FIELD TESTING OF HOUSE CHARACTERISTICS

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NOTE: **DISPONIBLE AUSSI EN FRANÇAIS SOUS LE TITRE:**

ESSAIS SUR LES LIEUX POUR DÉTERMINER DIVERSES CARACTÉRISTIQUES DE MAISONS CANADIENNES AVEC SYSTÈMES DE CHAUFFAGE À AIR PULSÉ

DISCLAIMER

This study was conducted for Canada Mortgage and Housing Corporation under Part IX of the National Housing Act. The analysis, interpretations and recommendations are those of the consultant and do not necessarily reflect the views of Canada Mortgage and Housing Corporation or those divisions of the Corporation that assisted in the study and its publication.

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The outcome of this project is very much the product of a team effort. Among many participants, contributors, and reviewers, the following deserve special mention:

From CMHC, *Don Fugler* supervised and directed the work, and thoroughly reviewed all stages of this project. He brought extensive CMHC experience to the project for many aspects.

Brendan Reid of Retrotec provided valuable insight during the development of possible duct leakage testing.

All of the homeowners that participated should be recognized for the voluntary contribution of their houses as test specimens and for a full day's disruption.

The project team was comprised of:
Ken Ruest, Paul Fettes, Michael Jezerinac, John Gusdorf, Bob Platts, Terry Robinson, and Anil Parekh,
Peter Moffatt and Brian Sikorski,
Richard Lind, Robin Barrett, Tim Shulz, and Oral Barkhouse,
and John Hockman and Robin Kelly.

EXECUTIVE SUMMARY

This project was undertaken to determine several performance characteristics of forced air heated houses in Canada. The testing was performed on 52 houses (12 in Halifax, 16 in Ottawa/Hull, 12 in Winnipeg, 12 in Vancouver) during the winter of 1992-93 to fill gaps in the research on housing in Canada.

Heating system duct leakage to outside the building envelope was tested in response to tests done in the U.S. that showed substantial duct leakage to outside the envelope. Basement depressurization in winter due to strong stack effects was studied. Room pressurization caused by heating system supply ducts was studied in response to concerns that pressurization could increase exfiltration. Wood moisture levels and house relative humidities were also measured to try to demonstrate a link. Bedroom carbon dioxide levels were monitored to see the magnitude of carbon dioxide levels possible in Canadian housing. Furnace and thermostat performance was studied, and the accuracy of homeowners' perceptions of their house's airtightness and relative humidity was evaluated.

It was very uncommon to see ducts outside the building envelope so duct leakage was not a major concern. Several houses in B.C., and a few in the other regions had ducts installed outside the envelope. In these houses duct leakage was occurring.

Average winter basement depressurization levels were usually around 5 Pa, although they were lower in the Vancouver area. Exhaust appliances were able to depressurize houses by over 5 Pa in about 40 percent of the houses.

Average long term bedroom CO_2 levels were typically in the 500 to 1000 ppm (parts per million) range. Short term peaks were greater than 1000 ppm in over 60% of the houses tested. ASHRAE suggests a 1000 ppm maximum for the control of odours and pollutants.

There was little evidence of significant pressurization or depressurization of rooms by forced air systems. Houses with oil or oil-to-gas conversion furnaces tended to have more powerful fans. Manitoba houses tested had a higher incidence of bedrooms with return and supply ducts so the rooms were less often pressurized.

Thermostat testing showed that when the furnace starts, the difference between the actual room air temperature and the temperature indicated by the thermostat thermometer is normally between +2.5°C and -2.5°C.

Householders were asked to assess their own homes in terms of airtightness and relative humidity. The correlation between their answers and the measured data was slight. About 42 percent of householders considered their houses of average airtightness. About 56 percent of those with very leaky houses were able to identify this condition. Most people characterized their house humidity as average to dry during the winter. Curiously, those houses labelled "dry" had a higher average indoor relative humidity than those labelled "average" in this group of householders.

1. INTRODUCTION

Despite the wealth of monitoring that has been undertaken in Canadian housing since the 1970s, many unknowns remain, particularly with regard to the range of house pressures which can occur. Canada Mortgage and Housing Corporation, as part of its ongoing mandate to improve the quality of Canadian housing through its technical research activities, retained a team led by Scanada Consultants Limited in association with Sheltair Scientific Ltd., Appin Associates, and Everts-Lind Enterprises to undertake a field project to test a sample of houses across the country.

The project objectives were:

- to determine the range of values for certain house characteristics where adequate data is currently lacking, and
- to identify priority areas for future research.

One of the prime concerns of this study was to determine if forced air heating system ducts leak to the exterior of the house envelope. Studies in the United States have shown significant leakage to the outside from duct work for heating or air conditioning systems.

Significant pressure effects due to mechanical system interactions have been measured in homes in the U.S. and in some R-2000 houses. Potential forced air heating pressures appear to dwarf wind, stack, flue, and exhaust fan effects, creating much larger pressure differentials than expected. Closed interior doors have been associated with room pressurization.

To develop a better understanding of the Canadian situation, duct leakage, room pressurization, winter basement depressurization, and several other supporting studies were performed across the country.

To provide a regional representation, a balance of houses were selected from the four major climate regions of Canada: Coastal BC (mild, damp), Prairies (cold, dry), Central (temperate) and Atlantic (cool, damp).

2. TEST METHODS

In each house studied, the tests listed below were performed (unless circumstances prevented testing). More detailed test protocol are included in Appendix A. Tests 1 through 3 were performed to determine a base of characteristics for each house and to help in the understanding of the other tests results. Tests 4 through 11 were performed to address the key concerns of the research project.

1) An airtightness test was performed on each house. This test was done to determine each house's airtightness characteristics since they may have an effect on many of the other tests performed.

2) Room air temperatures and relative humidity were measured in one central room at each level to quantify house temperature stratification (intentional or natural), and as reference data for the interpretation of other tests if required.

3) A combustion safety test was performed by measuring the house depressurization due to exhaust fans and other exhaust equipment such as clothes dryers, wood stove or fireplace flues, central vacuum systems etc. This test was done to determine the potential for combustion spillage or backdrafting and the possible effects the exhaust equipment might have on the basement depressurization monitoring.

4) Wall temperatures were measured for each level and each orientation to see if wall temperatures would correlate with areas of mould or condensation. Wall temperatures were to be taken where mould was found; however, no moisture troubled houses were encountered in the survey.

5) The wood moisture level was measured at one central framing member (in the basement where possible) to determine if wood moisture can be used as a good indicator of long term relative humidity in the house.

6) The neutral pressure plane was determined using smoke pencils. This information was gathered to determine if high basement depressurization (from the one week monitoring test) could be related to a high neutral pressure plane.

7) The thermostat and furnace operation were studied. The thermostat operation was studied to determine the range of performance characteristics of thermostats, such as thermostat

accuracy and the effect thermostats have on furnace cycle time (and furnace operation efficiency). The sensitivity of this test to temperature sometimes limited its application. Open doors, turning the furnace off for other tests, or airtightness testing that artificially cooled the house created abnormal cycles (ie. cycles that are longer in duration and start at a lower room air temperature). Solar gains, on the other hand, sometimes reduced the numbers of furnace cycles to two-three during the test period (typically 9:00 am to 4:00 pm). Where abnormal or forced cycles occurred, the data has been omitted from the analysis.

8) Room pressurization due to the furnace fan operation was measured in rooms with doors that could be closed off from the rest of the house. The pressure was measured relative to the remainder of the house. Supply duct flows were measured at registers wherever possible to see if the room pressurization was directly related to the flow from the supply duct. The flows were measured in Ontario and Nova Scotia by recording the time to fill a garbage bag (previously calibrated using a duct test rig), in Vancouver with a duct test rig (a CMHC apparatus that measures duct air flow by adjusting the speed of a fan placed in the flow until the pressure drop across the fan is zero), and in Winnipeg with a flow hood. The door undercut was also recorded. Where carpet was present, the measurement was normally taken between the top of the carpet and the bottom of the door.

9) Forced air heating system duct leakage through the building envelope was studied. The furnace fan operation effects on the house pressure were measured to determine if the ducting was leaking to the outside or drawing fresh air into the return air ducts.

10) Carbon dioxide (CO_2) levels were measured in the master bedroom to acquire further data on CO_2 levels in Canadian houses. In some cases the homeowners were asked to manually read and record the data at various intervals during the day while, in other cases, the data was recorded with data loggers. The monitoring was, in general, for periods varying from five to eight days.

11) Basement depressurization was monitored to determine the range that can be expected in Canada in the winter. To measure the largest depressurization, teams attempted to measure the cross-envelope pressure as low as possible in the house (ie. as far as possible below the neutral pressure plane). This usually meant passing the exterior pressure tap through the envelope at a basement window or combustion air supply although, where it was not possible to measure in the basement, a first floor opening was sometimes used. Manometers were usually located in the open basement or furnace room, depending on where the tube was passed through the envelope. Basement depressurization was recorded

manually by homeowners a few times per day in most houses and monitored with a data logger in three Nova Scotia houses. In British Columbia, some houses had no basement where the manometer could be installed so the first floor depressurization was measured. The measurements were recorded for approximately a week.

In addition a homeowner questionnaire was completed to gather information on the house operations and performance. This information could help to interpret the results of the tests performed.

2.1 Test Teams

The testing was performed by four teams, each responsible for one of the climatic regions. Sheltair Scientific Ltd. tested houses in Vancouver, Appin Associates in Winnipeg, Scanada Consultants Ltd. in Ottawa-Hull and Everts-Lind Enterprises in Halifax. Each test team consisted of two people; making it possible to complete all testing on a house in one day (with the exception of long term testing). In Nova Scotia, the field testing teams consisted of four people and this allowed them to tests two houses per day. As well as performing the tests in the Central Region, Scanada Consultants Ltd. coordinated the testing and development of test protocols, and performed the analysis and documentation of results.

2.2 House Selection

A total of 52 houses were chosen for this research project. Twelve houses per region plus four pilot houses in the Ottawa-Hull area were selected from networks of contacts from each team. The house selection criteria were as follows:

- contractor-built tract houses or houses representative of the housing stock
- forced air heating systems
- single family detached houses
- representative examples of pre-war, late 40s, 50s/60s/70s/80s, and new homes
- willingness of home owners to participate and record CO_2 and basement depressurization data for a week

A good mix of house ages and styles were selected in each region. Two of the houses, ON07 & MB11 met the R-2000 airtightness criteria of air changes per hour at 50 Pa and normalized leakage area. A few houses deviated from some of the criteria listed above such as: BC05 was a semi-detached, NS07 had a separate apartment on part of the second floor, NS10 and NS12 are older homes which did not have traditional duct work to each room.

2.3 Development of Testing Protocol

The test procedure that required the most developmental work was the duct leakage test procedure. The other tests were either straightforward tasks or already established test procedures. These other tests only required some standardization to ensure all teams would perform the tests the same way.

Four pilot houses were used to develop the duct leakage protocol and to do test runs of the full series of tests. These houses were ON01, ON02, PQ01 and PQ02.

Duct Leakage Test

With suggestions from CMHC researchers and the assistance of Brendan Reid of Retrotec, several methods were tested in an attempt find a test method to quantify duct leakage.

The trials to determine the protocol revealed a lot about the leakiness of duct work within the house. Pressurizing or depressurizing the entire supply and/or return system to the same pressure was not possible in the pilot houses. Even with the supply and return registers sealed, it was not possible to obtain the same pressure at each of the registers.

The method which was finally used by three of the teams consisted of measuring the effect of the furnace fan operation on the house pressure. The supply and return registers were first all blocked and then the furnace fan was turned on to pressurize the supply side and depressurize the return side of the duct work. The house pressure was measured before the fan was turned on and then with the fan on. If both the supply side and return side were leaking equally (or not leaking at all) to the outdoors, no house pressure change would be noticed. Then the supply side only was checked by isolating the return duct work from the effects of the furnace fan and repeating the test. Simulating the return side duct work resistance was achieved by closing the furnace fan compartment door until the pressure in the supply side was the same as in the first test. This test method is referred to as the "Furnace Fan Induced ΔP Method" in this report.

The other test method used by the Vancouver team consisted of sealing supply and return registers, and pressurizing both the return and supply sides of the duct work to the same pressure. The supply side was pressurized using the furnace fan while the return side was pressurized by another fan which was installed at one of the cold air return registers. Once the **duct work** was **pressurized** (ie. **+50 Pa** in the supply and return sides of the ductwork),

then the **house** was **depressurized** to the same pressure (ie. **-50 Pa**). If the duct work was leaking inward from the exterior of the house during the regular airtightness test, the pressure across these leaks is now balanced so no air flow should occur across these leaks. The difference in the ELA calculated from this one point test compared with the ELA of the full airtightness test accounted for the duct leakage to the outside. This test method quantifies the leakage more specifically than the other method. However, the duct work must be such that it can be pressurized equally throughout in order for this test to work. Some difficulties in achieving a uniform pressurization or depressurization of the duct work was encountered during the pilot test runs. This test method is referred to as the "Modified Airtightness Test Method".

Further duct leakage test method developments could provide a more accurate means of quantifying duct leakage. However, large duct leakage problems should have been detected with these two test methods in the houses tested in this project.

2.4 Variation of Test Methods

Duct Leakage

See above

Long Term Monitoring

Homeowner monitoring sheets were replaced with electronic data loggers for CO_2 monitoring in MB01-MB12 (except MB04, MB05, MB09) and NS01-NS12. Similarly, data loggers were used for basement depressurization monitoring in houses NS06, NS09, and NS11.

This application of data loggers provided a confirmation that the manual readings had captured the maximum and minimum CO_2 levels in houses where the home owners had recorded the data manually. In order to compare the data from houses where CO_2 readings were electronically logged to the ones with manually collected data, the readings at 7:00 am, 9:00 am, 4:30 pm, 6:00 pm and 11:30 pm were extracted from the electronically logged results. The times selected corresponded to the approximate times that the home owners had recorded data manually. For each house with the electronically logged CO_2 readings, the average, median, minimum and maximum CO_2 readings were calculated for all data points and for the extracted data points. The results of the extracted data are very close the values for the entire sample.

3. RESULTS

The variety of houses selected for the project form a very good sample of typical housing in Canada. Table 1 summarizes the types of houses found in the study.

Table 1: Summary of Houses Tested

	REGION				
HOUSE AGE	BC	MB	ON/PQ	NS	TOTAL
Pre-1940s	1		1	3	5
1940s & 1950s	5	4	2		11
1960s	2	1	4	2	9
1970s	1	3	2	1	7
1980s	2	2	6	3	13
1990s	1	2	1	3	7
BASEMENT TYPE					
Full Basement	5	10	14	12	41
Crawl Space	2				2
Slab on Grade	3				3
Mixed	2	2	2		6
NUMBER OF STOREYS					
1	3	5	5	4	17
1 1/2	3	3		3	9
1 3/4			1		1
2	6	4	9	5	24
2 1/2			1		1
FORCED AIR HEATING SYSTEM					
Gas	12	11	11		34
Oil			2	9	11
Electric		1	2	1	4
Wood			1	1	2
Wood/Oil				1	1

3.1 Duct Leakage

When houses were tested using the furnace fan-induced ΔP method (Manitoba, Ontario, Quebec, and Nova Scotia) house **depressurization** of 1 Pa or less was measured in 27 of the 37 houses when tested with supply and return sides connected. In three houses a **pressurization** of 1 Pa or less was measured. These pressures are considered insignificant.

Significant pressure differences (2 Pa or more) occurred in six of the houses (all in Nova Scotia) **when tested with supply and return sides connected**. An additional three houses showed significant pressure differences **when tested with the return side isolated**. Results for these 9 houses are summarized as Table 2. In six other houses there were visible signs of potential duct leakage. These six cases are listed in Table 3. Results for all of the houses tested are listed in Appendix C. No houses exhibited significant house pressurization (which would have indicated that return air leakage was dominant). The comments listed for houses with significant pressure differences show that there were several other factors that could have contributed to these pressure differences. Wind can affect the cross-envelope pressure differential by several Pa. Furthermore, the manometer location could be important if one part of the house was being pressurized with respect to another.

In Manitoba, there were several houses with an outdoor air duct; an undampered duct from outside the house connected directly to the heating system return air duct. These outdoor air ducts, common in Manitoba, are typically from 3 to 5 inches in diameter. Outdoor air ducts, often long and constructed from flexible ducts, tend to have high flow resistance. Flow through the duct under normal operating conditions is negligible. The outdoor air ducts are important as a reference because they may provide flow resistance of the same order as a stud space return duct that is open to the attic. The results of duct leakage testing in houses with outdoor air ducts are tabulated in Table 4. The fact that outdoor air ducts (open) didn't result in significant pressure differences across the building envelope suggests no house pressure difference may arise from cross-envelope leakage through long, highly resistive paths. Results of tests with the outdoor air duct open cannot, however, be expected to indicate the magnitude of direct leakage in ducts installed outside the envelope (eg. through crawl spaces).

In most of Canada, the potential for duct leakage lies mainly in pressurizing (or depressurizing) joist- and stud-spaces that are not sealed at the attic, header area, or envelope in general. This is not thought to generate substantial leakage due to the resistance of the path, the low ΔP within stud- or joist-spaces, and the intermittent frequency of furnace operation. Observations about the duct layout in houses visited in Manitoba, Ontario, Quebec, and Nova Scotia indicate that there were few cases where ducts passed outside the building envelope. As a result there is rarely a potential for direct duct leakage outside the envelope. In B.C., however, more ducts tended to be outside the building envelope (particularly in crawl spaces) and hence there was more potential for direct leakage from ducts to unconditioned space or vice versa.

Table 2: Houses Showing Significant Pressure Effects During Duct Leakage Testing

House ID	House ΔP (Pa) (supply and return effect)	House ΔP (Pa) (supply effect only)	Manometer Location	Wind Conditions	Notes
ON06	0.0	2.0	Basement	16 km/h	2nd Floor bathroom supply disconnected; potential for joist- and stud-space pressurization.
ON08	0.0	3.5	Basement	Calm	Powerful 3-speed fan, 120 Pa static duct pressure.
MB08	1.0	2.0	1st Floor	28-37 km/h	Duct has convoluted run & cold run through garage walls to room over garage. House ΔP fluctuating by 1 Pa.
NS02	4.0	3.0	1st Floor	Light	House ΔP fluctuating by 3 Pa, turbine exhaust ventilator.
NS03	3.0	2.0	1st Floor	20 km/h	House ΔP fluctuating by 5 Pa.
NS04	3.0	3.5	1st Floor	Light	
NS05	2.0	1.0	1st Floor	Light	Furnace draft inducer on.
NS06	3.0	3.0	1st Floor	Light	HRV comes on with furnace fan, NPP above 2nd floor ceiling.
NS12	2.0	N Avail	1st Floor	Light	

Table 3: Houses with Other Signs of Duct Leakage

House ID	House ΔP (Pa) (supply and return effect)	House ΔP (Pa) (supply effect only)	Manometer Location	Wind Conditions	Notes
ON03	-0.5	0.5	Basement - finished rm	7 km/h	Fresh air duct into return not blocked, house ΔP fluctuating
ON04	-0.5	-0.5	Basement	Calm	1 supply disconnected, house ΔP fluctuating
0N10	0.5	0.5	Basement	Gusty	Supply duct passes through crawl space
MB02	0.5	0.0	1st Floor	9 km/h	Balloon-framed exterior wall cavities used for return may be open to attic
MB10	0.0	0.0	1st Floor	17 km/h	Return ducts leaky, joist end caps poorly installed
MB12	0.0	0.0	1st Floor	30-39 km/h	Supply registers in crawl space - couldn't seal but closed supply dampers, house ΔP fluctuating by 1 Pa

Table 4: Houses Tested with Outdoor Air Duct Sealed and Opened to the Return

	O.A.D. Sealed		O.A.D. Opened				
House ID	House ΔP (Pa) (supply and return effect)	House ΔP (Pa) (supply effect only)	House ΔP (Pa) (supply and return effect)	House ΔP (Pa) (supply effect only)	Manometer Location	Wind Conditions	Notes
MB01	0.0	1.0	0.0	1.0	1st Floor	N/A	House ΔP fluctuating by 1 Pa
MB04	0.0	1.0	3.0	-1.5	1st Floor	25-30 km/h	House ΔP fluctuating by 3 Pa
MB07	0.0	0.0	-1.0	0.0	1st Floor	4 km/h	
MB08	1.0	2.0	1.0	2.0	1st Floor	28-37 km/h	House ΔP fluctuating by 1 Pa, 3" diameter O.A.D.
MB10	0.0	0.0	0.0	0.0	1st Floor	17 km/h	5" diameter O.A.D.
MB11	0.0	0.0	1.0	0.0	1st Floor	7 km/h	5" diameter O.A.D. - 14' of flex duct

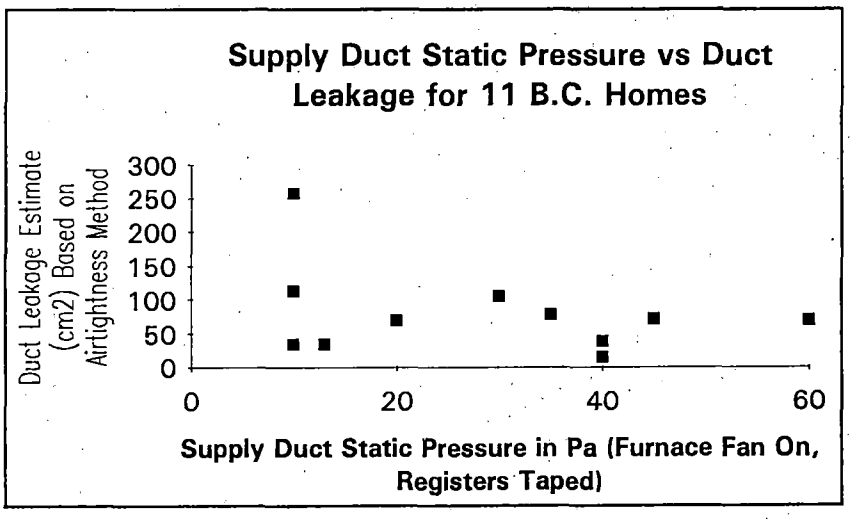
For houses in B.C., where a different test method was applied (see variation of test methods) the estimated ductwork ELA has been calculated along with the overall ELA for the building envelope. These results are summarized as Table 5. The B.C. test team has stressed that it may not be appropriate to compare the ductwork ELA to the house envelope ELA because they are two different types of leakage with different driving pressures.

Table 5: BC Duct Leakage Test Results based on the Modified Airtightness Test Method

House ID	Envelope ELA @10 Pa (cm2)	Envelope NLA (cm2/m2)	Envelope AC/H @ 50 Pa	Duct Leakage (cm2)	Pressure Tested (Pa)	Leakage Percent of ELA (%)	Foundation	Comments
BC01	6443	5.7	14.4	113	10	2	Full bsmt (walk-out)	
BC02	1510	3.5	9.8	39	40	3	Crawl Space	Crawlspace ducting taped, uninsulated, no wall cavity ducts
BC03	1041	2.1	3.2	35	13	3	Full bsmt (walk-out)	
BC04	3959	5.9	9.3	257	10	6	Full bsmt, Slab on grade	Duct runs through slab in front of house
BC05	2210	5.2	10.0	71	45	3	Slab on grade	No through-envelope return duct leakage. Supply duct runs through concrete slab which has no insulation below. Supply duct runs through garage: major leakage potential.
BC06	1472	3.4	6.0	69	20	5	Full bsmt	
BC07	1305	3.2	7.1	16	40	1	Slab on grade	Ducts run through uninsulated slab
BC08	2092	3.6	6.1	69	60	3	Slab on grade	Single return air grill on 2nd floor ceiling. This 14"-16" dia. plenum runs through the attic & is partially constructed of soundboard. Leaky furnace room is outside envelope. Mid-eff. furnace.
BC09	915	2.6	6.6	78	35	9	Crawl space	Furnace in unheated crawlspace. Filters at return air grills
BC10	1364	3.3	7.4	35	10	3	Full Bsmt	
BC11	3850	3.8	7.0	105	30	3	Full Bsmt	
BC12	N Avail	N Avail	N Avail	N Avail	N Avail	N Avail	Full Bsmt, Crawl Space	

Based on the B.C. results it is clear that in the majority of houses the furnace fan can pressurize the supply ducts to at least 10 Pa with registers sealed, even when leakage is substantial. Figure 1 illustrates that the ability to pressurize ductwork does not clearly indicate a lack of duct leakage. One system with an estimated duct leakage area of 100 cm^2 was pressurized to 30 Pa (static).

Figure 1: Supply Duct Static Pressure versus Duct Leakage



Comments On the Duct Leakage Test Methods Accuracy

It should be noted that the two test methods for duct leakage do present some limitations in accurately accounting for duct leakage. Nonetheless, major duct leakages would have been found if present and these tests and did serve the purpose to determine if duct leakage was a major concern in these houses.

For the furnace fan-induced ΔP method, the actual leakage is not quantified in volume of air or size of the leaks. The assumption that the leaks in and leaks out were equal if no house ΔP was produced by the furnace fan is correct with regards to the air flows in versus the air flows out. However, since the pressure in the supply side of the duct work is greater that the pressures in the return side of the duct work when the furnace fan is operated, the actual size of the leaks in the return side may be different then those in the supply side. Therefore, houses with no house ΔP changes (return and supply side ducts affected by the furnace fan) could have had large leaks in the return side with air flow entering the house at perhaps 10 Pa depressurization in the return ducts and small leaks in the supply side with air flow leaving the house at up to 30 Pa pressure difference across the leak.

With the modified airtightness test method, the ELA of the pressurized duct work test is calculated using the 'C' and 'n' values from the full CGSB test. Some error may be introduced since the 'n' value would change slightly from that of the full CGSB test. Another factor which may affect the accuracy of the test is the fact that, as with most measurement

in the field, airtightness testing is subject to equipment errors and environmental variations; two CGSB test on the same house with the same apparent conditions will generate slightly different ELAs. The ELA calculation is very sensitive to slight variations from test to test even if the conditions of the house appear the same for both tests. There is therefore some margin of error that is not clearly determined in assuming that the difference in the two ELAs is due to the duct leaks.

3.2 Basement Depressurization

The basement depressurization was recorded by the home owners by manually recording readings from an incline manometer or electronic pressure gauge. Only three houses' basement depressurization were recorded by data loggers (NS06, NS09 and NS11). The pressure-measuring device was set up to read the indoor/outdoor pressure difference. In most cases, the outdoor pressure tap was passed through a basement window. In a few cases the tube was passed through the header beside a dryer vent or in one case through a combustion air inlet. The pressures were measured at the header height or lower when the tube was through a basement window. In the Vancouver area, the maximum depressurization in some houses was measured from the main floor level since there was no basement in which to set-up the equipment (slabs on grade).

The pressures recorded included the effects from furnace operation (furnace fan and furnace flue effect), winds, stack effect and depressurization from exhaust fans if in use at the time the readings were taken.

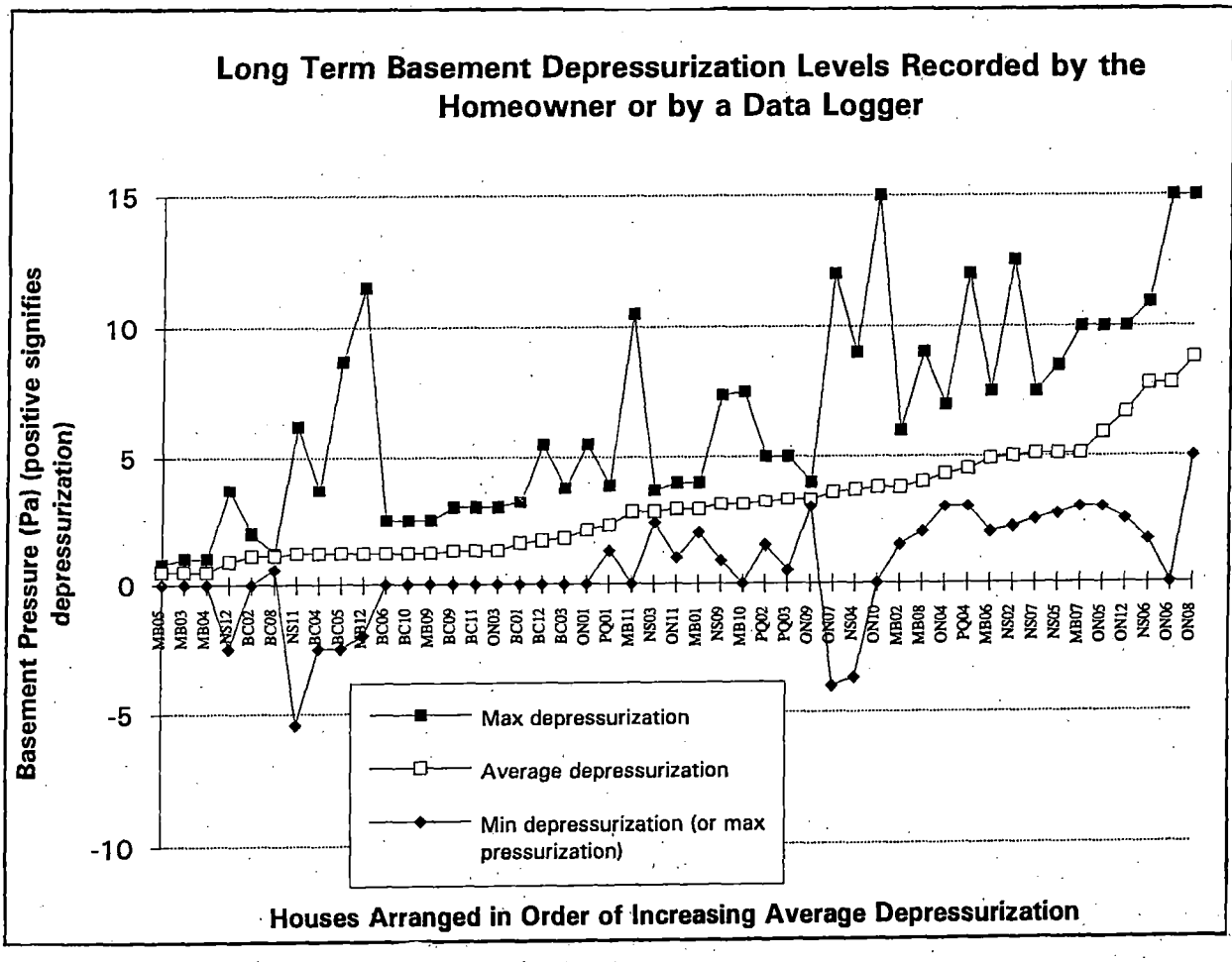
Based on the results of this test, basement depressurization levels in the winter averaged around 5 Pa, with maximums regularly between 10 and 20 Pa. Several basements were pressurized with respect to the outdoors at one time or another. The basement pressures encountered are summarized in Figure 2 and Figure 3, and detailed in Appendix C.

Monitoring of basement depressurization in the mild Vancouver area showed that average depressurization was clearly less than in the rest of Canada. This can be largely attributed to the fact that in the sample some homes had no full basements. As a result, the cross-envelope pressures were usually monitored on the first floor, closer to the neutral pressure plane than monitored in the other regions. Furthermore, the milder climate surely contributed to a much lower stack effect driving force than in the other areas tested. Depressurization in Vancouver could, therefore, be expected to be less.

The neutral pressure plane was determined for most houses tested because of the possible effect it may have on the maximum basement depressurization. This information is available in Appendix C.

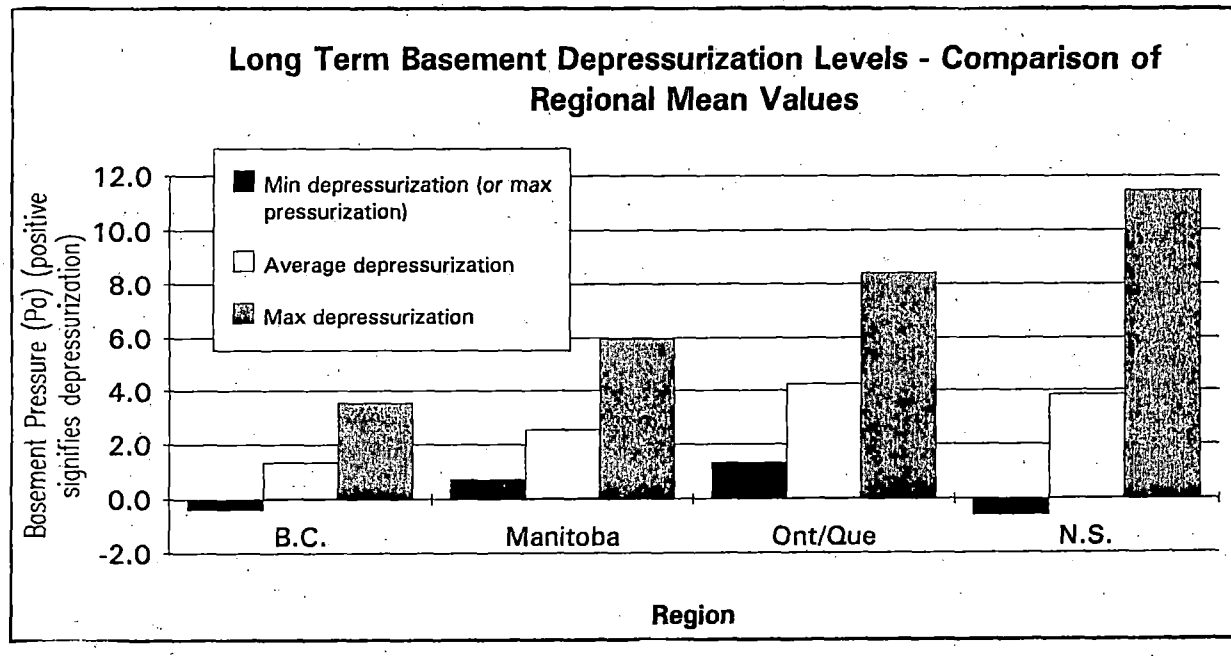
During the monitoring period in NS09, NS10, and NS11 a storm (and severe winds) passed through Nova Scotia. The data logging equipment captured fluctuations which were more attributable to the effect of wind gusts than sustained basement depressurization levels. Therefore, the spikes recorded with the data logging equipment in houses NS06, NS09 and NS11 have been removed for the data presentation in the two figures on basement depressurization. The readings from house NS10 were severely affected by south or south-west winds. On the other hand, strong winds from other directions seemed to have little or no effect on the basement depressurization. The data from this house has been removed from the figures on basement depressurization since it appears that the placement of the outdoor pressure tap was not adequately dampened against the wind effects.

Figure 2: Winter Basement Depressurization Found in Homes Monitored



On average, however, depressurization monitoring in Manitoba, Ontario, Quebec, and Nova Scotia showed similar results, with winter depressurization normally around 5 Pa.

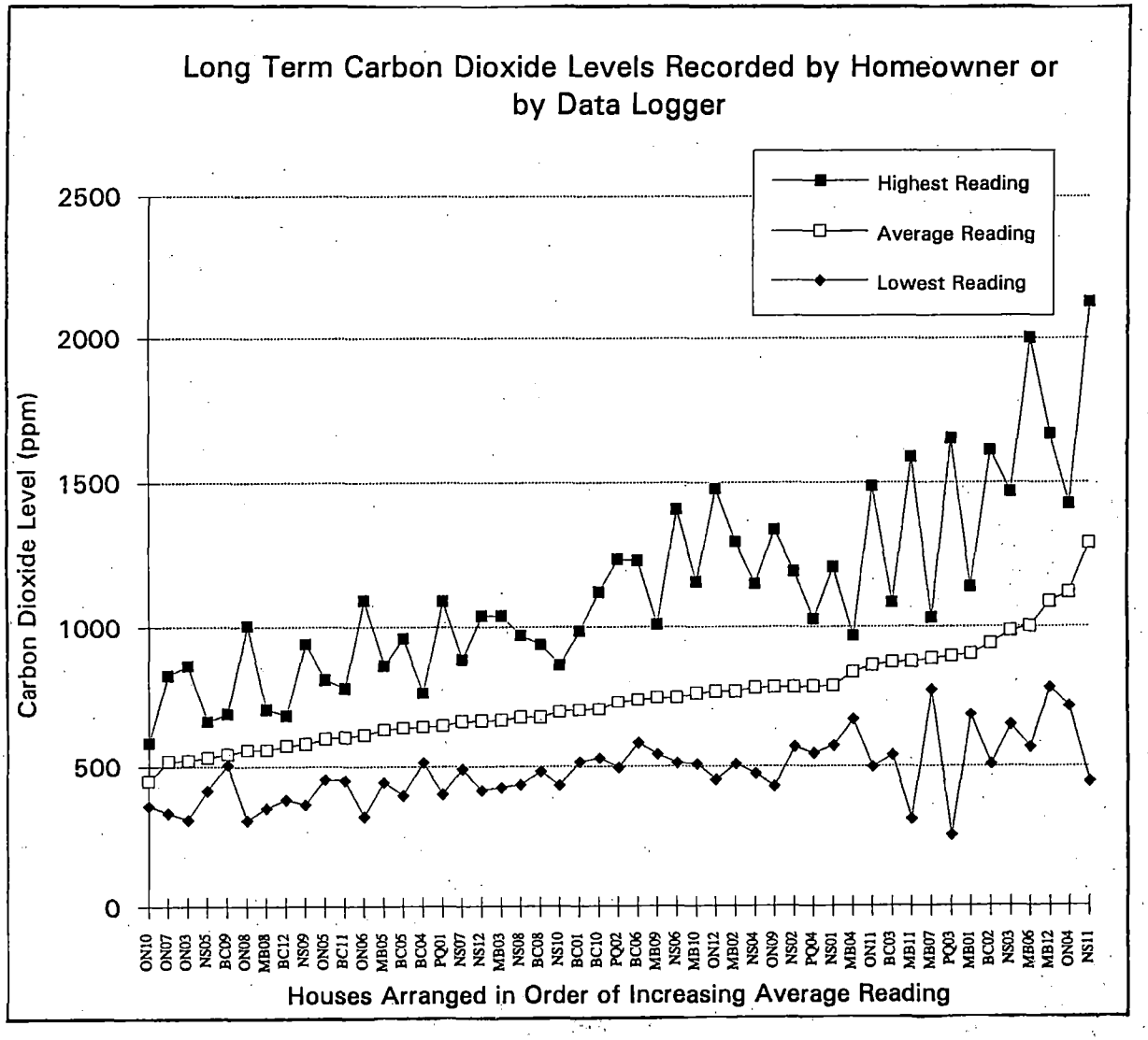
Figure 3: Comparison of Regional Basement Depressurization Data



3.3 CO_2 Levels

Figure 4 shows typical CO_2 levels recorded using the long term monitoring sheets (data loggers in Manitoba). Minimums are usually near ambient, 400 ppm (parts per million) to 600 ppm. Average levels range from 500 ppm to 1000 ppm, and most maximums are between 700 ppm and 1500 ppm. Two homes, however, had peaks of about 2000 ppm. There did not appear to be any significant regional variation in the CO_2 levels encountered. These results are listed in detail in Appendix C.

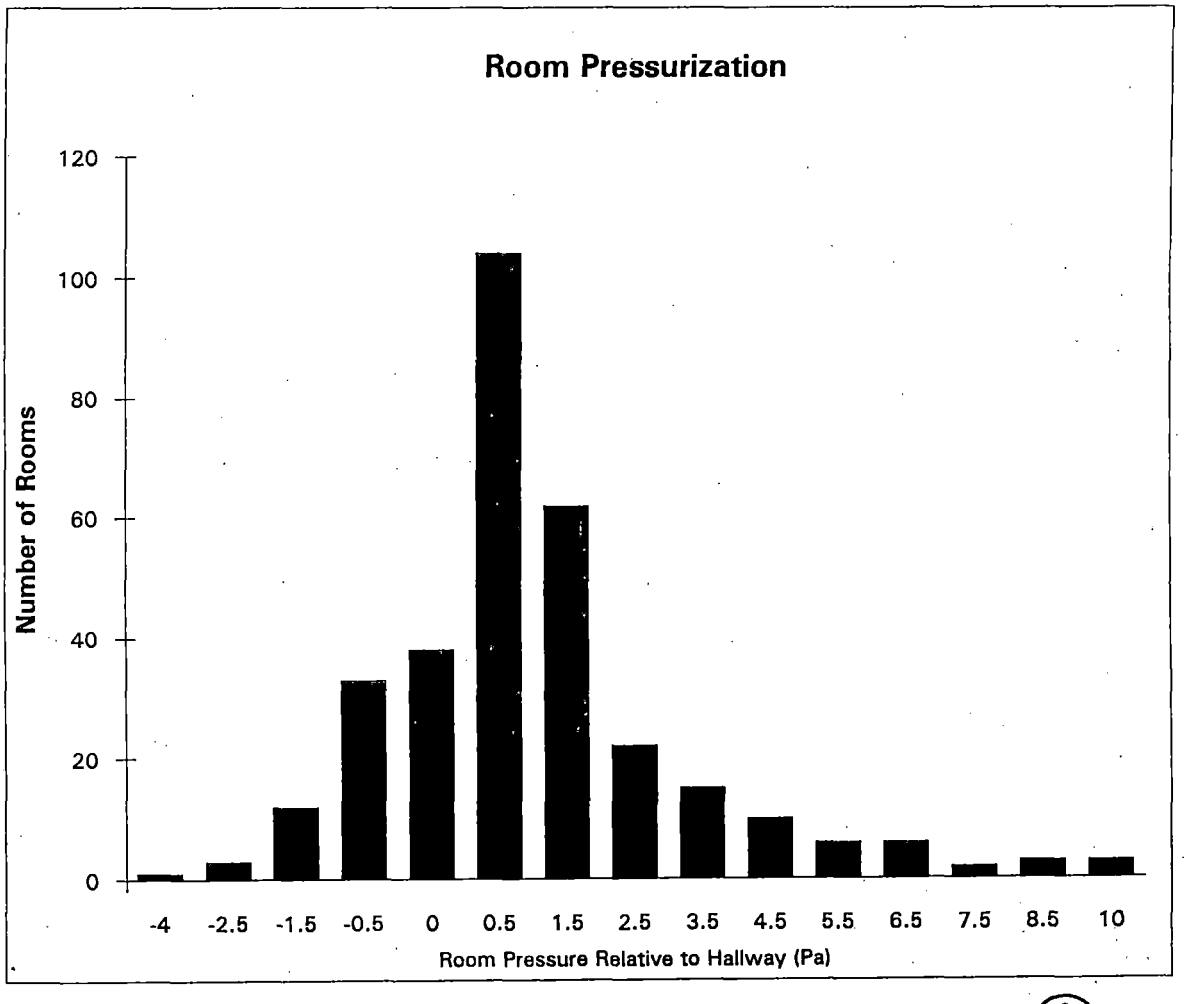
Figure 4: Carbon Dioxide Levels Found in Homes Monitored



3.4 Room Pressurization

A total of 320 room pressures were measured in the survey. Some 49 rooms (15.3%) were depressurized relative to the rest of the house. These were mostly but not all rooms which had return air ducts. Only 30 rooms (9.4%) were pressurized more than 4 Pa and all but four of these were in houses which contained either oil or oil-to-gas conversion furnaces. The oil furnace fans tend to be more powerful than those of the newer gas furnaces. The two highest readings recorded were 12.7 Pa and 15 Pa, both in the same oil heated house. The room pressures encountered are summarized in Figure 5. The detailed data can be found in Appendix C. Supply air flows were roughly measured to verify that there was some flow to pressurize the room during furnace fan operation. The pressure differential was measured under the door between the room in question and the adjacent corridor or central room. Basements, furnace rooms, and rooms with return air ducts represent the majority of the depressurized rooms. In Manitoba, where many homes have returns as well as supplies in the bedrooms, room pressurization was less likely.

Figure 5: Furnace Fan Pressurization of Rooms Relative to the Adjacent Hallway



3.5 Combustion Safety Testing

Exhaust devices were capable of creating a house depressurization over the house depressurization limit (HDL) of 5 Pa (defined in CMHC's "Chimney Safety Tests Users' Manual") in over 40% of the houses tested. One house, with three bathroom fans, a kitchen fan, a clothes dryer and a central vacuuming system operating, was depressurized by 21 Pa. The pressurization or depressurization effects of the furnace fan operation on the house pressure was not separately recorded in all cases. In some cases the furnace fan was operated during the test. If the furnace fan operation had a pressurization effect on the house at the location where the manometer was set-up, the actual depressurization effect of the exhaust devices could be higher than indicated in the table of results. The range of house depressurizations due to exhaust devices (including fireplaces and wood stoves where possible) was as indicated in Table 6.

Table 6: House Depressurization due to Exhaust Appliances

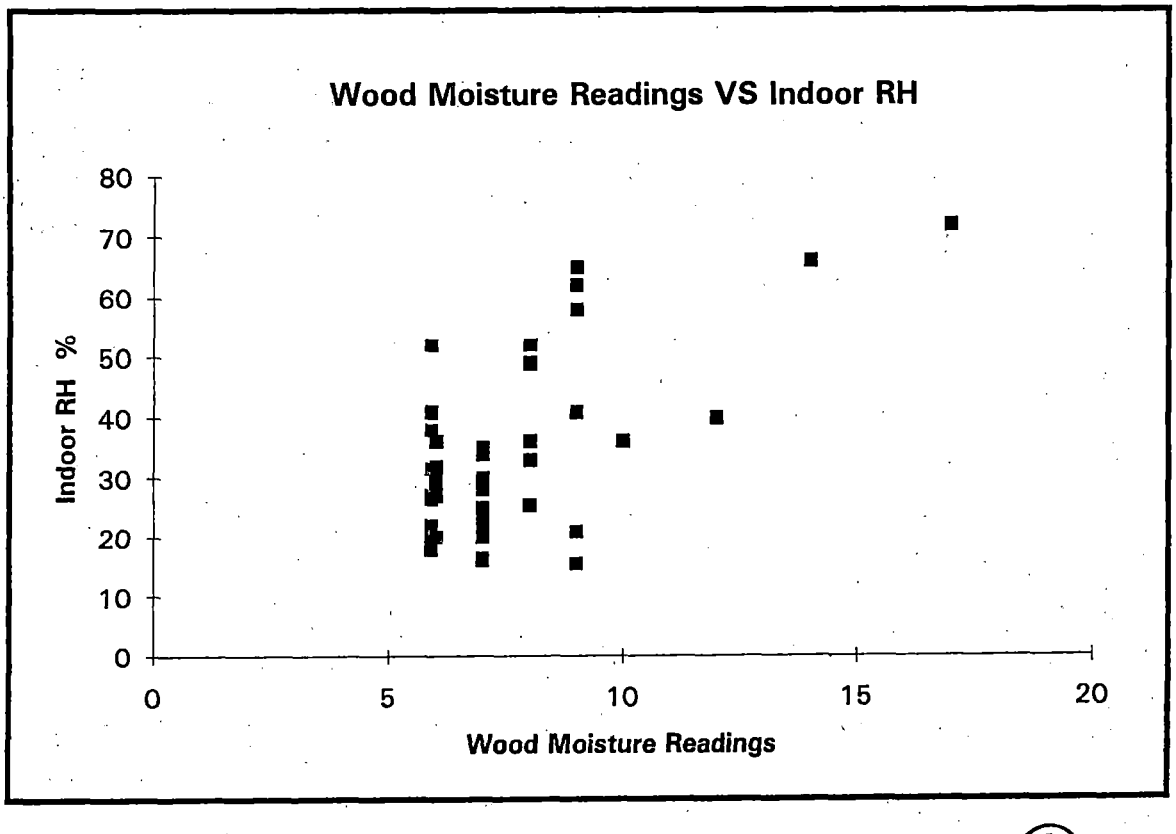
Depressurization (Pa)	Number of Houses
0.0 - 2.4	18
2.5 - 4.9	11
5.0 - 7.4	11
7.5 - 9.9	5
10.0 +	4
Not Measured	3
Total:	52

3.6 Moisture, Relative Humidity, and Envelope Performance

Wood moisture readings taken at interior framing members did not clearly show any relationship to long term house relative humidity. Wood moisture levels tended to be low, which may coincide with dry winter conditions. Regional variations did not reflect regional variations in winter relative humidities. It should be noted that the majority of houses were relatively moisture trouble-free. Possibly, if more houses had high indoor relative humidity levels, more wood moisture readings may have shown a correlation with indoor RH. The results of wood moisture readings are shown in Figure 6 and listed in detail in Appendix C. The measurements were not corrected for temperature and species; however, since most readings were taken at between 15°C and 20°C (i.e. small temperature corrections), it is not expected that corrections would yield a clearer trend, given the scatter of the uncorrected data.

The wall temperatures, the room air temperatures and relative humidities were not used in the present analysis since no moisture-troubled houses were found. However the information gathered may be of interest to some and is included in Appendix C.

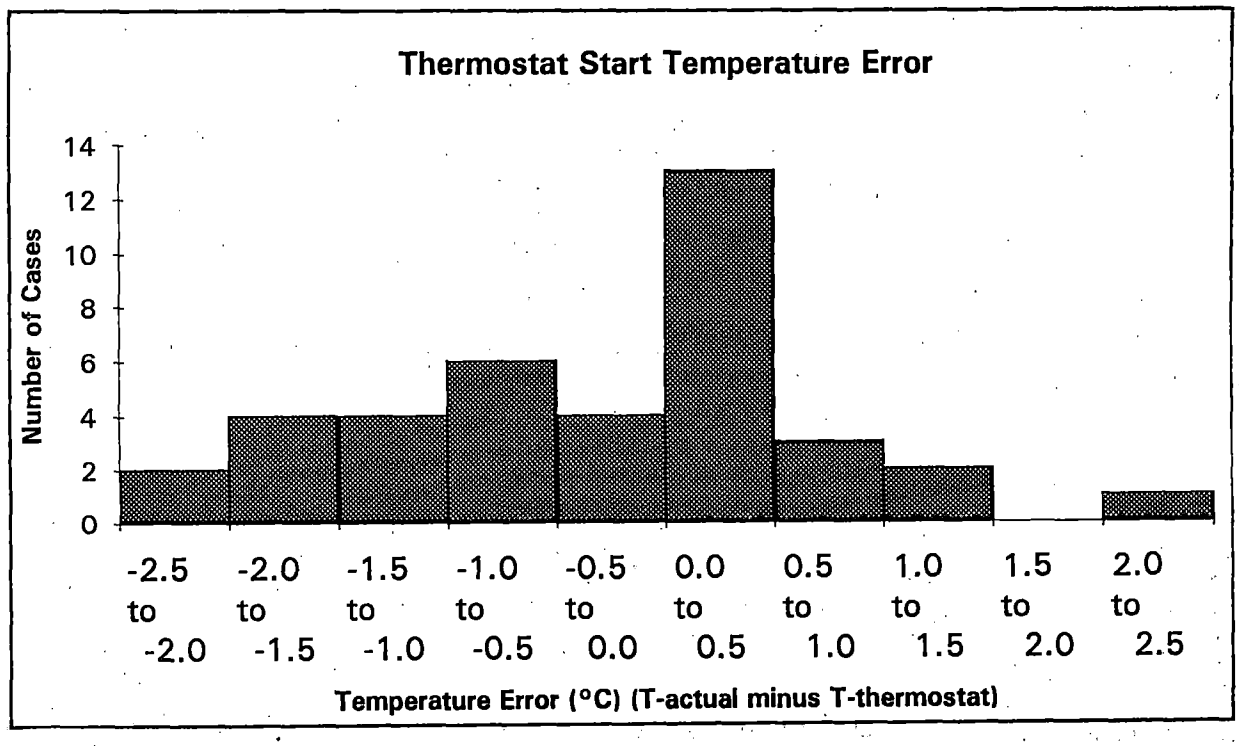
Figure 6: Wood Moisture Readings (unadjusted) and House Relative Humidity
Note: Readings were not corrected for wood temperature and species.



3.7 Thermostat Performance

Since the furnace cycle time was measured based on burner operation time, temperatures at the end of the cycle were measured when the burner stopped instead of when the fan stopped. This means the **thermostat span** (maximum air temperature after furnace stopped minus air temperature when furnace started) and the **stop temperature error** (actual air temperature minus indicated temperature when fan stopped) cannot be obtained from the data (the room air temperature normally continues to rise after the burner shuts off, until the fan shuts off). It was possible, however, to measure the **start temperature error** (actual air temperature minus indicated temperature when furnace started), which was negative in about half the cases and positive in about half. The results of thermostat evaluations are illustrated in Figure 7. Appendix C contains data related to thermostat performance collected from each of the test houses. In a few houses furnaces never came on during the test day and had to be forced into a cycle by cooling the house down (opening doors). These cases are noted; the thermostat data are of questionable value.

Figure 7: Operation of Household Thermostats
Note: Due to forced or abnormal cycles, the following house data has been removed: BC04, BC08, BC09, ON02, ON04, ON05, ON06, ON07, PQ03, MB09, NS01, NS11.



3.8 Homeowners' Perceptions of Airtightness and Relative Humidity

By comparing homeowners' evaluation of the airtightness of their house to the results of an airtightness test it was possible to determine if most people have a good feeling of their home's airtightness. Table 9 summarizes airtightness testing results and the homeowners' perceptions. The categorization for airtightness was as follows: above 5 AC/H @ 50 Pa = loose; 3-5 = average; less than 3 = tight.

Table 9: Homeowner Perception of Envelope Airtightness

Airtightness Test Says	Homeowner Says	Number of Cases
Tight	**Tight**	3
	Average	7
	Leaky	1
Average	Tight	4
	Average	8
	Leaky	3
Leaky	Tight	1
	Average	7
	Leaky	10
Data Not Available		8

A complete summary of homeowners' airtightness evaluations can be found in Appendix C. In B.C., all but two houses were leaky, as might be expected. Construction in the warmer B.C. climate is generally less airtight than in the other regions of Canada. There is a possibility that in B.C. homeowners say their houses are average for the area, not knowing they are leaky compared to other parts of the country. The perception of house airtightness may be quite regional. Regardless of house airtightness (leaky/average/tight) there was a large number of participants (40 percent) who felt their house was average. For tight houses the tendency toward correctly identifying the envelope's airtightness was slight; whereas for leaky houses it was quite strong.

Similarly, homeowners' perceptions of the relative humidity of their home were determined.

The winter evaluation in particular can be compared to the relative humidity measured in their house during testing. Table 10 summarizes homeowners' perceptions of house relative humidities during winter. Note that when they say their house is "dry" rather than "average", they may be comparing the difference between seasons rather than between houses, even though they were asked how they think their house compares to others.

Table 10: Homeowner Perceptions of House Relative Humidity

Region	Perception (Winter)	Number of Cases	Range of 1st Floor RH Measured (%)	Average 1st Floor RH Measured (%)
BC	Dry	8	34-58	49
	Average	2	38-50	44
	Humid	1	54	54
MB	Dry	5	18-42	32
	Average	6	16-31	26
	Humid	0	N/A	N/A
ON/PQ	Dry	7	9-39	25
	Average	5	20-29	26
	Humid	0	0	0
NS	Dry	6	28-33	31
	Average	3	17-33	25
	Humid	1	33	33
Overall	Dry	26	9-58	38
	Average	16	16-50	28
	Humid	2	33-54	44
Not Categorized		8	20-47	38

4. CONCLUSIONS

Duct leakage to outside the building envelope was too small to accurately quantify in most of the houses sampled. The absence of crawl spaces and ducts that pass outside the building envelope account for these findings. In the Vancouver area, however, typical house designs provide a greater opportunity for the problem to arise.

Winter basement depressurization levels found were typically around 5 Pa, with maximums in the 10 - 20 Pa range. Basement depressurization appeared less significant in the Vancouver area where the average house depressurization was never above 3 Pa. Combustion safety testing showed that the combined effect of operating all of the exhaust devices can produce significant houses depressurization. In 20 of the 52 houses tested, the exhaust equipment could create house depressurization greater than 5 Pa and up to a maximum of 21 Pa in one case.

Carbon dioxide testing showed that all but three houses had average CO_2 levels below 1000 ppm but that about 60 percent showed at least some excursions above 1000 ppm. In-depth study into conditions surrounding high or low average levels could shed some light onto which factors have large effects on CO_2 levels and which have negligible effects.

Room pressurization testing did not show significant pressurization of rooms. Of all the rooms tested, 86 percent were between +3 Pa and -3 Pa with respect to the adjacent hallway. Most depressurized rooms were furnace rooms, basements, or rooms with return air ducts. In Manitoba there was less room pressurization, probably because more bedrooms there tended to have return air ducts as well as supply air ducts.

Wood moisture measurements taken at interior framing members did not clearly indicate a relationship with long term house relative humidities. Further studies under a larger variety of house relative humidities may be more revealing.

Thermostat testing showed that the thermostat **start temperature error** is normally between +2.5°C and -2.5°C. Furthermore, accurate evaluation of thermostat field performance requires field identification of thermostat anticipator types and precise monitoring of maximum air temperatures reached after furnace fan shuts off.

Householder perceptions of house characteristics, such as airtightness and humidity levels, did not correlate well with measured values.