxide, nitrogen dioxide and nitric oxide suggested some seasonal variation, with higher levels in the winter. Attempts to correlate elevated levels with air change rates proved to be inconclusive.

In some of the Apple Hill houses, carbon dioxide and formaldehyde were found at levels exceeding existing guidelines. At least five houses frequently had basement radon concentrations that exceeded 6.0 pCi/L, the upper limit of indoor air quality guidelines for radon. It should be noted that the Kanata area of Ontario where the Apple Hill houses are located, has much higher background levels of radon than most other parts of Canada.

Two general recommendations were made by the authors of the indoor air quality component of the Apple Hill study:

> There is a fundamental need to continually evaluate and monitor residential air quality such that cost-effective control measures can be adequately defined.
>
> An awareness by both builders and homeowners about air quality is required, so that, unhealthy indoor air quality conditions are not imposed upon individuals without their knowledge or consent.
>
> (Cogeneration Associates, 1983)

Offerman, Dickinson et al (1982) monitored 10 houses in Rochester, New York for formaldehyde, aldehydes, nitrogen dioxide and radon and compared the results to an extremely leaky house.

Two of the ten houses were also monitored for particulates and gaseous pollutants that are associated with combustion. Three of the houses contained gas stoves and four had smokers. All but one of the houses were constructed with sealed polyethylene vapour barriers, and they had an average air change rate of 0.35 ach, ranging between 0.22 and 0.5 ach (an average specific leakage area of 2.4 ± 0.7 cm^2/m^2). The average rate of air change in this study was predicted from measured ELA's using the LBL infiltration model (Sherman and Grimsrud, 1980).

The leaky house that was monitored for comparison purposes had a predicted average air change rate of 1.17 ach with a high of 4.46 ach. The houses were monitored for one week periods during which tracer gas decay tests indicated that air change rates in the tight houses were relatively stable with an average standard deviation of 0.1 ach. The rate of air exchange in the leaky house varied considerably with a standard deviation of 0.65 ach.

The average radon concentrations ranged from below the detectable limit in the leaky house to 2.2 pCi/L in one of the tight houses. Several of the measurements approached the lower level (3 pCi/L) of existing guidelines for radon. Average formaldehyde levels ranged between .007 and 0.64 ppm, and all the measured levels were below the existing guideline for indoor air (0.1 ppm). It was noted that the houses with the highest aldehyde levels were also the only houses with any significant amount of new particleboard. Levels of nitrogen dioxide (NO_2) were consistently lower than outdoor concentrations in all but the one house with an unvented gas clothes dryer and range. The houses with gas stoves had average concentrations of 0.15 ppm, while houses with electric stoves had average NO_2 levels of .004 ppm. The two houses that were monitored for particulates, contained smokers and had 2-3 times the outdoor concentrations of respirable suspended particulates (RSP). There is no ambient standard for RSP's. The concentration of respirable particulates in one house slightly exceeded the ambient standard for total suspended particulates (some suspended particulates are removed in the upper respiratory tract and do not reach the lungs).

Because the concentrations of radon, formaldehyde and nitrogen dioxide were low in the tight houses they monitored, Offerman and

Dickinson (1982) concluded that the source strengths of these contaminants were low. They suggest that the key to having an energy-efficient house with both lower levels of ventilation and acceptable indoor air quality, is to construct and furnish it so that the pollutant sources are low.

> When designing houses to have low air-exchange rates, builders should be selective in choosing building materials that are not potential sources of indoor air pollution. Research has been initiated at Lawrence Berkeley Labs to study contaminant emission rates from various building materials. However, many sources of indoor air pollution are occupant-related and beyond the control of builders, such as tobacco smoking, use of unvented combustion appliances and toxic cleaning products, and selection of house furnishings constructed with urea formaldehyde based resins. Homeowners must accept responsibility for controlling these sources.
>
> (Offerman and Dickinson, 1982)

The only Canadian study examining air change and indoor air quality that has been published, monitored radon and formaldehyde in 12 relatively tight houses (NRC, 1982). The houses were monitored for four months, on a weekly basis, over a heating season and for two months during the summer. Air change rates were based on the 45 minute sampling period typical of the decay method of tracer gas analysis; formaldehyde concentrations were measured over one hour periods; 24 hour periods and seven days; while radon gas and radon daughters were measured on a daily basis.

The average air change rate for each house varied from 0.21 ach to 0.66 ach over the heating season, ranging from a low of .14 ach to a high of .78 ach. Unlike the results from the Apple Hill study (Cogeneration Associates, 1983), SF_6 tracer gas tests indicated that average monthly air change rates followed the changes in degree-day months (an indication of difference between inside and outside temperatures) and average monthly wind speed data. Average air change rates during the summer for those houses with air conditioning systems ranged from 0.12 ach to 0.40 ach while the two houses without air conditioning had average air change rates of 1.75 ach and 2.78 ach respectively. The rate of air change in the air conditioned houses was considerably lower in the summer than the winter, primarily because there is no temperature difference between inside and outside and little wind to drive infiltration during the summer months.

Average concentrations for formaldehyde ranged from 0.017 ppm to 0.058 ppm. The houses with the three highest levels of formaldehyde also had the largest variation. In the summer the average formaldehyde levels in these houses, all of which were kept closed up for the air conditioning, were well above the 0.1 ppm level recommended by Health and Welfare Canada. The authors suggest that the air change rates had a marked effect on formaldehyde concentrations but they initially failed to consider the differences in source strengths among the houses and, because of equipment failure, were unable to monitor outdoor levels of formaldehyde. In fact formaldehyde concentrations and air change showed poor correlations for individual houses. There was, however, a clear inverse relationship between the average monthly air change rates for all the houses and the formaldehyde gas concentration.

Before the summer monitoring commenced, occupancy patterns, home-owner habits and possible sources of formaldehyde were assessed. During the summer, outdoor formaldehyde levels were monitored as well. The three houses with the highest formaldehyde levels were all found to have significant sources. Each house was occupied by at least one smoker, two of the houses had installed new furniture during the monitoring period and one house had a new burglar alarm and new wallpaper installed, so there was extensive use of glue. In addition, all three houses were within less than 100 m of Highway 401 and were exposed to outdoor concentrations of formaldehyde that were almost 150 percent higher than the ambient levels near most of the other houses.

The average radon concentration over the heating season ranged from 0.3 pCi/L to 2.2 pCi/L with an overall average of 1.2 pCi/L. The average radon daughter concentration ranged from 0.0007 Working Levels (WL) to 0.0065 WL with an overall average of 0.0037 WL. The 0.02 WL limit established for housing in uranium mining and processing communities was exceeded once by a house that had the second highest average radon daughter concentration, the highest average radon gas concentration and, notably, the highest average air change rate.

During the summer months, on average, radon concentrations in the closed air-conditioned houses increased by 44 percent and radon daughter concentrations increased by 32 percent. In the two houses that utilized windows for summer cooling, concentration of radon gas and radon daughters dropped drastically in one case and actually increased slightly in the other. The house that exceeded .02 WL in the winter was not re-tested over the summer months.

The recommendations for future work made by the authors of the NRC report are similar to those made in other studies:

1) Survey a wider range of housing types.
2) Include houses with combustion appliances in the survey.
3) Monitor buildings of different tightnesses.
4) Sample houses in different geographical locations.

Standards For Oxides of Nitrogen

(All Standards Given For Nitrogen Dioxide)

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act	1 y	60	(0.03)	max. desirable [1]
			100	(0.05)	max. acceptable [2]
		24 h	200	(0.11)	max. acceptable
			300	(0.16)	max. tolerable [3]
		1 h	400	(0.21)	max. acceptable
			1 000	(0.53)	max. tolerable
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria	24 h	200	(0.10)	
		1 h	400	(0.20)	
	b) Maximum Concentration	0.5 h	500	(0.26)	at point of impingement (defined in Reg. 308)
	NAAQS U.S. EPA Primary & Secondary	1 y	100	(0.05)	
INDOOR	ASHRAE 62-73 Standards	1 y	200	(0.11)	
		24 h	500	(0.26)	not to be exceeded more than once per year
	Submarine Environment Standards U.S. Navy	90 d	940	(0.50)	limit
		24 h	1 880	(1.00)	limit
		1 h	18 800	(10.00)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	9 400	(5.0)	MAC[4], accepted by Canadian federal and provincial authorities for occupation stnd.
	NIOSH Recommendation (Status OCT. 1978)	15 m	18 000	(1.00)	Ceiling limit
	OSHA Standard (Status COT. 1978)	8 h	9 400	(5.00)	TWA [5]

NOTE:
1. For new industry in non-industrialized regions
2. Secondary objectives for established industrial areas
3. Objectives for heavily industrialized areas
4. Maximum Acceptable Concentration
5. Time Weighted Average

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Formaldehyde

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act		no standard		
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria		no criterion		
	b) Maximum Concentration	0.5 h	65	(0.05)	at point of impingement (defined in Reg. 308)
	NAAQS a) Primary U.S. EPA b) Secondary		no standard		
INDOOR	ASHRAE 62-73 Standards		300	(0.20)	TLV/10[3]
	Submarine Environment	90 d	615	(0.50)	limit
		24 h	1 230	(1.00)	limit
		1 h	3 690	(3.00)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	2 460	(2.00)	MAC[1]
	NIOSH Recommendations (Status OCT. 1978)	30 m	1 200	(1.00)	Ceiling limit
	OSHA Standards (Status OCT. 1978)	8 h	3 690	(3.00)	TWA[2]
			6 150	(5.00)	Acceptable Ceiling
		30 m	12 300	(10.00)	Maximum Ceiling

INDOOR RESIDENTIAL OTHER COUNTRIES

Sweden and Czechosovakia 1979	Maximum allowable indoor air quality standard 100 ug/m^3 (0.08 ppm) (Ref. 48)
Netherlands 1978	Maximum permissible concentration indoors 120 ug/m^3 (0.01 ppm) (Ref. 48, 20)

Denmark and West Germany considering 120 ug/m^3 (0.1 ppm) for indoor air quality (Ref. 20). Germany's occupational limit is 1200 ug/m^3 and 30 ug/m^3 for continuous exposure in outdoor air (1975) (Ref. 4)

NOTE:
1 Maximum Acceptable Concentration
2 Time Weighted Average
3 As specified in Sec.

(Ministry of Consumer and Commercial Relations, 1981)

5) Carry out year-long monitoring.

6) Conduct a physical survey of the house, survey occupancy patterns and homeowner's habits.

7) Identify specific areas of air leakage and potential formaldehyde sources.

A careful survey of the literature failed to turn up a single case study whose design would satisfy the above recommendations. Indoor air quality monitoring programs are expensive, time consuming, technically complex, and require a tremendous amount of co-operation from the people living in the homes. It has been suggested that in order to adequately characterize the indoor air quality in Canadian houses, a total of 160 dwellings in four different locations should be monitored for a period of one year (NRC, 1982).

Since none of the indoor air quality case studies that were reviewed in this section accounted for all the important variables and provided for adequate controls, it's impossible to draw any firm conclusions about the relationship between low rates of air change and indoor air quality, but some trends were evident. At the level of air change that is typical of tighter new construction and air sealed existing housing, the pollutant source strength plays a crucial role in contributing to high levels of contaminants. This can become less important at high levels of ventilation such as occur in the summer with the windows open (NRC, 1982). Although, even under these conditions the NRC study found a slight increase in radon concentration in one house.

In general, elevated levels of radon and carbon dioxide seem to be common in some of the newer tighter houses and in some existing houses that have been air sealed. But the results do not seem to be consistent. The situation is even more unpredictable with formaldehyde. Sometimes air sealing reduces its concentration, sometimes it becomes elevated and in some cases its concentration doesn't change at all.

High levels of relative humidity tended to exist in the homes with the highest levels of radon and formaldehyde. It would be instructive to monitor some houses where careful attention has been paid to the airtightness of the basement area, as well as the above ground area of the building shell. Research is also needed to investigate the relationship between indoor air circulation and the contaminant concentration in different rooms of a house. Better air circulation may eliminate chemical "hot spots" in some houses.

A number of researchers have attempted to predict the effects of reduced air leakage in houses on indoor pollutant levels using mathematical models (Silberstein, 1978; GEOMET, 1981). However, the usefulness of these models is severely limited by the gaps in our knowledge with respect to air change in housing, the source strength of pollutants and ultimately by the uniqueness of individual houses.

Many of those who have examined the indoor air quality in tighter houses have understandably recommended that more detailed research be undertaken. However a recommendation for education, made by the authors of the Apple Hill study (Cogeneration Associates, 1983), would appear to have the greatest pay-off in the near term. If both builders and homeowners were made aware of indoor air quality issues they, as Offerman and Dickinson (1982) suggest, could accept responsibility for controlling pollutant sources. And ultimately the informed homeowner can decide on the kind of air quality that he is willing to tolerate or deem acceptable.

2.8 SUMMARY

There is a tremendous variation in the airtightness of Canadian houses which appears to be related to the quality of workmanship rather than simply house style or age. Within a single house there is significant variation in the level of ventilation over the course of a heating season, since the rate of air exchange is dependent on such variables as wind speed and direction, inside/outside temperature difference and frequency of furnace operation. Two houses can have the same level of airtightness (identical specific leakage areas) but widely different air change rates at any given time. If the rate of air change in a typical new house can vary from 0.2 to 0.6 air changes per hour over the same heating season, then the accidental openings in a building envelope may not be able to guarantee an adequate supply of air under all conditions.

The tracer gas decay test method that is commonly used to quantify air change rates, can only provide a glimpse of what the level of ventilation in a house is at any given time, which may not be representative of the average situation. Concerns have also been raised about the accuracy of this test method over the short-term. It appears that under some conditions the tracer gas stratifies instead of mixing evenly with house air. A tracer gas technique that employs perfluorocarbon emitters and samplers may overcome many of the disadvantages of the decay method.

A number of attempts have been made to use the equivalent leakage area of a house, as determined by fan depressurization, to predict its level of ventilation. The large number of variables that affect the rate of air change in a house make this a complex task, and to date, the results have not been reliable.

The problems associated with quantifying ventilation rates has severely limited our ability to clearly characterize the impacts of air sealing on air exchange. However,there is a general consensus in the literature that professional air sealing techniques can improve the airtightness of existing houses by 20 to 40 percent, reducing their average natural air change rates to between 0.3 and 0.6 ach.

Air sealing existing houses does not appear to reduce their rate of air change below that of conventional new houses with one possible exception. Electrically heated houses that had been built subsequent to 1970, in some cases, were tighter than new houses after air sealing. (It should be noted that air sealing work tends to be carried out in older homes, where it may be difficult to even attain the level of tightness found in modern houses.)

There is a distinct lack of information in the literature about the effects of reduced ventilation on indoor air quality. Much of the monitoring of indoor air quality to date has been carried out in conventional houses to assess the impact of specific pollutant sources, such as gas stoves. The research that has been directed at tight houses has been very cursory and narrow in its focus. Pollutant levels have been measured in relatively tight houses without monitoring any control houses with which to compare the results. Existing houses have sometimes been monitored only after airtightening. In the few studies where adequate controls were provided, the results were inconclusive. Either the sample size was too small, the houses were not representative of existing housing stock, the occupants' behaviour was not characterized adequately, the adequacy of air circulation within the house was not addressed, and/or no inventory of pollutant sources as made.

It is apparent from the literature that air sealing a house does not necessarily elevate indoor pollution levels. Indoor air quality is determined by the rate at which contaminants are emitted into the house air, the extent to which they mix with house air, the rate at which they are removed from the house, and the sensitivity of the occupants - these factors vary widely from house to house and within the same house over time. In some reported cases, air sealing did raise the level of indoor air contaminants where there was a reduction in the rate of air change and no corresponding reduction in the source strength of indoor pollutants. However, the concentration of contaminants, such as radon and formaldehyde, were decreased in some houses after air sealing; presumably because their access points to the living spaces had been sealed.

A review of the literature demonstrated repeatedly that houses with high concentrations of a particular contaminant, were often ones with a strong pollutant source. Houses with unvented gas stoves, a significant amount of new particleboard, new furniture, smokers or high levels of outdoor pollutants were often the ones with elevated levels of indoor contaminants -not simply the tightest houses. Some houses with measured air change rates of less than 0.2 ach had low concentrations of indoor air contaminants, while some houses with air change rates that exceed 0.5 ach had levels of a number of contaminants that exceed existing standards and guidelines.

There is a need to provide homeowners, builders and air sealing contractors with information that will help them identify existing or potential air quality problems that might be affected by air sealing or low ventilation rates. High levels of indoor air contaminants are often associated with high levels of relative humidity and moisture problems, but the absence of humidity problems does not guarantee acceptable air quality, as is commonly assumed.

A separate concern which overlaps the air quality issue, is the need for an adequate air supply for combustion appliances. This is an air quantity problem and was not dealt with in this section of the report. The introduction to Part 1 of this report lists some useful references in this area.

In reviewing the existing indoor air quality literature, it appeared as though a significant amount of work has been interpreted to coincide with the self-interests of the sponsor. For those who intend to do further reading on indoor air quality issues, it is important that papers be read critically with the interests of the sponsoring body in mind.

Natural gas associations may tend to shy away from conclusions that suggest unvented gas appliances contribute to air quality problems (Little, 1981). An association of electrical utilities, on the other hand, might be interested in demonstrating such a connection (GEOMET, 1981). Engineering professionals allied with the nuclear industry may be interested in associating energy conservation activities with increased frequency of radiation-induced lung cancers (Runnals, 1982). And energy conservation firms, after spending years promoting air sealing to reduce energy consumption, are not likely to raise an alarm about poor indoor air quality in tight houses.

Part 3 of this report will investigate measures to improve indoor air quality in both airtight and conventional houses.

PART 3: MEASURES TO IMPROVE INDOOR AIR QUALITY

If it is assumed that low rates of ventilation are responsible for indoor air quality problems, the logical solution is to increase the rate of ventilation. However, as much of the literature reviewed in Part 2 demonstrated, a tight house does not necessarily have poor indoor air quality.

To date, the majority of the research into controlling the levels of contaminants in indoor air has centered around controlled ventilation strategies. Similarly, the common regulatory approach to insuring acceptable indoor air quality has been to set minimum standards of air change. However, as it has become more apparent that the source strength of pollutants plays a major role in determining the quality of indoor air, the literature has begun to focus on the control of the pollutant sources themselves.

Part 3 provides an overview of what is known about reducing indoor air pollution and reviews existing ventilation standards for residential buildings. For a comprehensive survey of indoor air pollution control and low pollution construction techniques, consult:

> Canada Mortgage and Housing Corporation. Indoor Air Pollution and Housing Technology. Bruce Small and Associates, 1983.

3.1 IDENTIFYING PROBLEM HOUSES

To meet both objectives of conserving energy and improving indoor air quality it would be useful to be able to identify problem houses without resorting to an expensive monitoring program. The literature is relatively limited in this area but there are a few reports that are relevant; for example:

> Girman, J.R. et al, Pollutant Emissions Rates From Indoor Combustion Appliances and Sidestream Cigarette Smoke. Lawrence Berkeley Laboratory, 1982.

Silberstein, S., Energy Conservation and Indoor Pollution. Energy and Buildings, Vol. 2: 185-189, 1979.

Traynor, A.V. et al, Exclusion List Methodology For Weatherization Program in the Pacific Northwest. Lawrence Berkeley Laboratory, LBL-14467, 1982.

Silberstein (1979) developed a model to predict the effects of tighter building envelopes on indoor pollution levels, that considers the lower pollution production from the heating system resulting from the lower heating demand. The model suggests that if there is a 75 percent reduction in air change, the carbon monoxide levels contributed by furnace and stove pilot lights would quadruple. Assuming a ventilation rate of 0.25 ach, the model predicts that it would take 4.5 hours for carbon monoxide levels to fall below the Environmental Protection Agency ambient standard after one hour of oven (gas-fired) use. The author suggests that pilot lights should be eliminated and kitchens should be ventilated before airtightening a house.

Girman et al (1982) measured the emission rates of a gas-fired stove, gas-fired unvented space heater, kerosene-fired unvented space heater and sidestream cigarette smoke in a specially constructed environmental chamber where ventilation could be precisely controlled. They concluded that the emission rates of nitric oxides from all four combustion appliances and tobacco smoking were high enough to be of concern, in both single rooms and entire houses, when ventilation is reduced. The authors went as far as to suggest that because the emissions from the unvented space heaters were so high, even under relatively high rates of ventilation, serious consideration should be given to restricting their use.

Traynor (1981) recommends that any residential energy conservation program should include an indoor air quality audit in order to protect the occupants from elevated levels of pollutants. Pollutant sources with a narrow range of emission rates would be inventoried by way of a questionnaire or visual inspection. For example, a questionnaire could assess:

1) the amount and age of indoor particleboard

2) the amount of smoking

3) the amount of concrete and other building materials known to emit radon or formaldehyde

4) the number, location, and ventilation schemes of all combustion appliances.

Those pollutant sources with unknown source strengths, such as radon (source strength can vary by factors of 1,000 from house to house), carbon monoxide, and combustion products from appliances, such as forced-air furnaces and woodburning stoves, would have to be quantified by on-site measurements. Nitrogen dioxide and radon concentrations can be measured quite simply and cheaply with passive monitors (require no external power), but it's expensive and time consuming to measure carbon monoxide, formaldehyde and particulates. A source list of readily available monitoring devices is included in Appendix B.

The Bonneville Power Administration was concerned about the effect that its weatherization program might have on people's health, so it developed an exclusion list which was intended to limit airtightening activities to those houses that lacked major sources of pollutants (Nero, 1982). The power company was primarily concerned about carcinogens such as radon and suspected carcinogens such as formaldehyde and benzo(a)pyrene (a by-product of wood and tobacco combustion), so its exclusion list ruled out airtightening in 70 percent of the eligible homes. Air quality monitoring was not carried out so this list was by necessity, overly conservative.

Homes lacking major sources of indoor air pollutants were defined as having the following characteristics:

1) a full crawl space with cross ventilation and a ground cover vapour barrier (uncommon in eastern Canada)

2) no woodstoves or unvented combustion appliances

3) municipal water supply or a surface water source

4) wood frame construction

5) no urea formaldehyde foam insulation.

The list ignores indoor air pollutants such as cigarette smoke and particleboard.

Nero recommended that more houses could be airtightened if radon levels were quantified by monitoring the houses or by characterizing the source strength in the area. If levels were high, then the power company could offer to undertake remedial measures before air sealing. Similarly, air sealing could be carried out in houses with gas ranges which had ventilation hoods and in houses with UFFI, if the measured levels were low.

The Bonneville Power Administration recently filed an Environmental Impact Statement on the effects of expanding their weatherization program to all houses, as it proposes to meet future demands for electricity through energy conservation (Bonneville Power Administration, 1983).

3.2 INDOOR POLLUTION CONTROL STRATEGIES

The literature on indoor air pollution control strategies, aside from controlled ventilation, is minimal. Control strategies are sometimes incorporated as part of a report on a specific pollutant. Two examples are:

Budnitz, R.J. et al. Human Disease from Radon Exposure: The Impact of Energy Conservation in Residential Buildings. Energy and Buildings, Vol. 2: 209-215, 1979.

Bowen, R.P., Shirtliffe, C.J. and Chown, G.A. Urea Formaldehyde Foam Insulation: Problem Identification and Remedial Measures for Wood-Frame Construction. National Research Council of Canada, Division of Building Research, Building Practice Note #23, 1981.

Budnitz suggests that the best approach to passive radon control is to eliminate the pathways into the building. Radon enters houses through the floor/wall joints, the basement floor drain, around loose fitting pipes, and through cracks in the concrete. Auxier et al (1974) tested a number of sealants and found sealing the foundation walls and floor with epoxy paint reduced the concentration of radon daughters in the air by 75 percent. Aside from actively ventilating a house, Budnitz notes that an electrostatic precipitator or other particle filters could reduce the concentrations of radon daughters in the air, although radon gas would continue to flow into the house at the same rate. Radon control continues to be under active research, particularly in the Scandinavian countries. One of the methods currently being tested is direct ventilation of the radon source in much the same way that a septic tank or sewer is vented.

Bowen et al (1981) lists a series of remedial measures to reduce the concentrations of formaldehyde in homes with UFFI. Since the pollutant source is outside the living space of the house, like radon, the rate at which formaldehyde enters the house air can be slowed by sealing the inside surface of the interior walls. In this situation, the rate of air change would be reduced and formaldehyde levels would drop at the same time. At the other end of the spectrum, the pollutant source can be eliminated by removing the insulation from the walls and ceiling.

There are three papers that provide a useful summary of potential control strategies. These include:

Lord, D. Controlling Indoor Air Pollution in Energy Efficient Environments. National Research Council, Washington, D.C., 1982.

Nero, A.V. et al. Exclusion List Methodology For Weatherization Program in the Pacific Northwest. Lawrence Berkeley Laboratory, LBL-14467, 1982.

Canada Mortgage and Housing Corporation (CMHC). Indoor Air Pollution and Housing Technology. Bruce Small, 1983.

Lord divides pollution control strategies into three major categories: source control, dilution and ventilation, and removal.

Source Control

1) Isolate the pollutant source from the indoor environment. (For example, make occupants who smoke, do so outdoors.)

2) Contain the pollutant source by using paints or films. (Seal the basement walls and floor against radon, for example.)

3) Exhaust the pollutant near its source. (A vent hood over a gas range would be an example.)

Dilution and Ventilation

1) Uncontrolled air exchange through openings in the building envelope.

2) Natural ventilation through open windows, vents or chimneys.

3) Mechanical ventilation.

Removal

1) Mechanical filters and electrostatic air cleaners.

2) Devices that remove gas and vapour.

Bruce Small (CMHC, 1983) lists 16 factors which can help reduce indoor air pollution. They include:

1) Increased Ventilation

2) Decreased Ventilation

   - where outdoor sources are significant

3) Adsorption on Interior Surfaces

   - some pollutants attach themselves to the surface materials in the house

4) Gassing-out Time

   - source strength of some pollutants diminishes with time

5) Low Emission Materials

   - materials can be selected with low rates of pollution emission

6) Source Removal

7) Modified Combustion Processes

   - maintenance, adjustment or redesign of combustion appliances

8) Changes in Design

   - change house design and construction practices to lower pollution

9) Changes in Maintenance Practices

   - reduce reliance on volatile chemical cleaning products

10) Air Filtration

11) Use of Sealants

12) Adjustment of Product Formulation

    - modify the constituents of building materials and furnishings that pollute

13) Treatment of Final Product

    - treat product at factory to reduce out-gassing

14) Ventilation at Source

15) Human Factor Control

    - deliberate reduction of polluting activities

16) Warning Devices and Controls.

Nero et al (1982) lists a series of control techniques that the authors felt were most promising for use in utility sponsored weatherization programs. These include removal of unvented combustion appliances and installation of range hoods for gas stoves; a combination of electrostatic air cleaning and mechanical filtration to remove particulates and lower the concentration of radon daughters; "scrubbing" the air for formaldehyde by passing the gas through water where it would be absorbed, or by passing it over a solid surface where it would be adsorbed (attached); and improved air circulation to increase the rate at which radon daughters and other "reactive" contaminants would attach to indoor surfaces. Reactive contaminants are those compounds, like radon daughters and nitrogen dioxide, that readily attach themselves to indoor surfaces.

The Ontario Ministry of Municipal Affairs and Housing is currently preparing a paper that will outline new ideas and practical guidelines for householders interested in maintaining or improving the quality of their indoor air.

Of all the indoor air pollution control strategies presented in the literature, constant or automatic mechanical ventilation has received an inordinate amount of attention. Many researchers assume that if some minimum level or air change is guaranteed by a mechanical system then concerns about indoor air quality should be alleviated.

3.3 VENTILATION

According to Berk et al (1980) adequate air change is required in all occupied buildings to:

1) Establish a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) released into the environment by human activities.

2) Remove excess heat and moisture from internal sources.

3) Dilute human and non-human odours to acceptable levels.

4) Remove contaminants produced by activities, furnishings, construction materials, etc. in occupied spaces.

Mechanical ventilation systems consisting of a fan driven exhaust system, sometimes balanced with a fan driven fresh air supply, are commonplace in commercial, industrial and even farm buildings. Until recently little consideration has been given to forced ventilation in single-family dwellings. It's always been assumed that wind and temperature differences between inside and outside of a house would be sufficient to move air through the unintentional openings in the building's envelope. Mechanical ventilation provides the occupants with the ability to directly control the ventilation rate to meet their needs. Mechanical ventilation systems are a necessity in air-tight low energy houses where natural infiltration has been reduced to a minimum.

The impact of mechanical ventilation on indoor air quality in relatively tight houses in Rochester, New York was studied by Offerman (1982). When mechanical ventilation (with heat reclamation) was used, the average air change rate increased by 80 percent, from an average of 0.35 ach to 0.63 ach. This resulted in a 50 percent decrease in radon gas concentrations from 1.0 pCi/L to 0.5 pCi/L, a 21 percent decrease in formaldehyde, a 30 percent decrease in respirable particulates, and the relative humidity decreased from 39 percent to 35 percent. The average indoor concentration of nitrogen dioxide increased because the ambient levels outdoor exceeded the indoor levels. Lebret et al (1982) monitored 286 kitchens for nitrogen dioxide and found that ventilation hoods over gas ranges reduced the average NO_2 concentration by 15 percent.

Hollowell et al (1982) monitored the effect of mechanical ventilation in two new energy efficient houses. Air change rates increased from 0.1 ach to 0.3 ach. This resulted in a dramatic drop in levels of carbon dioxide, radon gas and nitric oxide. However the change in air change had little effect on nitrogen dioxide, sulphur dioxide, formaldehyde and ozone.

Formaldehyde, nitrogen dioxide, suspended particulates and radon daughters (not radon gas) are considered to be reactive contaminants. They readily combine with indoor surfaces by absorption or adsorption so that an increase in ventilation rate will not result in an equivalent decrease in the levels of these contaminants. Offerman (1982) suggests that if the reactivity of a contaminant is particularly high, relative to the air exchange rate in a well-mixed space, neither increasing or decreasing ventilation would have a significant effect on its indoor concentration.

A mechanical ventilation system was installed in a house in Maryland that had radon levels well above the existing standard (Nazaroff et al, 1980). The rate of air exchange was systematically increased over two weeks from the natural ventilation rate of 0.2 ach to 0.6 ach. It was only at 0.6 ach that the radon levels dropped below the existing guidelines. No attempt was made to seal the pathways through which the radon gas was entering the house.

3.3.1 Mechanical Ventilation Strategies

Mechanical ventilation strategies break down into two broad categories: unbalanced mechanical exhaust systems and balanced ventilation systems. The former approach uses a fan to exhaust stale air from the house and depends on the unintentional openings in the building envelope to supply the fresh make-up air. The latter strategy employs two fans, one to exhaust stale air and the other to draw in fresh air from outside. Both approaches require a distribution system to effectively ventilate the entire house. Mechanical ventilation systems usually operate at a predetermined speed, but in some cases can be pre-set to speed up when indoor humidity levels increase. Centralized mechanical ventilation systems provide the opportunity to reclaim some of the heat that is normally carried out of the house by exfiltrating air.

Sherman and Grimsrud (1982) examined the impact of a mechanical exhaust system, a mechanical exhaust system with heat recovery, and a balanced system with heat recovery (commonly called an air-to-air heat exchanger) on the total ventilation and energy load of a house. Their results demonstrated that the effectiveness of the ventilation system is critically dependent on the leakiness of the building envelope. An exhaust system with heat recovery appeared to be the most appropriate system for a relatively leaky house because it created a very small additional ventilation and heating load. Exhaust systems increase the rate of infiltration through the building envelope but decrease the amount of natural exfiltration, significantly reducing the naturally driven part of ventilation.

A balanced ventilation system, such as an air-to-air heat exchanger, appeared to be most appropriate for tight houses since it's impact on total ventilation is heavily influenced by the rate of natural ventilation. In a leaky house, natural ventilation through the unintentional openings in the building envelope will combine with the additional ventilation supplied by a balanced system, such that the total ventilation will be greater than would exist with an unbalanced exhaust system (which diminishes the effect of naturally driven ventilation).

The Housing and Urban Development Association of Canada (HUDAC) has drafted guidelines for the design and installation of residential controlled ventilation systems in Canada (HUDAC, 1983). The draft guidelines recommend that a fan induced exhaust system should operate continuously at a low speed to remove moisture and pollutants. To balance the system, an intake is supposed to be provided to supply air for ventilation and for combustion appliances. The exhaust system draws air from all bathrooms and the kitchen, through ducts which ultimately vent the stale air to the outdoors at a centralized location. The intake system uses the furnace fan and the existing forced-air distribution system to draw air into the house and distribute it to the rooms. For houses with hydronic, electric baseboard or radiant heating systems, an intake fan would be required.

HUDAC suggests that the intake equipment should be sized to provide make-up air for all the house's exhausting devices, including furnace and hot water heater flues. According to the Ontario Research Foundation (EMR^b, 1983), the demands of some combustion appliances are important enough to warrant their own air supply without relying on the house's ventilation system.

Balanced ventilation systems with heat recovery provide the opportunity to reduce the energy losses associated with ventilation because warm exhaust air can be used to pre-heat incoming fresh air. A number of researchers have tested the ability of air-to-air heat exchangers to reclaim heat. Their results are reported in the following papers:

Hamlin, T., and Besant, R.W. Air-to-Air Heat Exchanger Performance Evaluation for Low Energy Houses in Saskatoon, Saskatchewan. Dept. of Mechanical Engineering, University of Saskatchewan, 1982.

Fisk, W.J., Roseme, G.D. and Hollowell C.D. Test Results and Methods: Residential Air-to-Air Heat Exchangers for Maintaining Indoor Air Quality and Saving Energy. Lawrence Berkeley Laboratory, LBL-12280, 1981.

Fisk, W.J. and Turiel, I. Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics. Lawrence Berkeley Laboratory, LBL-13843, 1982.

Offerman F.J. et al. Residential Air Leakage and Indoor Air Quality in Rochester, New York. Lawrence Berkeley Laboratory, LBL-13100, 1982.

Fisk (1981) (1982) tested several heat exchangers in the laboratory and found that the least efficient model reclaimed 43 percent of the heat from the exhaust air stream, while the most efficient model reclaimed 84 percent of the heat that was potentially available from the exhausting air. Hamlin and Besant (1982) tested 13 heat exchangers under operating conditions during a typical Saskatchewan winter. They found that the heat transfer effectiveness of the heat exchangers ranged from 18 percent, when the unit had frosted up, to 60 percent. The most significant finding they reported was that most of the heat exchangers were installed or operated improperly.

Offerman (1982) monitored nine heat exchangers in the field, including two units that were designed to transfer both heat and water vapour. While these heat exchangers would be useless in cold climates where the objective is to exhaust water vapour to the outside, Offerman's results suggest that they may be ineffectual in controlling contaminants that are water soluble, such as formaldehyde.

Fisk (1982) estimates that the operation of an air-to-air heat exchanger can reduce a house's ventilation heating load by 5.3 to 18 gigajoules ($63 to $213 worth of heating oil). This potential for energy saving has precipitated a number of economic analyses of air-to-air heat exchangers (Fisk, 1981, 1982 and Offerman, 1982, Roseme, 1980). Not surprisingly, it's sometimes difficult to justify the installation of a $1,000 heat exchanger, strictly from an investment perspective. Considering the utilitarian role of mechanical ventilation in helping to control indoor air quality and humidity, the value of such cost-benefit analyses is questionable.

Mechanical ventilation systems are already the principle means for ventilating Swedish homes. Approximately 50 percent of the installed mechanical ventilation systems are exhaust systems and 50 percent are air-to-air heat exchangers (Harryssen, 1982). In France, 40 percent of the single-family dwellings and 80 percent of the multi-story flats have mechanical ventilation (Bates and Jardinier, 1982). In Canada, whole house ventilation is a relatively new phenomenon even though there already are 10,000 operating air-to-air heat exchangers installed in single-family dwellings (Allen, 1983).

At what point does one install a centralized mechanical ventilation system? Hamlin and Besant (1982) suggest that air-to-air heat exchangers are only warranted when the house has an airtight vapour barrier or when there are serious humidity or indoor pollution problems. However, some governments have taken the guesswork out of ventilation by passing airtightness standards that, in most cases, make controlled ventilation practical.

3.3.2 Ventilation Standards

Harryssen (1982) lists 0.2 ach as the minimum air change rate that is required in a typical house to control moisture. The Swedish Building Code stipulates that occupied buildings must be mechanically ventilated at a rate of 0.5 ach. The maximum airtightness value of a building's envelope is required to be 3 ach at a 50 Pa pressure difference.

Proposed revisions to the Code will set a maximum airtightness value of 1.0 ach at a 50 Pa pressure difference, and will require heat recovery from exhaust airstream of the ventilation system.

The Danes have also set a standard of 0.5 ach to maintain acceptable air quality and conserve energy at the same time (Fangar, 1979). In Finland the current airtightness standard is 4 ach at 50 Pa, however, it has been proposed that this eventually be reduced to 2 ach at 50 Pa once the building industry had adopted airtightness as a goal. The standard on which many regulatory bodies in North America and Europe are basing their ventilation standard is ASHRAE 62-1981.

Ventilation for Acceptable Indoor Air Quality

ASHRAE 62-1981 is intended to ensure that buildings have an acceptable level of indoor air quality. This is defined as air that doesn't contain contaminants that exceed concentrations known to impair health or cause discomfort to the occupants.

To ensure acceptable air quality, ASHRAE establishes minimum rates of air change. For residential occupancy, outside air must be supplied at a rate of 5 litres/second (L/s) per habitable room. An additional 25 L/s and 50 L/s must be available on an intermittent basis for bathrooms and kitchens respectively. In commercial buildings ASHRAE specifies higher ventilation rates for spaces where smoking is permitted. As noted in Section 1.3, this standard is currently under revision and may be requiring higher air change rates in the future.

Recognizing that ventilation is only an indirect solution to the control of indoor contaminants, the ASHRAE standard provides for an alternative approach that sets maximum concentration guidelines for certain contaminants. These include the following:

Carbon Dioxide	2500 ppm
Formaldehyde	0.1 ppm
Radon	0.01 WL

Ontario has not yet adopted ASHRAE 62-1981, but it has been recommended that the standard form the basis of the Canadian Standards Association ventilation standard (EMR, 1984). The draft HUDAC ventilation system guidelines uses the ASHRAE standard's ventilation procedure for ensuring acceptable air quality.

The Canadian Standards Association recently sponsored a review of the basic precepts, practices and problems associated with whole house ventilation with a view to identifying the potential for standards (Canadian Standards Association, 1983). The author found no reason to recommend that new ventilation standards or airtightness standards be established until we fill the serious gaps in our knowledge with respect to airtightness, air change rates, safe levels of contaminants and the effectiveness and reliability of mechanical ventilation systems.

It was recommended that a "practice manual" on home ventilation be prepared to assist homeowners and contractors in understanding the problem of maintaining acceptable indoor air quality and to guide them in selecting an appropriate ventilation system. The author also identified eight major studies that must be undertaken, in his opinion, before any kind of ventilation standards can be established.

3.4 SUMMARY

Twelve years ago the prevailing attitude was that, "the solution to pollution depends on dilution." While that approach to outdoor air pollution control solved some localized problems, it caused problems elsewhere. Just as we now attempt to control outdoor pollutants at their sources, the source strengths of indoor pollutants must be reduced. Pollutants like radon can be reduced by sealing the cracks in the basement to keep the radioactive gas from infiltrating into the house. Other pollutants, such as nitrogen dioxide, can be kept at low levels by venting the gas to the outside from the area where it is produced. Still other pollutants, such as formaldehyde, could be minimized by selectively choosing building materials and furnishings for their low pollution characteristics. Houses that lack significant sources of pollutants can be tightened with the least risk of compromising the indoor air quality. If pollution control measures are carried out during energy conservation activities, the indoor air might be of better quality after tightening than before.

Unintentional air leakage cannot provide a house with a constant source of adequate ventilation. Mechanical ventilation provides the occupants with direct control over their fresh air requirements and the opportunity for heat reclamation from exhausting air. Extremely airtight houses can have good air quality if mechanical ventilation is used in combination with pollution control measures. The air supply requirements of combustion appliances should be dealt with separately.

It is often mentioned in the literature that a ventilation rate of 0.5 ach will maintain an acceptable level of air quality, if there are no significant pollutant sources. This, however, is an over-simplification and is not well supported by experimental data. The American Society of Heating, Refrigeration and Air Conditioning Engineers has set a ventilation standard based on the number of habitable rooms in a house. And for the first time in a ventilation standard, ASHRAE is making an attempt to address the sources of indoor air quality problems by setting maximum indoor standards for specific contaminants.

CONCLUSION

Over the past five years there has been a growing concern over the quality of indoor air and its potential impact on human health. The issues involved are not simple or readily resolved, but like the concerns over low levels of chemical contaminants in the food we eat and the water we drink, they are often controversial. This literature review has presented an overview of the existing body of knowledge on the effects of air sealing on indoor air quality; an increasingly popular energy conservation measure that can influence the level of pollutants in indoor air.

In the introduction to this report it was suggested that the salient question was: how tight is too tight? The answer is that it depends. It depends on the type and strength of the pollutant sources in the house, on how well those pollutants mix with the indoor air, and on whether and how much you deliberately ventilate a tight home.

It is evident from the literature that simply air sealing a house does not necessarily elevate indoor pollution levels. It is clearly not the villain that some people understand it to be. The level of indoor air pollution is determined by the rate at which pollutants are emitted into house air, the extent they mix with house air and the rate at which they are removed from the house. It is the combination of these factors that should be of concern.

Air sealing a house can reduce indoor air pollution levels from pollutant sources that are outside of the living space, such as radon from surrounding soil and formaldehyde from urea formaldehyde foam insulation. Air sealing can increase indoor pollution levels if it reduces the level of ventilation, and there is no corresponding reduction made in the source strength of the indoor pollutants.

The work reviewed in this report suggests that air sealing measures rarely reduce the level of ventilation in existing houses to below what is characteristic of conventionally constructed new houses. The one consistent exception are those electrically heated houses that were constructed after 1970. However, ventilation in both the new and old housing stock is uncontrolled and highly variable. The unintentional openings through which air change takes place may not be able to guarantee an adequate supply of air under all conditions. This lends support to the desirability of providing mechanical ventilation for houses to guarantee a minimum level of ventilation, but this is no more the solution to indoor air quality problems than air sealing is the cause.

There are significant gaps in our knowledge about the emission rate of indoor pollutants, their rate of diffusion through the house, the actual concentrations of contaminants that occupants ingest, the sensitivity of different individuals, and the health risks of extended exposure to low concentrations of pollutants. It is easy to point to the need for more and better research to fill those gaps, but in the short-term it is critical that people are made aware of what is known about the sources of indoor air pollution, the associated health risks, pollution control strategies, the conditions where air sealing will reduce indoor air quality, and the conditions where air sealing will enhance it.

TECHNICAL INFORMATION RESOURCES

Lawrence Berkeley Laboratory

A surprising amount of indoor air quality literature has been generated by researchers at the Lawrence Berkeley Laboratory in California. Since 1978, LBL has had a Building Ventilation and Indoor Air Quality Program. For those interested in reviewing their recent work, the mailing address is:

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Air Infiltration Centre

The Air Infiltration Centre (AIC) was established in 1979 by the International Energy Agency to provide technical support for active research in air infiltration in buildings. The AIC publishes a quarterly newsletter: the Air Infiltration Review, sponsors an annual international conference, and publishes AIRBASE: a bibliographic database which includes short abstracts. The AIC can be contacted at:

Air Infiltration Centre
Old Bracknell Lane
Bracknell
Berkshire RG124AH
Great Britain

Canada's national representative is:

Robert Dumont
Division of Building Research
National Research Council
Saskatoon, Saskatchewan
S7N OW9

ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AECB	Atomic Energy Control Board (CANADA)
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
EPA	Environmental Protection Agency (U.S.A.)
CMHC	Canada Mortgage and Housing Corporation
EMR	Energy, Mines and Resources Canada
HUDAC	Housing and Urban Development Association of Canada
MOL	Ontario Ministry of Labour
NAAQS	National Ambient Air Quality Standards (U.S.A.)
NCRP	National Council on Radiation Protection (U.S.A.)
NRC	National Research Council of Canada
OMMH	Ontario Ministry of Municipal Affairs and Housing
OSHA	Occupational Safety and Health Administration (U.S.A.)
SRC	Saskatchewan Research Council
TLV	Threshold Limit Values

GLOSSARY

Acute--When referring to the health effects of air pollutants, acute means those effects that immediately follow the exposure and disappear with the removal of the air pollution.

Air Barrier--A carefully installed covering of the interior of a structure to minimize the uncontrolled passage of air into and out of a dwelling; most commonly a continuously sealed 6 ml polyethylene sheet.

Air Change Per Hour (ach)--A unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour.

Air Infiltration--This is the process by which outside air enters a building through cracks, joints, and other nonintentional openings. The air-infiltration process allows the trading of outside air for inside air (see 'tightening').

Airtightness--The degree to which unintentional openings have been avoided in a building's structure.

Ambient Air--That portion of the atmosphere, external to buildings, to which the general public has access.

ASHRAE--American Society of Heating, Refrigeration, and Air Conditioning Engineers.

Benzo-(a)-Pyrene (BaP)--A tarry, organic material composed of five aromatic rings. BaP has been shown to induce cancers in animals.

Building Code--A legal instrument that is in effect in a province, administered by local government, the provisions of which must be adhered to if a building is to be considered to be in conformance with law and to be suitable for occupancy and use.

Building Envelope--The enclosure created by the components of a house that physically separate the heated living space from outdoors.

Carbon Dioxide (CO_2)--A colourless, odourless gas, heavier than air that arises from the complete combustion of carbon. Carbon Dioxide is a normal constituent of air, amounting to 0.03% by volume.

Carbon Monoxide (CO)--A colourless, odourless toxic gas of approximately neutral density relative to air arising as a result of the incomplete combustion of carbon-bearing materials.

Carcinogen--A material capable of causing cancer.

Chronic--When referring to the health effects of air pollutants, chronic means those effects that are delayed and are exhibited after one or repeated exposures.

EPA--Environmental Protection Agency

Epidemiological--As used here, epidemiological refers to statistical studies that attempt to relate health effects due to small exposures to pollutants by observing human populations exposed naturally or in employment.

Equivalent Leakage Area (ELA)--The total area of all the unintentional openings in a building's envelope, often expressed in square centimetres (cm^2).

Fan Depressurization--A large fan is used to exhaust air from a building in order to create a pressure difference across the building envelope; an analysis of the flow rate through the fan at different pressure differences provides a measure of airtightness.

Formaldehyde (HCHO)--An organic chemical widely used to link one molecule to another. Formaldehyde-based glues and binders are widely used, in plywood, particleboard, and furniture, for example.

Guidelines--Criteria recommended by government agencies, professional organization, or other groups. Guidelines are not legally binding.

Hemoglobin--The molecule in the blood responsible for oxygen transport. The globin molecule has sites on which oxygen can bind. In this way oxygen is carried from the oxygen-rich lung tissue to the remainder of the body. Carbon monoxide (CO) can also bind to the hemoglobin. Because CO binds to the hemoglobin better than oxygen, this can interfere with the transport of oxygen to the tissue.

Infiltration--The act of permeating with a liquid or a gas by passing through interstices; as used here, the introduction of air to the building from the outside through cracks or other openings.

Micro--A prefix meaning one millionth, abbreviated as μ . For instance, a microgram (ug) is one millionth of a gram.

Milli--A prefix meaning one thousandth, abbreviated as m. For instance, a milligram (mg) is one thousandth of a gram.

Million Electron Volts (MeV)--This is a measure of energy suitable for atomic particles. A MeV is the energy gained by one electronic charge in passing through a potential of one million volts. One MeV is approximately 4.4 x 10-20 kWh.

NAAQS--National Ambient Air Quality Standards

Nano--A prefix meaning one billionth, abbreviated as n. For instance, a nanogram (ng) is one billionth of a gram.

NIOSH--National Institute of Occupational Safety and Health

Nitrogen Oxides (or Oxides of Nitrogen) (NO_x)--All oxides of nitrogen except nitrous oxide as measured by test methods prescribed by EPA.

Normalized Equivalent Leakage Area--Also called the Specific Leakage Area (SLA), this is determined by dividing the ELA of a house by the surface area of its above ground envelope in order to compare the relative airtightness of different size hours.

NRC--National Research Council

Organics--A general term for compounds containing carbon.

OSHA--Occupational Safety and Health Administration

Pico--A prefix meaning one trillionth, abbreviated as p. For instance, a picogram (pg) is one trillionth of a gram.

Pico Curie (pCi)--10^{-12} Curie. The Curie is a measure of radioactivity. A curie is 3.7×10^{10} disintegrations per second.

ppm--Parts per million; when used applying to air pollutants, refers to litres of pollutant per million litres of air.

Radon (Rn)--A colourless, radioactive, inert, gaseous element formed by the disintegration of radium.

Radon Daughters--Product of the radioactive decay of radon. Radon decays by emission of a particle (charged helium nucleus) to polonium (Po). Subsequent decays through the release of a - and b - particles (electrons) result in lead (Pb), bismuth (Bi), and polonium nuclei. The radon daughters discussed in this document are the short-lived daughters through polonium-214. The decay of the radon leaves a charged metal atom that can attach to dust. If the dust is lodged in the lung, the a- and b- particles emitted by the radioactive nuclei damage the tissue. This damage can result in cancer.

Reactive--Some contaminants, such as radon daughters, nitrogen dioxide and ozone, readily attach themselves to surfaces instead of remaining mixed with air.

Retrofit--The thermal improvement of an existing house or structure.

Respirable Suspended Particulate (RSP) Matter--RSP are particles less than 3.5 microns in diameter. RSP tends to be carried to and lodge in the deepest part of the lungs during breathing action.

Standards--Criteria enacted by statute or regulation and are legally binding.

Threshold--As used here, refers to a concentration or exposure below which no health effects occur.

Tightening (also air sealing) - see air infiltration-- Tightening is the process of sealing cracks, joints, and other nonintentional paths by which outside air may enter a residence.

Time-Averaged--Refers to concentration levels averaged over time.

Total Suspended Particulate (TSP) Matter--The quantity of all suspended particles. See Respirable Suspended Particulate Matter.

Working Level--A quantity of short-lived radon daughters that will result in 130 thousand million electron volts (MeV) of potential alpha (a) particle activity per litre of air (see: Million Electron Volt, Radon Daughters).

CONVERSION FACTORS

1 ppm CO	=	1150 ug/m^3
1 ppm CO_2	=	1800 ug/m^3
1 ppm NO_2	=	1880 ug/m^3
1 ppm HCHO	=	1230 ug/m^3

NOTE: Values at $25^{o}C$ and 1 atm. pressure (760 mm Hg)

(Ministry of Consumer and Commercial Relations, 1981)

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APPENDIX A

Standards For Carbon Dioxide

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act		no standard		
	Ontario Environmental Protection Act a) Ambient Air Quality Criteria b) Emission Standards		no criterion		
	NAAQS a) Primary U.S. EPA b) Secondary		no standard		
INDOOR	ASHRAE 62-73 Standards		9.0×10^5	(500)	TLV/10[2]
	Submarine Environment Standards U.S. Navy	90 d	0.8% 0.5% for Trident and later class submarines		average reading, levels not to excee 1%, tactical situation permitting
		24 h	1.0%		limit
		1 h	2.5%		emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	9.0×10^6	(5000)	
	NIOSH Recommendations (Status OCT. 1978)	10 h	18 000	(10,000)	TWA[1]
		10 m	54 000	(30,000)	Ceiling limit
	OSHA Standards (Status OCT. 1978)	8 h	9.0×10^6		TWA

NOTE: 1 Time Weighted Average

2 As specified in Sec. 3.3., ASHRAE Standard 62-73

(Ministry of Consumer and Commercial Relations, 1981)

Standards For Carbon Monoxide

AIR TYPE	STANDARDS	Averaging Period	Ave. Concentration ug/m^3	(ppm)	COMMENTS
AMBIENT	Canadian Ambient Air Quality Objectives Federal- Clean Air Act	8 h	6 000	(5.22)	max. desirable[1]
			15 000	(13.04)	max. acceptable[2]
			20 000	(17.39)	max. tolerable[3]
		1 h	15 000	(13.04)	max. desirable
			35 000	(30.43)	max. acceptable
	Ontario Environmental Protection Act				
	a) Ambient Air Quality Criteria	8 h	15 700	(13.00)	
		1 h	36 200	(30.00)	
	b) Maximum Concentration	0.5 h	6 000	(5.22)	at point of impingement (defined in Reg.308)
	NAAQS U.S. EPA Primary & Secondary	8 h	10 000	(9.00)	max. standards based on other than annual ave. not to be exceeded more than once a year
		1 h	40 000	(35.00)	
INDOOR	ASHRAE 62-73 Standards	1 y	20 000	(17.39)	
		8 h	30 000	(26.09)	not to be exceeded more than once per year
	Submarine Environment Standards U.S. Navy	90 d	17 250	(15.00)	limit
		24 h	230 000	(200.)	limit
		1 h	230 000	(200.)	emergency limit
WORK PLACE	ACGIH Standards (TLV's)	8 h	57 500	(50.00)	accepted by Canadian federal and provincial authorities for occupational standard
	NIOSH Recommendations (Status OCT. 1978)	10 h	40 000	(35.00)	TWA[4]
		15 m	30 000	(10.00)	Ceiling limit
	OSHA Standard (Status OCT. 1978)	8 h	57 500	(50.00)	TWA

NOTE:
1 For new industry in non-industrialized areas
2 Secondary objectives for established industrial areas
3 Objectives for heavily industrialized areas
4 Time Weighted Average

(Ministry of Consumer and Commercial Relations, 1981)