Evaluation of Energy Performance of Nine Identical Row Houses in Montreal

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ABSTRACT

A detailed evaluation of the energy performance of nine identical row houses, built in 1994 on the same street by the same contractor, was performed in response to the homeowners' complaints. The energy audit was performed between January and March 1997 and covered both the house envelope and the heating system. This paper presents the process followed in this evaluation and the major problems noticed, such as leaky envelope, unexpected pathways for cold air, or closed dampers of the heat recovery unit. A comparison with some reference or target values is also presented. Finally, the impact of some energy conservation measures is evaluated.

INTRODUCTION

An association of homeowners contacted the authors in the fall of 1996, looking for an unbiased evaluation of the quality of their houses. All the houses were built in 1994 on the same street, by the same contractor, and were sold at an average price of CAN$ 265,000 (Labrèche 1997), which for the Montreal area represents upper-class construction. Each house has three floors, plus a basement: partly finished, partly a garage. The total heated floor area is about 230 m^2 (2475 ft^2). Most complaints concerned cold floors, cold drafts, condensation on some windows, and nonuniform heating of the house (e.g., lower temperature in the kitchen on the first floor and in some bedrooms on the second floor and higher temperature in the living room on the first floor).

The technical specifications, concerning the thermal resistance of the exterior envelope, comply with the minimum requirements from the Quebec regulation for energy conservation in new houses (Quebec 1992). The windows account for about 30% of the gross exterior wall area, or about 16% of total heated floor area. The heating is provided by a warm air furnace with a heater element of either 18 kW or 20 kW. The outside air is preheated by a heat recovery unit (HRU). Since the unit does not have fans to circulate the exhaust and outside air, the warm airstream comes directly from the supply outlet of the furnace, and the fresh air intake is connected with the return air duct, just before the furnace. Seven houses also have an air-to-air heat pump. The supply diffusers are installed on the floor, under the exterior windows. Baseboard heaters are installed on the third floor, in the bathroom, and in the finished basement, each one with its own thermostat. The owners declared that the use of baseboard heaters is very random. Electricity is the only source of energy used in these houses.

APPROACH

The evaluation of the energy performance of these houses was performed between January and March 1997. The following activities were performed at each house:

1. Infrared thermography and house inspection.
2. Evaluation of airtightness of the exterior envelope using the blower door test and a qualitative inspection with smoke pens.
3. Short-term monitoring of three to seven days with a time-step of either 16 s or 32 s for: (a) the electricity demand for heating, and (b) the indoor air temperature and the supply air temperature in two representative rooms.
4. Analyses of utility bills over the past 12 to 24 months, and the estimation of normalized annual energy performance. Comparison with reference values.

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5. Development of a computer model using the AUDIT2000 software and calibration with the utility bills.
6. Recommendations for improving the energy performance, and the evaluation of corresponding energy and cost savings by using the computer model.
7. Presentation of a detailed report to each homeowner.

In order to show the differences in performance between the nine houses, the results are presented in terms of an average value for all nine houses plus or minus one standard deviation (e.g., 20.3±2.9°C or 5.8±0.9 ACH).

Infrared Thermography and Visual Inspection

Infrared thermography, which was performed from the exterior of the houses, started around 7:00 p.m. when the outside air temperature was about −10°C (14°F). It revealed no significant leaks. The infrared camera was also used inside the house while the blower door was in operation maintaining a pressure difference of 20 Pa between outside and inside. Views of the ceiling revealed a large plume of cold surfaces corresponding to (a) the spaces between floor joists and (b) the voids in the thermal insulation of the exterior walls and roof. Similarly, studs spaces of the exterior wall were cold for the first meter from the party wall. The electric outlets on the exterior wall provided a direct path for cold air.

The inspection revealed the following:

- In three houses, condensation or ice was formed on the lower edge of the inside surface of windows; degradation of the windows' wooden frames was noticed. Moreover, in many of the houses, condensation was noticed between the two window panes, indicating the degradation of the seal gasket.
- In almost all houses, the floor surface in the kitchen was much colder than in the rest of the house.
- In six houses, both dampers of the heat recovery unit were found completely closed or almost closed (3 mm to 5 mm gap), indicating that the warm air system did not bring outside air into the house. For instance, during the visit to house no.1, the relative humidity in the living room was 65% because natural air infiltration alone was insufficient to evacuate the humidity loads generated by the process of growing orchids in the master bathroom. In that particular house, the electric wiring to the motorized dampers was found disconnected. Moreover, the fresh air intake duct to the HRU was not even connected to the outside inlet.
- The supply airflow rate was measured at each diffuser using a balometer; the total airflow rate supplied to rooms was 376±51 L/s (797±109 cfm), which corresponds to 1.66±0.19 L/s per m^2 of heated floor area (0.32±0.04 cfm/ft^2), or 2.4±0.3 ACH. On average, the total warm air is distributed to each floor as follows: 40.9% to the first floor, 27% to the second floor, 21.8% to the third floor, and 10.3% to the basement.
- In three houses, the fireplace dampers were always open, resulting in both additional air infiltration due to the stack effect and cold drafts as expressed by the owners.

Evaluation of Airtightness of the Exterior Envelope

The blower door test was used to evaluate the airtightness at 50 Pa pressure difference between inside and outside. The results can be summarized as follows:

- The air infiltration rate at 50 Pa for the whole sample was 5.8±0.9 ACH, which is much higher than that measured in new houses in Quebec: 3.07 ACH (Eval-Iso 1994), 3.33 ACH (Hamlin and Gusdorf 1996), and 3.9 ACH (Zmeureanu et al. 1998). For the sake of comparison, the target for an R-2000 house is equal to 1.5 ACH; extreme air infiltration rates of 6.42 ACH to 7.02 ACH at 50 Pa were measured in four houses.
- The average equivalent leakage area was 0.11±0.02 m^2 (1.21±0.17 ft^2), and the normalized leakage area was 9.5±5.2 cm^2/m^2 of the exterior wall.

These results indicated that the air infiltration rate is much higher than one would expect in new houses.

Significant leaks around glazing and electric outlets were visualized by using a smoke pencil while the blower door maintained a pressure difference of 20 Pa.

Short-Term Monitoring

Data loggers were installed in two representative rooms to measure (a) the air temperature in the middle of the room at 0.6 m height and (b) the air temperature at the supply diffuser. Another data logger was installed in the air duct leaving the furnace. In those houses where the dampers of the HRU were open, three more data loggers were installed to measure the air temperature in both streams: outside air and exhaust air. Clamp-on sensors connected to data loggers were also installed to monitor the electricity consumption of the furnace heater.

The measurements revealed the following:

- In five houses, the furnace is controlled in the AUTO mode; that is, the fan operates only when the electric heater of the furnace is on, to satisfy the demand. In four houses, the furnace fan runs continuously, regardless of the heater operation. Under this type of operation, when the heater is off, the supply air could be cooler than the room air, and since the air diffusers are installed on the floor, it could create uncomfortable cold drafts for people; e.g., the supply air temperature in house no.5 can get as low as 15°C (59°F) (Figure 1).
- In eight houses, the maximum supply air temperature measured on the second floor (usually in the master bedroom) is lower than that on the first floor by 3.3°C to

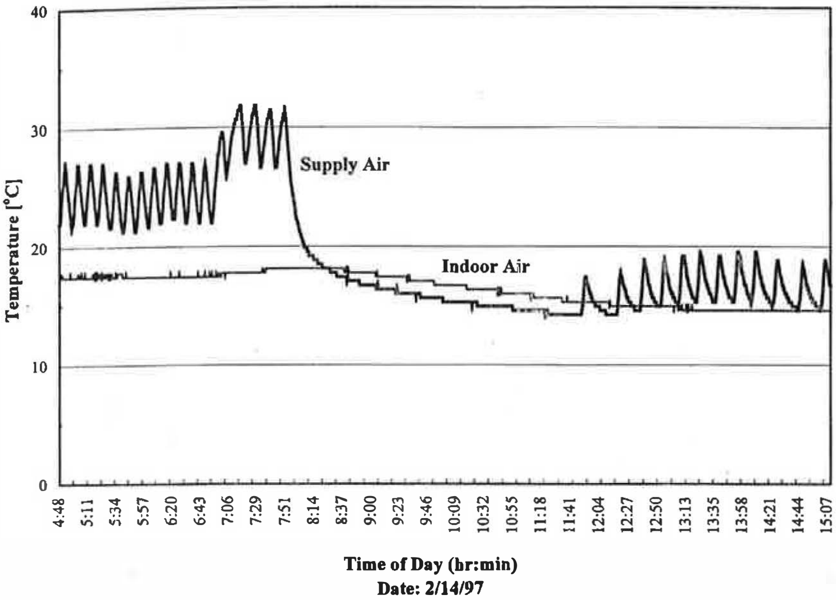

Figure 1 *Variation of supply air temperature and indoor air temperature in the master bedroom of house no. 5.*

13.2°C (6°F to 24°F), indicating important heat losses from the ducting system within the floors and vertical walls (Figure 2). One owner had recorded the important steps in the construction process and was able to report that the ducts had not been insulated during the construction, as required by the manufacturer of furnace. Moreover, in one unfinished basement, the investigation team noticed that only some ducts were insulated, which coincides with the owner's observation. These measurements also suggest that the cold infiltrating air must circulate within the floor and wall assemblies, explaining why some floors are cold.

- The difference between the minimum air temperature measured on the first floor near the thermostat location and the thermostat setpoint indicated that there are some problems with the calibration of thermostats. The measurements of this difference, called the "measured throttling range," are between 1.5°C and 4.8°C (3°F to 9°F) (Table 1). It is worth mentioning that the contractor installed different types of thermostat in these houses.

Evaluation of Energy Performance

The utility bills covering at least 12 to 16 months and the complete heating season of 1995 and 1996 were analyzed in order to normalize the energy performance for the weather

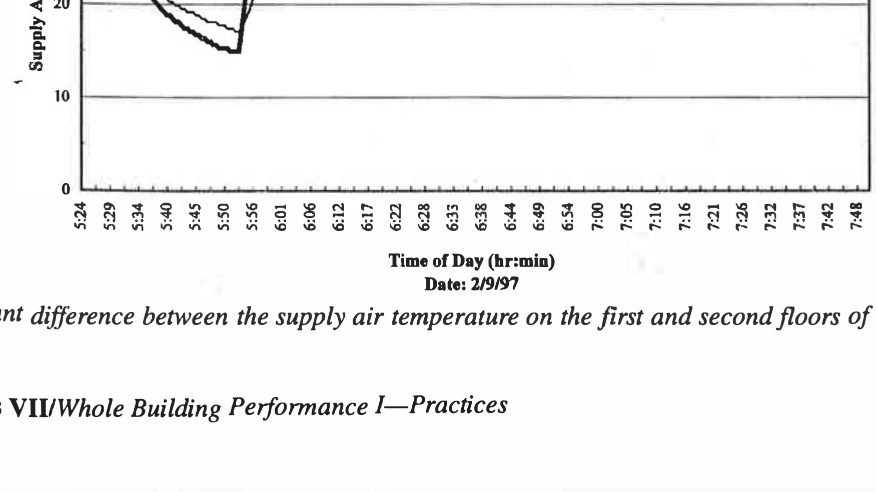

Figure 2 *Significant difference between the supply air temperature on the first and second floors of house no. 7.*

TABLE 1
Difference Between the Minimum Air Temperature Measured Near the Thermostat and the Thermostat Setpoint

House	Thermostat Setpoint °C (°F)	Minimum Air Temperature Measured on the First Floor °C (°F)	Measured Throttling Range °C (°F)
1	22.2 (72)	19.5 (67)	2.7 (5)
2	22.2 (72)	17.4 (63)	4.8 (9)
3	21.7 (71)	18.8 (66)	2.9 (5)
4	23.3 (74)	19.5 (67)	3.8 (7)
5	20.0 (68)	16.1 (61)	3.9 (7)
6	20.0 (68)	17.0 (63)	3.0 (5)
7	22.2 (72)	19.2 (67)	3.0 (5)
8	22.2 (72)	17.4 (63)	4.8 (9)
9	21.0 (70)	19.5 (67)	1.5 (3)

conditions. The weather-normalization technique is based on the assumption that the energy consumption in a house is composed of a non-weather-dependent component (e.g., for lighting, appliances, domestic hot water), which is almost constant throughout the year, and a weather-dependent component, which varies linearly with the outdoor temperature. First, the energy signature of the house is estimated by assuming a simple linear regression between the daily average energy performance (consumption and cost) and the corresponding daily average outdoor temperature:

$$\text{Energy} = a + b \cdot T_o \qquad (\text{kWh/m}^2\cdot\text{day})$$

$$\text{Cost} = c + d \cdot T_o \qquad (\$/\text{m}^2\cdot\text{day})$$

Second, the normalized annual energy consumption and cost are evaluated for an average year by using the energy signatures and the frequency of occurrence of several temperature bins, using daily outdoor temperatures recorded by Environment Canada at the Dorval airport between 1973 and 1995. The annual normalized energy consumption is broken down in two components: (1) the non-weather-dependent energy use (e.g., domestic hot water, lighting) and (2) the weather-dependent energy use, that is, for heating and cooling (Table 2). It is worth mentioning that the cooling energy consumption is negligible compared with the heating consumption.

All costs presented in this paper are in Canadian dollars. The electricity rate for residential consumers, corresponding to the utility bills, was the following: (1) \$0.379/day, plus (2) \$0.0459/kWh for the first 30 kWh/day, plus (3) \$0.0579/day for the balance of consumption.

The results can be summarized as follows:

- the normalized energy consumption of all houses was 123.7±24.7 kWh/m^2·yr, and the normalized energy cost was 7.75±1.6 \$/m^2·yr, or 1771±419 \$/yr;
- the heating consumption represents 57±14% of the total electricity consumption;
- the heating cost was 4.2±1.0 \$/m^2·yr, compared with about 6.0 \$/m^2·yr as indicated in the published information about this housing development (Labrèche 1997).

TABLE 2
Energy Performance of the Nine Houses and Some Important Driving Variables

	House								
	1	2	3	4	5	6	7	8	9
Normalized Annual Energy Consumption (kWh/m^2·yr)	92.0	86.4	147.3	162.3	139.5	113.2	130.2	119.7	123.7
Normalized Annual Energy Cost (\$/m^2·yr)	6.0	5.7	9.6	10.5	8.5	7.4	7.4	6.8	7.8
Heating Cost (\$/yr)	821	644	678	941	1418	917	816	961	1455
Control of Furnace	Auto	Auto	On	Auto	On	Auto	Auto	On	On
Thermostat Setpoint (°C)	22.2	22.2	21.7	23.3	21[1] 16[2] 19[3]	20[1] 16[2] 19[3]	21.1[1] 18.3[2] 18.3[3]	22.2	21.0
Infiltration Rate at 50 Pa (ACH)	4.79	6.57	6.42	5.36	5.72	7.02	6.6	5.06	4.58
Heat Pump (Yes/No)	Y	Y	Y	Y	N	Y	Y	Y	N
Dampers of HRU (Closed/Open)	C	O	O	C	C	O	C	C	C

[1] Thermostat setpoint during the occupied period of day.
[2] Thermostat setpoint at night.
[3] Thermostat setpoint during unoccupied periods.

There is a significant variation in the energy consumption and cost for heating between these nine houses. Some differences in the energy performance of the houses cannot be explained by the differences between the driving variables. The driving variables considered in this study are the operation mode of the furnace (continuous or auto), thermostat setpoint value, infiltration rate measured at 50 Pa, installation of a heat pump, and the position of dampers in the heat recovery unit (open or closed). Following are some examples.

- The heating cost for house no. 9 is about 120% higher than that of house no.2; this difference can be explained by the following facts: (1) house no. 9 does not have a heat pump, and (2) the furnace was reported to be continuously operated. However, other important variables do not play the expected role in explaining the large difference in heating cost; for instance, the infiltration rate and the thermostat setpoint of house no. 9 are lower than those of house no. 2, and the dampers of its HRU are closed, that is, no energy is used for preheating the outside air.
- The heating cost of house no. 7 is about 27% higher than that of house no. 2, even though the infiltration rates are almost equal and both furnaces are operated in the AUTO mode. Moreover, in house no. 7, the thermostat setpoint is reduced at night or during the day when nobody is at home. In addition, the dampers of the HRU of house no. 7 are closed.
- Although the air infiltration rate measured in house no.5 is greater than in house no. 9 (ratio of 1.25), they have almost equal heating costs (ratio of 0.97). One might conclude that this situation is the result of changing the thermostat setpoint in house no. 5 outside the occupied period.

The large and unexplained differences could be caused by the random changes of the thermostat setpoint and the fan operation mode, which were not declared by the house's owner during the interview. This result emphasizes the important role of people's behavior on the heating energy consumption and cost.

The ratio between the normalized energy consumption and that of an recently built, average house in Montreal, based on an evaluation with software (based on a large database that takes into account the socio-economic factors and people's behavior) was 0.96±0.23; only two houses, no. 5 and no. 9, have a normalized heating consumption greater than that of an average house. These results indicate that the electricity consumption of heating for most houses is lower than or almost equal to that of an average house; it is also lower than that predicted by the developer.

Development of a Computer Model

A computer model of each house was developed using the AUDIT2000 program developed at National Resources Canada and was calibrated using the utility bills. The difference, for the whole sample, between the estimated annual energy consumption and the normalized energy consumption based on the analysis of utility bills was about 18%. These models were then used for the evaluation of potential energy and cost savings, which can be obtained through cost-effective renovations or change of the thermostat setpoint.

Recommendations for Improving the Energy Performance

Since these houses are very new, and they comply with the minimum requirements of the Quebec regulation, the owners were not interested in expensive renovations. Therefore, the recommended renovations are concerned with the following.

- The reduction of the air infiltration rate through caulking around window and door frames, weather-stripping of moveable parts such as doors and access traps, and installing foam gaskets in the electrical outlets. The target of 3.6 ACH was selected as being the average of measured values from recently built houses; however, a reduction of 2.2 ACH on average is very difficult to achieve through the renovation of an existing house. Therefore, the predicted cost savings of 283±132 \$/yr, or about 31% of the annual heating cost, should only be viewed as the maximum potential savings. This measure will also improve the thermal comfort by reducing the cold drafts.
- While the above recommended measure might help in reducing air infiltration into the house, a better solution would be to improve the air barrier of the exterior envelope from the exterior by removing the brick or from the interior by opening the drywall. It would reduce the air infiltrated within the floor and vertical walls, thus avoiding the cold floors. However, this measure is not recommended due to its high implementation cost compared to the annual energy savings for heating.
- The balancing of HRUs for providing the minimum rate of outdoor air, to reduce the humidity level of indoor air and eliminate the condensation on windows. The energy cost is expected to increase by 230±135 \$/yr, or about 24% of the annual heating cost.
- The installation of an air-to-air heat pump in house no. 9. The energy cost is expected to be reduced by about \$540.00/yr.
- The reduction of the thermostat setpoint for the unoccupied periods during the day or at night. The cost savings are estimated at 120±86 \$/yr, or about 13% of the annual heating cost.
- The calibration or replacement of thermostats.
- The closing of fireplace dampers, when they are not used.

CONCLUSIONS

Although the annual energy cost for heating of these nine houses compares well with that of an average house in Montreal, their comfort performance was found not acceptable by the owners. The energy efficiency and the comfort could be both ameliorated by increasing the airtightness of the exterior envelope. Builders should pay more attention to this aspect, since it is more cost-effective to reach the target during the construction of a new house than to renovate an existing one.

It is clear that a careful commissioning of the heating system was not done. Some obvious problems affecting the quality of the indoor thermal environment should have been discovered and eliminated before the owners moved in. Under the present conditions, the following activities were recommended to be undertaken: (1) the balancing of the ducting system to satisfy the thermal loads in each room, (2) the balancing of the HRU to bring into the house the required outside air and to preheat it, and (3) the installation of a thermostat with a small throttling range to prevent low air temperatures in the rooms.

The owners should also pay more attention to the setting of the thermostat and close the fireplace dampers when it is not used.

This case study showed the importance of using an integrated approach for the design, construction, and commissioning of a house as well as for the evaluation of its energy performance by considering the interactions between all subsystems, such as the exterior envelope and heating system, and their impact on the people's perception of thermal comfort. It also showed the impact of people's behavior on the heating energy consumption and cost of identical houses.

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