Energy Efficiency and Indoor Air Quality in R-2000 and Conventional New Houses in Canada

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ABSTRACT

The R-2000 Home Program has been in the forefront of improvements in the energy efficiency of Canadian housing since 1981. Over the years, Natural Resources Canada (NRCan) has measured energy use and indoor air quality in R-2000 and new conventional houses to determine whether they are improving. This paper presents the results of a survey of 163 new conventional and 63 R-2000 houses. Results show that the Canadian housing continues to become more airtight and more energy efficient in all regions of the country. By comparison, R-2000 houses consume about 31% less space heating energy than new conventional housing. Monitoring results also show that the increasing airtightness has created a need for dedicated mechanical ventilation systems for preventing indoor air quality problems in conventional houses. The R-2000 houses adequately address the ventilation issues and have shown no IAQ related problems.

Introduction

The objective of the R-2000 Home Program, since its inception in 1981, has been to improve the energy efficiency of new low-rise dwellings. The program fulfills its objective by encouraging the supply and purchase of energy efficient new houses, by developing technical standards for more energy-efficient construction practices, materials, and technologies and by increasing consumer awareness of the advantages of these houses. The R–2000 Program has been one of the reasons for Canada being at the leading–edge of housing in the world. Others countries have followed suit by either emulating this Program or signing license agreements (e.g. Japan) to use the R-2000 concept.

To be certified as R-2000, a house must meet a number of criteria (NRCan1994) including:

- minimum insulation levels for ceilings, above ground and below ground walls, depending on degree day zones;
- windows must be a double glazed with thermally broken frames, or better (almost all are low-e and argon-filled in practice);
- balanced mechanical ventilation systems meeting minimum ventilation rates (all R-2000 houses have heat recovery ventilators);
- an energy use target which depends on the climate and size of the house;
- all gas, propane and oil-fired space and water heating equipment must be direct vented or induced draft to avoid possible backdrafting and contamination of indoor air;
- each house is individually blower-door tested, and must have an airtightness of

better than 1.5 air changes per hour at 50 Pa of depressurization;

- carpeting, flooring, paints, varnishes, adhesives, and cabinet work must be chosen from a list of low emission material and products.

The R-2000 Program has also led major changes to the tract built houses in Canada over last two decades. During the initial years of R-2000 housing (1982-85), R-2000 houses were about 50% more energy efficient than new conventional houses. From the beginning, the R-2000 housing practices began diffusing into conventional housing. For example, although vapor barriers were common practice from about 1965, airtight barriers were unknown before they were introduced by the R-2000 program, but are now common practice. Similarly, heat recovery ventilators were developed for the R-2000 program, and are now found in significant and increasing numbers in merchant built houses.

New non-R-2000 houses (also referred to as conventional houses) are slowly but surely approaching the R-2000 energy efficiency targets. Every four or five years, Natural Resources Canada (NRCan) has commissioned field-monitoring studies to examine and evaluate the energy and indoor air quality performance of R-2000 and new conventional houses.

The main objective of this paper is to compare the energy efficiency and indoor air quality in recently built R-2000 and conventional houses in Canada. As part of the study, 163 conventional houses built in 1990 through 1996, and 63 R-2000 houses built in 1983 through 1995 were evaluated (Hamlin & Gusdorf 1997). The sample houses were selected from each geographical regions of the country and represented major types of single-detached housing (one-, one-and-half- and two-storey). However, it should be noted that the sample houses were not selected using any statistical criteria. Therefore, the comparison is based on interpretation of a fairly large sample of houses, which, in our view, quite well represents the trends in energy and indoor air quality performance of recently built Canadian housing. The paper also briefly summarizes features of the new draft of the R-2000 Technical Standard, which will come into effect in the fall of year 2000.

Methodology

The study involved the following stages:

- Development of field data monitoring protocols to gather house characteristics and energy use data in a consistent manner;
- Selecting a number of field teams across Canada to conduct the house audits to gather data on: building envelope characteristics; space heating; water heating; ventilation system; indoor air quality parameters such as profiles of CO_2, temperature and relative humidity, formaldehyde, total volatile organic compounds; PFT tests for measuring air change rates; and utility bills for one to two years;
- Entering house data into files for the HOT-2000 energy simulation program;
- Reconciliation of HOT2000 simulated energy performance with utility bill data;
- Parametric analyses using standard operating conditions to estimate the impact of conventional and R-2000 construction practices.

Results and Discussions

Numbers and Sizes

Table 1 shows the regional distributions and average sizes of the houses in this study. House volume is measured directly because it is required for airtightness testing; floor area is calculated as volume divided by 2.5 meters. The national volumes are weighted according to the number of existing houses. On average R-2000 houses are larger than new conventional houses in all regions of Canada, averaging 22% larger for the country. The difference varies from 3% in British Columbia which has the largest conventional houses to 38% in the Prairies where conventional houses are slightly smaller than the national average. In Quebec, which has the smallest conventional house, R-2000 houses are only 9% bigger. The larger volumes of R-2000 houses probably reflect the fact that they are generally in the higher end of the housing market.

Table 1. Regional Distributions and Average Sizes of R-2000 and Conventional Houses

Region	New Conventional Houses			R-2000 Houses			Differences
	Number	Volume (m^3)	Area (m^2)	Number	Volume (m^3)	Area (m^2)	in Vol. & Area
British Columbia	20	840.4	336.2	8	867.4	347.0	3%
Prairies	69	621.7	248.7	16	859.1	343.6	38%
Ontario	20	721.6	288.6	12	904.2	361.7	25%
Quebec	30	447.0	178.8	14	488.8	195.5	9%
Atlantic	24	514.1	205.6	13	593.7	237.5	16%
NATIONAL	163	651.6	260.6	63	792.2	316.9	22%

Thermal Characteristics

Table 2 shows the thermal insulation levels of building envelope components based on the sample of new conventional and R-2000 houses. The thermal insulation levels in R-2000 houses are significantly higher than in new conventional houses. The average opaque (non-window) components of R-2000 houses have 39% higher insulation levels; the smallest difference occurs in the ceilings (24%), and the largest difference is in the lower basement walls below ground (52%). Table 3 shows the types of mechanical equipment found in the conventional and R-2000 houses. As shown, about 34% of conventional houses have heat recovery ventilators (HRVs) installed while about 53% of conventional houses are still without any dedicated ventilation systems. In contrast, all R-2000 houses are equipped with HRVs. The high-efficiency fossil fuel space heating systems have major uptake in R-2000 houses, while it is interesting to note that more than three-quarters of new housing have mid or high efficiency furnaces/boilers.

Table 2. Thermal characteristics of the New Conventional and R-2000 Houses

Housing Characteristics		New Conventional	R-2000
Sample Size		163	63
Ceiling insulation (RSI)	Range	3.58 to 9.80	4.85 to 10.83
	Mean	5.84	7.26
Main wall insulation (RSI)	Range	1.86 to 4.20	2.44 to 6.64
	Mean	2.85	3.58
Basement walls above grade (RSI)	Range	0.27 to 5.50	1.37 to 5.93
	Mean	2.00	2.84
Upper basement walls below ground (RSI)	Range	0.20 to 4.79	1.17 to 5.56
	Mean	1.74	2.60
Lower basement walls below ground (RSI)	Range	0.20 to 4.79	1.17 to 4.90
	Mean	1.70	2.59
Windows (RSI)	Range	0.23 to 0.61	0.24 to 0.78
	Mean	0.37	0.43
Airtightness (air change per hour at 50 Pa)	Range	1.99 to 4.28	1.14 to 1.44
	Mean	3.10	1.24

Table 3. Mechanical Systems Characteristics of the New Conventional and R-2000 Houses

Systems Characteristics		New Conventional	R-2000
Percentage of houses with Ventilation Systems	HRVs	34%	100%
	Balanced central	9%	
	Exhaust only	4%	
	No system	53%	
Main heating fuel	Electricity	37%	40%
	Fossil fuel	63%	60%
Percentage of houses with fossil fuel space heating equipment in each efficiency range	Low (< 80%)	23%	11%
	Mid (80% to 90%)	48%	17%
	High (> 90%)	29%	73%

Airtightness and Natural Air Change Rate

The airtightness of houses is measured as the number of air changes per hour (ach) produced when the house is depressurized to 50 Pa below ambient pressure by a blower door. The airtightness data are shown in Figure 1 and Table 4 by period of construction and region. The national averages are weighted according to the number of houses built the time period. As shown, the average airtightness of new conventional houses is about 3.10 ach and for R-2000 houses it is 1.24 ach at 50 Pa pressure difference.

Table 4. Average air changes per hour at 50 Pa pressure difference (airtightness) by region and period for conventional and R-2000 houses

Region	Pre 1921	1921 - 1945	1946 - 1960	1961 - 1970	1971 - 1980	1981 – 1990	1991-	R-2000
B.C	23.64	13.48	11.93	7.78	7.35	5.71	4.28	1.44
Prairies	9.14	9.10	4.99	3.65	3.18	2.84	1.99	1.34
Ontario	16.16	14.21	7.93	7.44	6.48	4.22	2.82	1.14
Quebec	13.51	15.63	11.21	8.94	8.40	7.23	3.27	1.22
Atlantic	9.09	6.23	6.28	6.32	5.34	3.90	3.14	1.35
NATIONAL	13.72	12.19	8.27	6.90	6.11	4.76	3.10	1.24

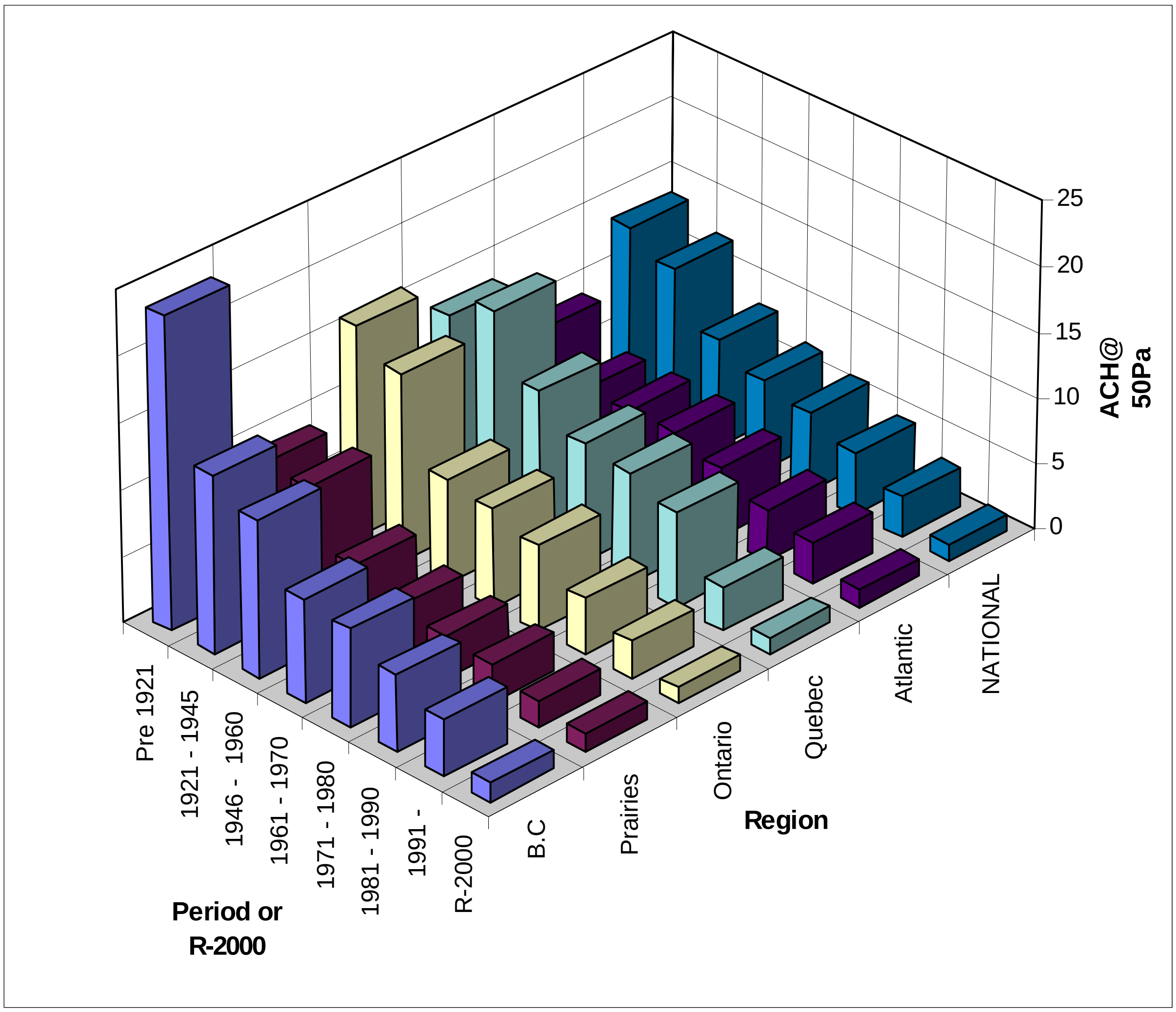

Figure 1. Average Air Changes per Hour at 50 Pa Pressures Difference (Airtightness) by Region and Period for Conventional and R-2000 Houses

The natural air change rate of a house is the rate at which it exchanges air with its environment without any mechanical ventilation. The natural air change rate must be measured or simulated under a particular set of conditions of indoor temperature and outdoor temperature and wind speed. For determining the need for mechanical ventilation, natural ventilation is generally simulated during a "critical month," the warmest month during which windows are likely to be closed. Houses with critical natural air change rates of less than 0.35 air changes per hour (ach) are likely to have indoor air quality problems unless they have enough mechanical ventilation to bring the total ventilation rates up to that amount (ASHRAE 1989; Gusdorf and Hamlin 1995). HOT2000 simulations indicate that in about 90% of new conventional houses the air change rate was less than prescribed 0.35 ach requiring a mechanical ventilation capacity of about 40 to 65 L/s to meet the comfort conditions. About 64% of these new conventional houses did not have dedicated central ventilation systems. In contrast, the HRVs found in all R-2000 houses provide adequate balanced ventilation. (The new 1995 National Building Code (NRC 1995), now adopted in most regions, emphatically requires a central dedicated ventilation system). HRVs use about 85 to 125 Watts, and their annual energy use of 750 to 1,100 kWh/y, or 2 to 4% of space heat energy, is more than saved by heating load reductions.

Heat Losses by House Components

Figure 2 compares the average heat losses through various parts of house envelopes for new conventional and R-2000 houses. As shown, the major difference in heat loss is mainly due to application of full-height below grade wall insulation in R-2000 houses, which is still not adopted in most new conventional houses (See Table 2 which shows that below grade insulation levels are 52% higher in R-2000 houses). The average heat loss through the windows is higher in R-2000 houses due to the use of larger window areas. Overall heat loss through an average new conventional house is about 14 GJ (or 11%) more than an average R-2000 house, despite the fact that R-2000 houses average 22% larger.

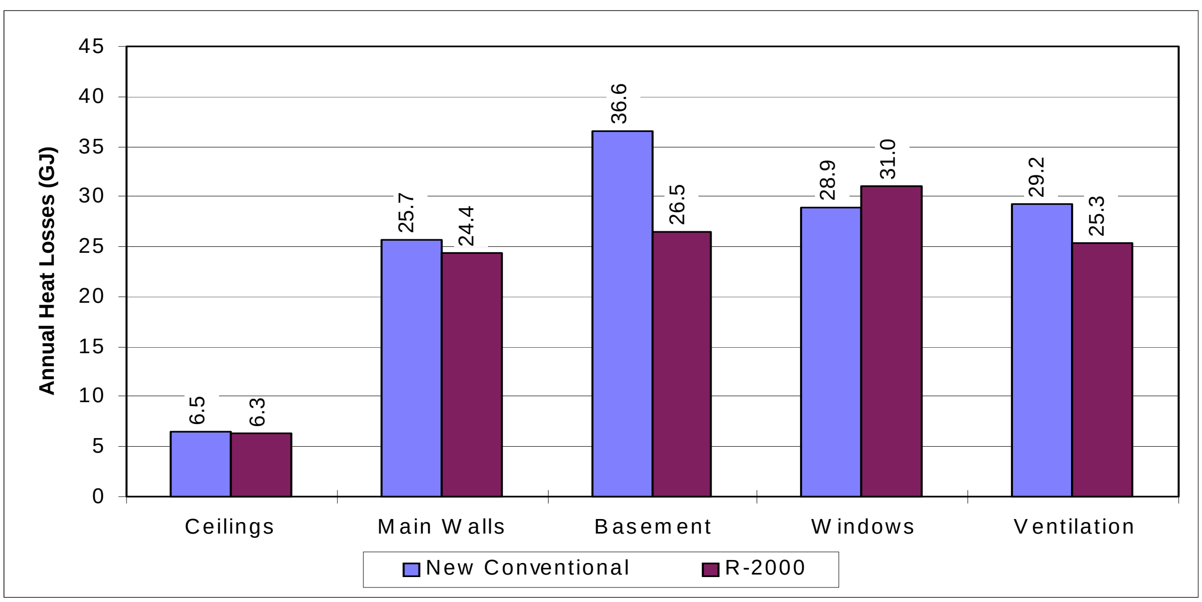

Figure 2. Average Heat Losses by Component for New Conventional and R-2000 Houses

Solar Gains

The analyses of usable of solar gains through the windows showed that in most R-2000 houses the usable solar gains as percentage of total space heat load were about 3.9% higher than in new conventional houses as shown in Figure 3. The higher solar contribution in R-2000 houses is mainly due to better orientation and site-specific parameters considered during the house design and planning stage.

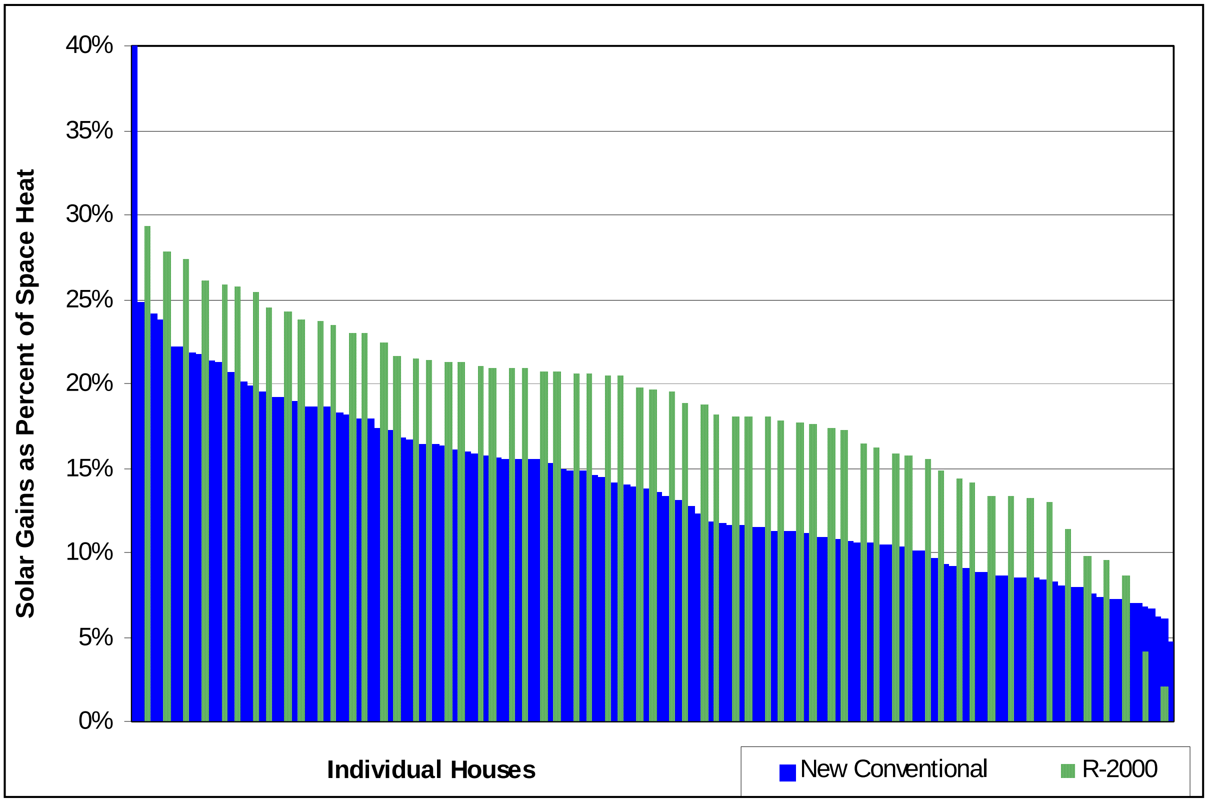

Figure 3. Usable Solar Gains as Percentages of Total Space Heat Load

Energy Use

Energy use by houses can be compared in a number of ways. For example, Figure 4 – based on the STAR Database (CMHC1992) and this study – compares the average amounts of energy used for space heat and hot water in houses of several age groups with R-2000 houses for comparison. The steady progression toward less energy use is clear, as is the fact that R-2000 houses use less energy despite their larger size. Figure 5 shows the total amounts of energy used for space heat, hot water, lighting and appliances for five categories of houses: conventional houses built in 1984 and in 1988, similar houses built according to the Model National Energy Code for Houses (NRC 1997), R-2000 houses built according to the current standard, and R-2000 houses built according to the new standard to be adopted this summer. Again, the progression toward greater energy efficiency is clear.

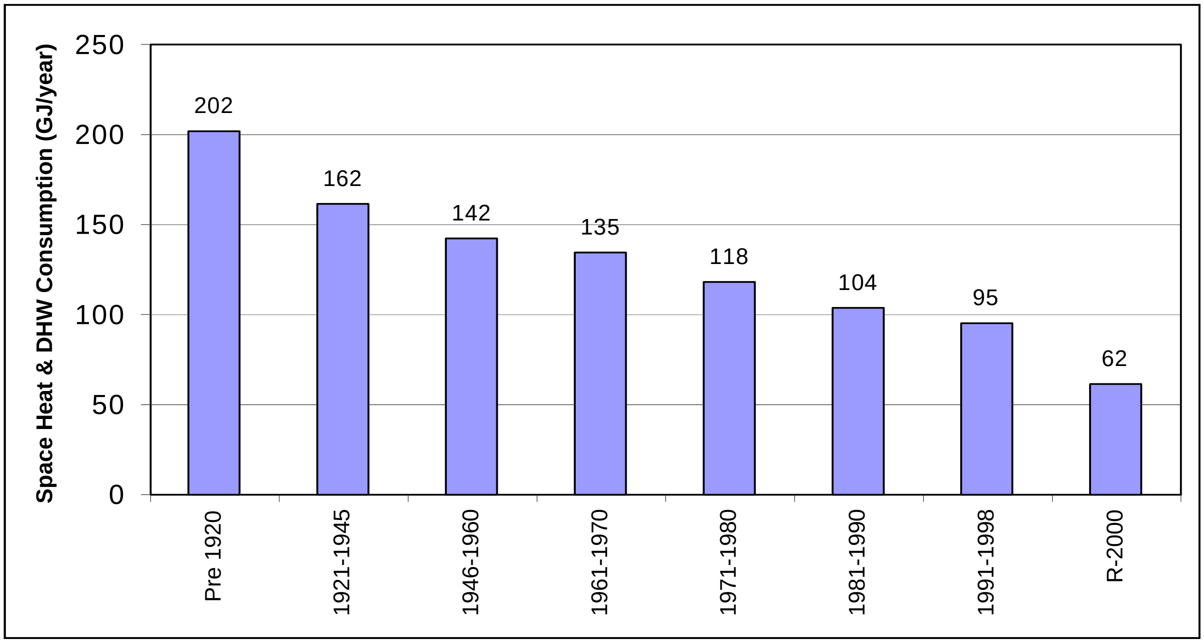

Figure 4. Average Energy Use by Period of Construction with R-2000 for Comparison

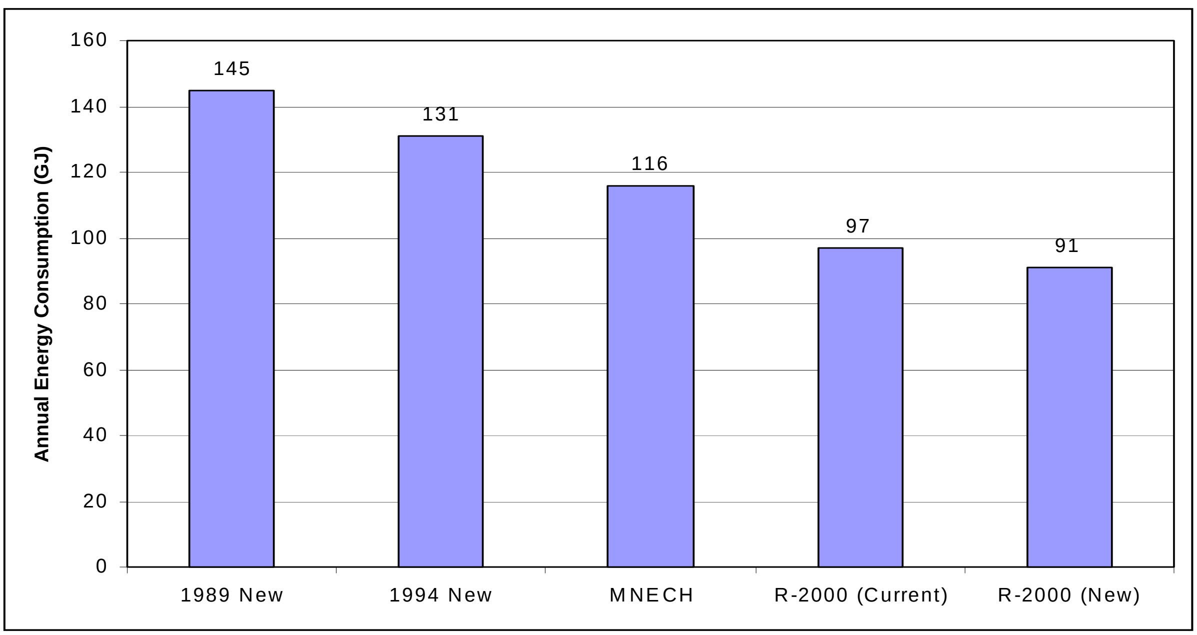

Figure 5. Energy Use by Five Categories of Houses

The 163 new conventional houses in this study use an average of 93 GJ per year for space heating and had an average volume of 652 m^3. According to the 1989-90 survey of new conventional houses (EMR 1992), those built in 1989 used 112 GJ, or 20% more, for a similar average volume of 640 m^3. The 63 R-2000 houses in this survey used an average of 64 GJ, or 31% less than the new conventional houses, and have an average volume of 792 m^3.

In order to eliminate the effects of indoor temperature settings and energy use for appliances and lighting, space heat energy was simulated using a set of standard conditions. Then the effects of house size and climate were eliminated by dividing the resulting space heat energy by degree days and heated floor area. The resulting normalized space heat energy is shown in Table 5 which shows that on and average the R-2000 house has about 41% less space heating requirements than a newly constructed conventional house. The above un-normalized difference of 31%, and the normalized difference of 41% are both based on HOT2000 simulations which have been corrected by comparisons with metered consumption.

Table 5. Comparison of normalized average space heating consumption

Type of House	Number of Houses	Space Heat Energy (GJ/y)		Normalized Space Heat Energy (kJ/(DD·m^2·yr))	
		Range	Mean	Range	Mean
New Conventional	163	24.8 to 245.6	93	34.1 to 199.5	82
R-2000	63	9.8 to 167.9	64	16.4 to 145.3	48

The EnerGuide for Houses Program is the Canadian home energy efficiency rating system developed by NRCan. It uses standard operating conditions and normalization by degree days and house size to produce rating numbers between zero and 100. A rating of zero would apply to a house with five times more energy consumption than current practice. A rating of 100 indicates a house with no purchased energy. R-2000 houses built to the current standard achieve ratings of 80 or more. The average EnerGuide Ratings of the new conventional and R-2000 house in this study are shown in Figure 6. Except for British Columbia, the R-2000 houses in all regions have average ratings of 79.6 or greater, and the national average is exactly 80. (The reason the R-2000s in British Columbia average only 74.3 is that five of these eight houses were certified under the defunct Quality Plus program that did not require blower door tests on each house). The EnerGuide Ratings for the new conventional houses range from 69.3 in British Columbia to 75.5 in Quebec, and average 73.3 for Canada.

Indoor Air Quality

The indoor air quality (IAQ) parameters formaldehyde (HCHO) and total volatile organic compounds (TVOCs) were measured in 73 of the new conventional houses and 24 of the R-2000s. As shown in Table 6, the average levels of both HCHO and TVOCs are significantly lower in R-2000 houses, and the maximum levels of TVOCs are almost four times lower. According to Health Canada (Health Canada 1989), formaldehyde levels should be below 0.05 ppm and action is required when levels exceed 0.1 ppm. While there are a few houses of both types that exceed the 0.1 ppm limit, the average new conventional house is over the 0.05 ppm level, but the average R-2000 house is just over one-half that level.

Volatile organic compounds (VOCs) are chemical pollutants. As many as fifty individual VOCs are normally found in air samples from residential environments. Measuring all relevant individual VOCs is expensive and time consuming, so a single test of total volatile organic compounds is often used as an indicator. The TVOCs level below which no effects can be detected is 200 micrograms per cubic meter (μg/m^3) while above 3,000 μg/m^3 most people will experience discomfort. As shown in Table 6, the average TVOCs in new conventional houses were about 588 μg/m^3 while in R-2000 houses it was about 388 μg/m^3.

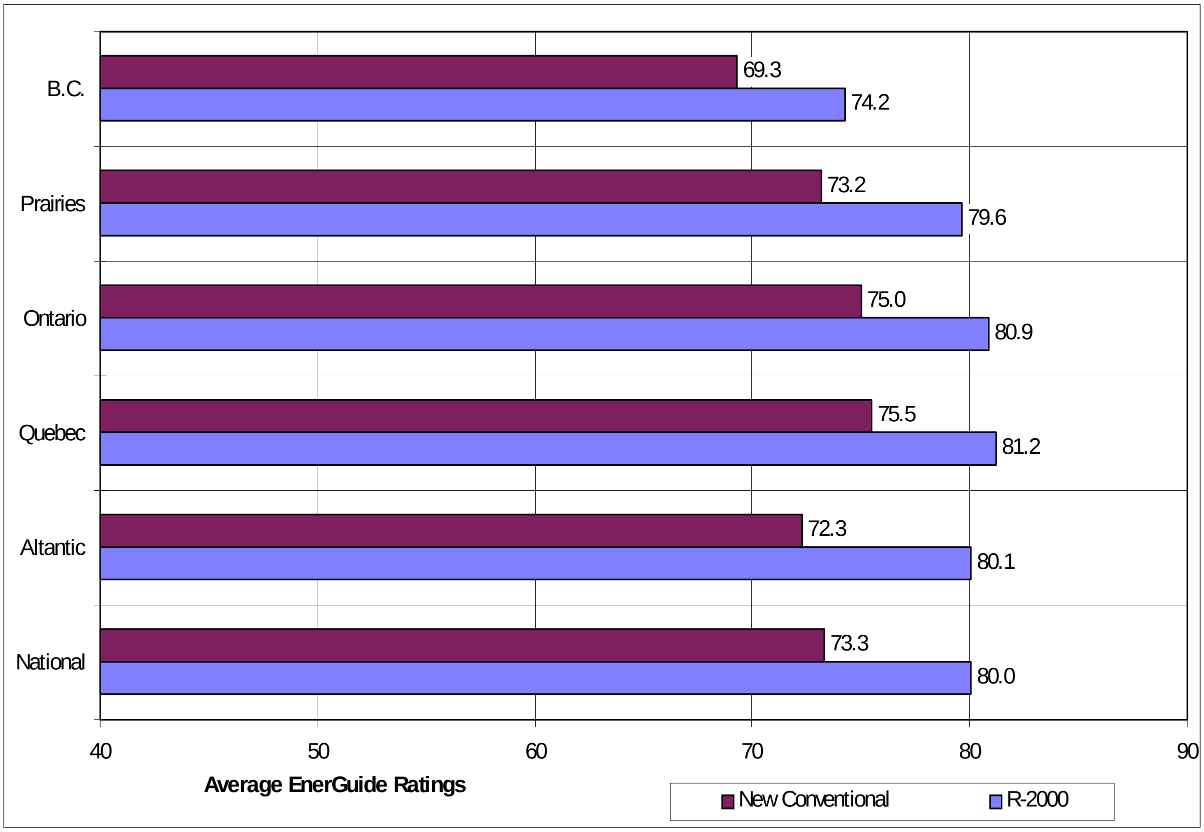

Figure 6. Averge EnerGuide for Houses Ratings

Table 6. Concentration of HCHO and TVOCs in conventional and R-2000 houses

Type of House	Number of Houses	Formaldehyde (ppm)		TVOCs (μg/m^3)	
		Range	Mean	Range	Mean
New Conventional	73	0.008 to 0.141	0.053	40 to 2806	571
R-2000	24	0.012 to 0.140	0.027	80 to 730	388

R-2000 Technical Requirements in the Year 2000

To keep the R-2000 Program at the leading edge of innovative solutions for energy efficient and healthy housing, the R-2000 Program undertook an exhaustive review of the current

Technical Standard during last eight months. The main aim was to ensure that technical stipulations reflect current energy–efficient trends and technologies in the industry, as well as to provide a clearer definition of requirements for some technical aspects. The review process involved more than 170 participants representing home builders, building trades, trade associations, architects and engineers, consultants and regulators. The process was based on the very important criterion that any change to the R-2000 Technical Requirements must not increase the current costs associated with the delivery of R-2000 houses, which is about C$5,000 (US$3,400 or less than US$11/m^2) more than a similar conventional house. The following is a list of some of the major changes affecting energy efficiency (Parekh 2000):

- Introduction of a pre-approval method as an alternative to HOT2000 analyses;
- Raising the thermal performance requirements for windows;
- Requirements for energy efficient air distribution systems such as electronically commutated motors (ECM) or other equivalents;
- Co-venting of space and water heating appliances no longer permitted which will promote the use of high-efficiency space heating and water heating equipment;
- Raising the energy performance requirements for cooling systems;
- Requirement for the commissioning of heating, cooling and ventilation systems;
- Expanding the IAQ pick list options and environmental features.

It is expected that the new standard will come into effect in the fall of 2000. The new standard will improve the energy-efficiency of new housing by a few percentage points while not putting any additional cost burden on builders or housing affordability.

Summary and Conclusions

Canadian housing continues to become more airtight and more energy efficient in all regions of the country. Although R-2000 houses continue to be significantly tighter and more energy efficient than new conventional houses, the gap is narrowing. Based on the results evaluated, new conventional houses consume an average of 93 GJ per year for space heating. By comparison, R-2000 houses consume about 64 GJ/year – or about 31% less than the new conventional housing. When normalized for floor area and climate, R-2000 houses use 41% less. New conventional housing has reduced its space heating requirements by about 17% in the last decade.

ASHRAE standards, previous studies, and the HCHO and TVOC concentrations from this study indicate that increasing airtightness creates a need for dedicated mechanical ventilation systems for preventing indoor air-quality problems in the conventional houses. This is one of the most glaring deficiencies found in the current conventional houses where more than 64% of the sample houses have either no ventilation systems or systems which may be inadequate. The recent adoption of the 1995 National Building Code by number of provinces should alleviate this problem. The R-2000 houses adequately address the ventilation issues and have shown no IAQ related problems.

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