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SURVEY OF MOISTURE LEVELS IN ATTICS

Submitted to:

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DISCLAIMER

This study was conducted by Buchan, Lawton, Parent Ltd 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.

EXECUTIVE SUMMARY

A survey of twenty residential buildings was conducted to observe the impact of ventilation strategies on moisture accumulation in attics. The objectives of the survey were to record attic lumber moisture content levels over a period of one year and to assess the ventilation characteristics of the attics in order to account for the recorded moisture levels.

The sample homes represented a range of ages, construction types and attic venting formats. Five of the houses were located in a coastal climate. Two test protocols, developed specifically for this project, were applied to the sample. The test protocols determined attic airtightness and attic air change rates. Moisture monitoring equipment was installed in each attic, and periodic measurements were taken for one year.

This report presents the findings of the survey and offers an assessment of the two test procedures used.

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1.0 INTRODUCTION

It is a well established fact among homeowners and the building science community that moisture accumulation in residential attics is a widespread problem. Past experience suggests that adequate ventilation of the attic space alleviates moisture problems in some cases. Some recent research has indicated, however, that excessive attic ventilation can be counter-productive. In order to gain insight into this apparent contradiction, Buchan, Lawton, Parent Ltd has completed a survey of twenty residential buildings for Canada Mortgage and Housing Corporation. The objectives of the survey were to record attic lumber moisture content levels over a period of one year and to assess the ventilation characteristics of the attics in order to account for the recorded moisture levels.

The twenty sample homes selected represented a range of ages, construction types, and attic venting formats. Five of the houses were located in a coastal climate. Two test protocols, developed specifically for this project, were applied to the sample. The test protocols determined attic airtightness and attic air change rate. Moisture monitoring equipment was installed in each attic, and periodic measurements were taken for one year.

This report presents the findings of the survey and offers an assessment of the two test procedures used.

The methodologies for physical characterization, including airtightness testing, air change testing, and moisture data collection are briefly described in the next section. Section 3 presents the survey results in addition to an assessment of the performance of the airtightness and air change test protocols. The fourth section offers a discussion of the observed relationships between the sets of test data. Section 5 details an attempted validation of an attic moisture model and the conclusions are stated in Section 6.

2.0 METHODOLOGY

This section briefly describes the procedures followed in each of the three main components of the survey work: house characterization, including airtightness testing; air change testing; and moisture monitoring. Each is separately detailed. Subsection 2.4 presents estimates of the errors associated with each method. Note that the test protocols for attic airtightness and air change rate were developed in projects preceding this survey.

2.1 House Characterization

For all houses in the test group, detailed dimensional data was gathered, including house and attic geometry, attic venting strategy, etc., to produce the site plans contained in Appendix B. Sketches of the site in plan view and photographs of the house and the attic interior were taken. Wood species for attic lumber and sheathing were obtained from the identifying grade stamps.

An innovative dual zone and depressurization method developed by Sheltair Scientific Ltd[1] was used to further characterize the test homes. This was a two-part test that yielded the airtightness of the attic proper, the airtightness of the interface between the attic and the house, and the airtightness of the house itself. Two calibrated fans were required; one was hard-ducted to the attic space from the outdoors, and the other exhausted from the interior house space to the outdoors.

In the first part of the test, the attic was pressurized with respect to the outdoors. Leakage from the attic to the house through the interface resulted in a lesser pressurization of the house space. The house fan was used to reduce this pressurization to zero. In the second part of the test, the house was depressurized with respect to the outdoors and to the attic. Again, attic-to-house interface leakage resulted in a minor depressurization of the attic space. The attic fan was adjusted to reduce this depressurization to zero. Both parts of this test required careful iterative adjustment of both fan controls in order to achieve the desired steady state pressures. It proved particularly difficult to adjust the attic flow rate in the second part of the test to maintain the attic at the outdoor pressure. It was found that significant changes in flow to the attic had a minimal effect on attic pressure readings. This occurrence was more pronounced in the attics that had a larger venting area. In addition, it was found that this part of the test was

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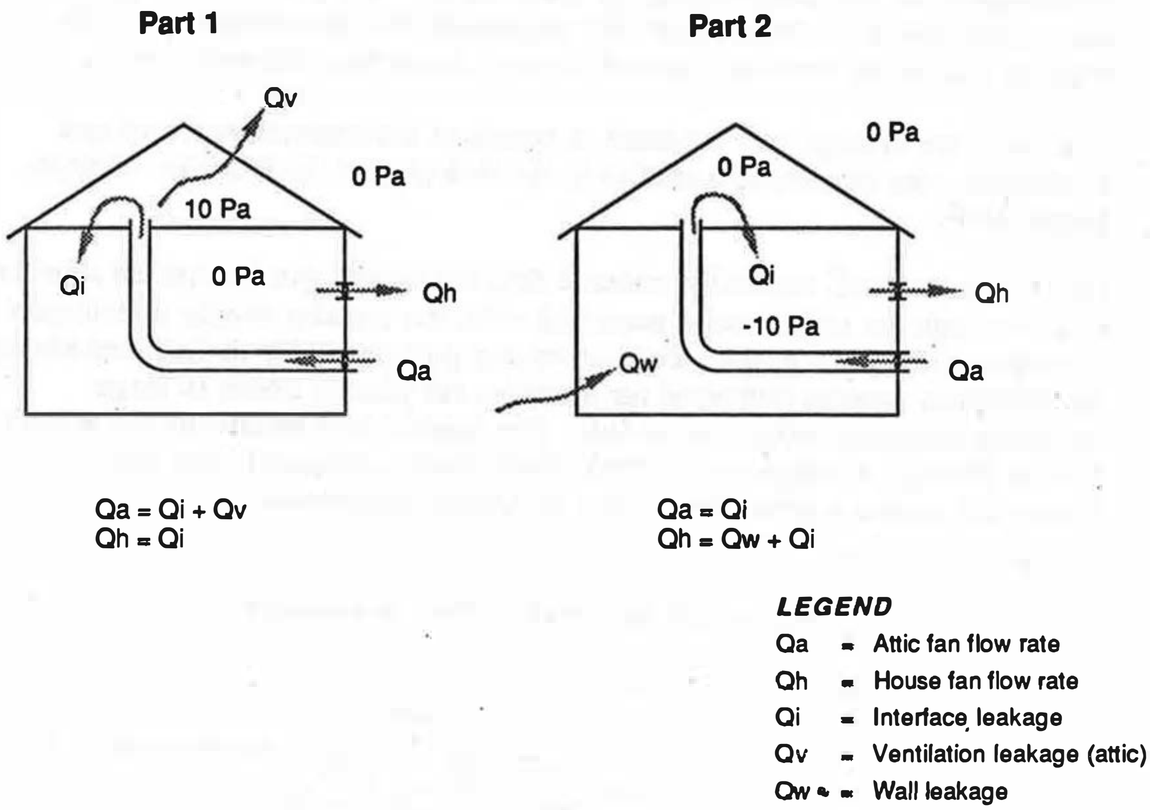
1 Sheltair Scientific Ltd, **Developing a Procedure for Determining Air Tightness Characteristics of Attic Spaces**, Draft Report, prepared for Canada Mortgage and Housing Corporation, National Office, Ottawa, Ontario, August, 1989.

very susceptible to wind. Figure 2.1 shows the pressures for the house, attic, and outdoor zones (pressure denoted by 'p') and the measured house and attic flows (flows denoted by 'Q').

Figure 2.1 **Airtightness Test Schematic**



Note that manipulation of the two measured flows (Q_a and Q_h) yielded the flow at 10 Pa through the attic ventilation, the attic-to-house interface, and the exterior walls of the house. From these flows, the associated Equivalent Leakage Areas (ELA) were determined.

Detailed procedures for this test are provided in Appendix A-1. Comments on the level of effort and accuracy associated with the test are offered in Section 2.4.

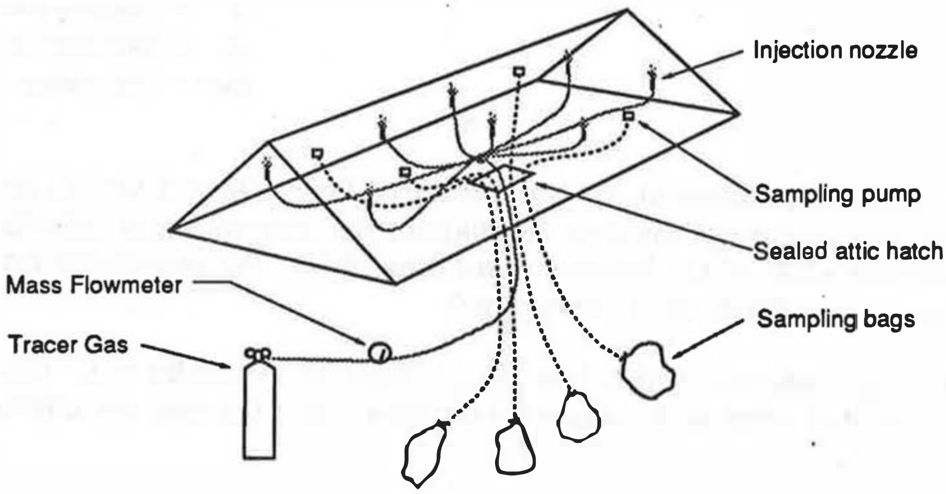
2.2 Air Change Measurements

Unlike airtightness characteristics, the air change rate of an attic space is dependent upon many factors associated with the outdoor weather. In order to investigate the effects of weather conditions on measured air change rates, the air change testing performed was more extensive than the airtightness testing; all homes were tested twice--once in warm weather and again during cold weather. In addition to this base regimen of air change tests, a 'detailed' test regimen was applied to five of the test homes. The detailed plan consisted of six tests each conducted under differing wind and temperature conditions. Two of the six tests involved a modification of the methodology in order to perform a dual-zone tracer gas test. The dual-zone tracer gas test permitted the determination of the leakage rate of air from the heated house volume into the attic space.

The basic air change test protocol, a constant concentration tracer gas technique, was developed specifically for this project by Buchan, Lawton, Parent Ltd[2].

Using this method, carefully metered SF_6/air tracer gas is injected into the attic through an eight-nozzle manifold with the nozzles evenly distributed throughout the attic space. Four sampling pumps evenly distributed among the injection nozzles delivered air samples via plastic hoses to large sampling bags located in the house. The hosing and extension cords were routed through a temporarily fitted taped shut, cardboard attic hatch. Figure 2.2 shows a schematic of the air change apparatus.

Figure 2.2 **Air Change Test Schematic**



[2] Buchan, Lawton, Parent Ltd, **Attic Air Change Testing: Protocol Development**, Draft Final Report, prepared for Canada Mortgage and Housing Corporation, National Office, Ottawa, Ontario, August, 1989.

Two sets of air samples, time-averaged over a half hour period, were drawn after a one-hour stabilization period. Gas chromatography analysis applied to the two sets establishes the mean steady-state concentration of SF_6 in the attic.

In the modified test, a carbon dioxide gas mixture was injected into the attic space in a fashion identical to the basic air change test. In addition, an SF_6/air mixture was continuously injected into the return air grille of the heating system with the furnace fan functioning. Sampling hoses from the attic and house were routed to sampling bags outside the building where the actual samples were drawn from the bags. This was done in order to prevent cross-contamination of the two tracer gas zones by the sampling pumps. A Nova absorption CO_2 analyser was used to measure the steady state concentration of CO_2 in the attic space, and gas chromatography was used to determine steady state SF_6 concentrations in the attic and in the house. From this, the flow rate of air from the house into the attic space was determined.

Details on the procedures used in both variations of the air change test are presented in Appendix A-2.

2.3 Moisture Monitoring

Site visits were made approximately on an monthly cycle to the test homes between October, 1989 and November, 1990 to collect moisture data. The collected data included temperatures and relative humidities of indoor and attic air (in addition to time-averaged humidity content of indoor air), snow cover on the roof, and a series of mid-face and surface moisture content readings of the attic lumber.

The moisture content readings were taken with Delmhorst meters. The mid-plank figures were obtained from a series of permanently installed moisture sensors consisting of a pair of moisture pins and one thermocouple. A typical installation would include six of these sensors: one on each gable, two in a bottom ceiling joist or truss chord, and two in a top truss chord or rafter. The thermocouple readings were incorporated with the accompanying moisture meter readings to produce temperature-compensated moisture content values.

The referenced paper suggested that plywood readings can be spurious in nature and difficult to interpret. Furthermore, the requirement that pins be inserted precluded the sheathing from permanent sensor instrumentation, as the shallow insertion depth would have lead to difficulties associated with pins tending to fall out. For these reasons, sheathing moisture content data was collected with a surface probe from approximately five locations. The average, highest and lowest values were recorded, and no surface temperature measurement was attempted. The resulting uncompensated sheathing temperatures were intended as observations of seasonal moisture patterns only, not absolute moisture content values. The equation used was recommended for unidentified SPF material above and below fibre saturation by van Rijn and Onysko[3].

for readings M,

where: $M \le B$,

$MC = (1.50 - 0.0081T)\,M + (0.57 - 0.043T)$

where: $M > B$

$MC = (3.0 - 0.028T)\,M - 25.0$

where: MC = temperature compensated moisture content
M = is the meter reading
T = is the temperature in Celsius
and: $B = (25.57 - 0.043T) / (1.50 - 0.02T)$

Details on the moisture pin installation and monthly visit procedure are provided in Appendix A-3.

In order to enable sheathing moisture comparisons with the various other compensated values, the sheathing surface temperature was estimated assuming a steady-state, one-dimensional heat conduction between the known top rafter wood and outdoor temperatures. Errors associated with this assumption are discussed in Section 2.4.

2.4 Error Analysis

In order to interpret the numerical results of the next section, the error associated with the test methods is estimated in this section. A formal treatment would include an estimate of total systematic uncertainty (affected by apparatus) and random uncertainty (affected by personnel and environment related factors). As this type of analysis was beyond the scope of this project, a more informal approach was taken. Systematic uncertainty, "accuracy", was summed in quadrature for methods involving compound measurements and stated. Random uncertainty, "measurement error", was estimated qualitatively only where appropriate.

[3] G.J. van Rijn & D.M. Onysko, **A Note on Species and Temperature Correction of Moisture Measurements in Lumber Using Resistance Measurement Techniques Above and Below Fibre Saturation**, Forintek Canada Corporation, Ottawa, Ontario, February, 1989.

2.4.1 Attic Ventilation Area

The free venting area was most easily estimated in cases where vents were discreet (as opposed to continuous). The accuracy of these estimates was calculated (Appendix A-4) to be ±17 per cent. For attics with continuous soffit venting, however, the actual areas were difficult to compute. The problem was further compounded by the obvious constriction of venting apertures by insulation, which cannot be estimated. For this reason, the accuracy of the estimated vent area, where continuous soffit venting was provided, was unknown.

2.4.2 Air Tightness - Accuracy

The values of the various equivalent leakage areas were subject to considerable error. In Appendix A-4, the accuracy of the ventilation and house ELA's were estimated at ±13 per cent, and interface ELA measurements at ±7 per cent.

A larger amount of inaccuracy in this test was a result of the difficulty in maintaining a 10 Pa pressure difference between the two zones and a 0 Pa pressure difference between the attic and outdoors in the second part of the test. Transducer, calibration and human error, and wind-induced pressure fluctuations all contributed to this random error. In Appendix A-4, the combined effect of these random component errors was estimated at ±20 per cent.

Although it was technically incorrect to combine systematic and random errors, it was arguable that an exception could be made in the case of ELA. This was because the equation for ELA (Appendix A-4) substituted the inter-zone pressure difference term with the metered flow at 10 Pa. Mathematically, an error in this pressure difference has the same effect as a component error in the metered flow on the final ELA. A conservative method of combining these errors would be to sum them in quadrature. This yielded an overall accuracy of ±24 per cent for ventilation and house ELA values and ±23 per cent for interface ELA values determined in the first part of the test.

It was often found, during execution of this test, that the measured pressure differences between the attic and indoor zones with respect to the outdoor zone were very easily affected by even mild gusts of wind. As well, there was an apparent mild correlation between wind speed, as posted in Table 3.2, and the observed disagreement between the interface ELA values calculated during the first and second parts of the tests. This was not a surprising result considering that wind induced pressure variations of 4 Pa were encountered by fan testing personnel during standard depressurization tests.

It could be argued that the test would be improved by expanding the protocol to include flow measurement at 3 or more pressure drops in order to allow a regression and subsequent airtightness analysis. This was attempted during most of the airtightness testing. Although two or three attics could be successfully tested at 3 points, generally it was found that the flow required to pressurize the attic space to 20 Pa would often exceeded the capacity of the Retrotec fan used for testing. In conclusion, the protocol should not be altered, but limited to research work and calm weather conditions. It should only be undertaken by qualified personnel experienced in depressurization testing.

It was noted that, on average, using a good apparatus such as that used in this survey, the typical test duration was between five and eight man-hours.

2.4.3 Air Change Testing

The attic air change and interface leakage results had an estimated accuracy of ±11 per cent and ±14 per cent respectively (Appendix A-4).

As in the airtightness test, the air change test has a significant source of random error. It may be recalled from the test methodology that the steady-state concentration determined the air change rate. This concentration was averaged from the four values corresponding to the four quadrants of the attic volume. The methodology was based on the premise that this average represented the true average concentration through the attic space.

In the development of the protocol[4], the initial testing incorporated thirty sampling locations which were eventually reduced to four. Although no actual error analysis was performed, it was observed that the mean of the four centroidal samples differed from the mean of all thirty samples by less than 7 per cent (2 per cent to 6.6 per cent) for six tests. Considering this, it would be prudent to estimate the random error of the air change results in this project due to SF_6 stratification and short circuiting at ±10 per cent.

2.4.4 Moisture Monitoring

Lumber Measurements

The raw meter readings were temperature compensated. According to the source of the compensation equation[5], the compensated readings had the following accuracies:

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[4] Buchan, Lawton, Parent Ltd, **Attic Air Change Testing: Protocol Development**, Draft Final Report, Canada Mortgage and Housing Corporation, National Office, Ottawa, Ontairo, August, 1989.

[5] Forintek Canada Corporation, **Moisture Content Correction Tables for the Resistance-Type Moisture Meter**, Ottawa, Ontario.

If the compensated moisture content (MC) was less than 9%, then the accuracy was ±1% MC.

If the compensated MC was between 9 and 22%, then the accuracy was ±2% MC.

Since the thermocouple readings used for compensation are accurate to ±1 per cent, temperature inaccuracies would have little impact on the above accuracy values for MC.

Sheathing Measurements

Since surface temperature measurements were not collected for sheathing moisture measurements, these were estimated. The previously referenced paper suggests that a 5°C error in temperature measurement would affect the compensated moisture content by no more than 1 per cent MC. It was estimated that the actual sheathing temperature measurements were, at most, ±5°C For the estimated sheathing moisture content, the errors are stated as follows:

If the compensated MC was less than 9%, then the accuracy was ±1.5% MC.

If the compensated MC was between 9 and 22%, then the accuracy was ±3% MC.

3.0 OBSERVATIONS AND RESULTS

The observed house characteristics and the results of the attic airtightness, air change and moisture monitoring work are presented in the following sub-sections. Generally, it was found that the data varied greatly from house to house. For this reason, the detailed house characterization, test, and moisture monitoring data is presented in a house-by-house fashion in Appendix B.

3.1 Observed Characteristics of Test Homes

The group of test homes was selected to include a variety of ages, construction types, attic and venting formats, and two climates. The resulting group consists of fifteen homes in the Ottawa region and five homes in Charlottetown, P.E.I. The Ottawa area homes are prefixed with an 'O' and the Charlottetown homes are prefixed with an 'M'. Houses marked with an asterisk received the detailed regime of air change testing.

Table 3.1 **Observed House Characteristics**

House	Location	Age	Stories	Roof Type	Venting Type	Estimated Venting Area (cm2)
O-1	Nepean, Ont.	1970	2	gable	CS	2300
O-2	Ottawa, Ont.	1968	1	gable	S & G	2700
O-3 *	Manotick, Ont.	1987	1	gable	CS & R & G	29300
O-4 *	Manotick, Ont.	1987	2	hip & gable	CS & M & G	3900
O-5	Ottawa, Ont.	1972	1	gable	CS & T & G	3400
O-6	Gloucester, Ont.	1988	2	gable	CS & M	6100
O-7	Ottawa, Ont.	1968	1	gable	S & M	1500
O-8 *	Gloucester, Ont.	1971	2	gable	CS & M	2500
O-9	Ottawa, Ont.	1960	1	hip	CS & M & T	6200
O-10*	Ottawa, Ont.	1960	1	gable	S & G	1900
O-11	Gloucester, Ont.	1985	2	gable	CS & M	2300
O-12 *	Gloucester, Ont.	1972	2	gable	CS & M	2200
O-13	Gloucester, Ont.	1985	2	gable	CS & R	8500
O-14	Goulburn, Ont.	1987	1	gable	CS & G	7000
O-15	Gloucester, Ont.	1968	2	gable	CS	3600
M-1	Charlottetown, PEI	1971	1	gable	S & G	1400
M-2	Charlottetown, PEI	1979	1	gable	G	600
M-3	Charlottetown, PEI	1956	1	hip & gable	G	300
M-4	Charlottetown, PEI	1964	1	gable	G	1000
M-5	Charlottetown, PEI	1975	1	gable	G & T	1600

Legend
CS = Continuous Soffit
S = Soffit
G = Gable
M = Mushroom
R = Ridge
T = Turbine

* = Detailed House

3.2 Airtightness Test Results

The airtightness testing results are presented in Table 3.2 as ELA values for the ventilation of the attic, the interface between the attic and the house, and for the exterior walls. All posted ELA values were calculated by multiplying the measured flow (at 10 Pa) by a factor of 4 (very close to the actual calculation prescribed in the standard for airtightness testing of homes).

Table 3.2 **Airtightness Test Results**

House	Date m/d/yy	Wind Speed kph	House ELA* cm2	Attic ELA Ventilation cm2	Estimated Venting Area cm2	Ventilation Difference ** %	Interface ELA Part 1 cm2
O-1	8/28/90	18	940	1700	2300 (est)	-20	330
O-2	5/23/90	11	-	2500	2700 (act)	-10	460
O-3	6/5/90	27	-		29300 (est)	Unable to pressurize attic	
O-4	7/31/90	27	620	3600	3900 (est)	-10	250
O-5	7/11/90	12	500	2500	3400 (est)	-20	300
O-6	8/21/90	12	1100	4700	6100 (est)	-20	330
O-7	8/22/90	6	-	2300	1500 (act)	50	400
O-8	12/1/89	10	-	5100	2500 (est)	100	280
O-9	7/26/90	8	290	3900	6200 (est)	-40	450
O-10	5/22/90	15	330	2200	1900 (act)	20	280
O-11	6/4/90	32	420	1300	2300 (est)	-40	350
O-12	11/30/89	28	-	2400	2200 (est)	10	-
O-13	8/30/90	8	1200	2900	8500 (est)	-70	400
O-14	9/20/90	15	-	5700	7000 (est)	-20	20
O-15	8/23/90	11	470	5500	3600 (est)	50	220
M-1	6/19/90	25	400	1900	1400 (act)	40	330
M-2	6/20/90	10	200	800	600 (act)	40	280
M-3	6/21/90	13	900	2100	300 (act)	550	400
M-4	6/19/90	13	490	3100	1000 (act)	210	380
M-5	6/18/90	25	750	1600	1600 (act)	0	460
Mean			615	2937	4415		329

NOTE: * House ELA does not include interface ELA
** Ventilation Difference = 100 x (Attic ELA - Est. Venting Area) / Est. Venting Area

The determination of the free venting area of the attics was difficult for many of the houses equipped with continuous soffit venting. In such cases, the ventilation areas were estimated by using a fixed perforation area per unit length soffit. In most attics, with either continuous or discreet soffit venting, the measured free area was constricted somewhat by the attic insulation. It is felt, therefore, that these estimated ventilation area values (denoted in Table 3.2 as 'est') cannot be directly compared against the ventilation ELA values for the same house.

Ten of the homes had measurable ventilation areas. These actual areas are posted in Table 3.2 as 'act'. A comparison of these areas against their ELA counterparts reveals that the measured ventilation area is consistently higher. This is an expected result, since the so-called ventilation ELA must include leakage through joints in the sheathing and shingles, as well as, all other attic construction.

Note that House O-3 could not be tested. This house had a combination of gable, ridge, and continuous soffit venting with a ventilation area in the order of 30,000 cm^2. When attempting to fan test this attic, a pressure of 10 Pa was not achievable.

The interface ELA values produced by the first part of the test are posted in Table 3.2.

3.3 Air Change Test Results

Table 3.3 presents the air change test results for all homes in the test group, including the extended regime of air change tests. The column showing interface flow applies only to the two dual-zone tracer gas tests performed on these homes.

The measured attic air change rates vary greatly from house to house and, for some houses, from test to test. The rates obtained for other homes are very consistent. For instance, the six air change rate values measured for House O-3 are all between 11 and 15 air changes per hour. Houses O-14, M-2, O-7, and O-2 show fairly consistent air change rate values as well. Other houses show large discrepancies between values (for instance, House O-13).

The measured attic air change rates ranged from 1.1 ACH (House O-10) to 33 ACH (House O-8). The average air change rate for each house was determined in order to assess the distribution of air change values among the test group. Figure 3.1 shows the frequency distribution of attic air change rates. The warm and cold air change test results were averaged to obtain one attic air change rate for each house.

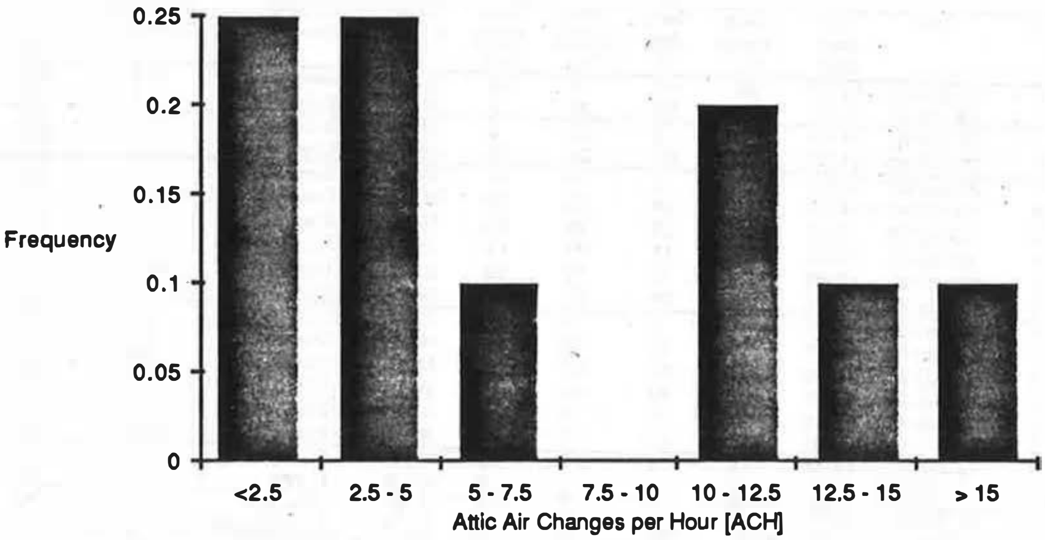
Note that 60 per cent of the test group had air change rates between 1.0 and 7.5 ACH. Thirty per cent of the group had average air change rates between 10.0 and 15.0 ACH. The remaining 10 per cent had air change rates between 15.0 and 33 ACH.

Clearly, attic air change rates are very weather dependent. An inspection of Table 3.3 shows that three dominant driving forces affect air change rates: wind direction, wind speed, and the temperature difference between the attic and the outdoors. Section 4.0 of this report provides a discussion on the effect these factors have on measured air change rates.

Table 3.3 **Air Change Test Results**

House	Test	Date	Test Start Time	Temp. House °C	Temp. Attic °C	Temp. Outside °C	Wind Speed (kph)	Wind Direction	Weather Conditions	Air Change Rate/Hour	Interface Flow (L/s)
O-1	1	24-Jan-90	11:00	20	10	5	24	S	Sunny	6.5	N/A
	2	26-Jul-90	15:00	26	52	31	7	W	Sunny	2.6	N/A
O-2	1	22-Jan-90	11:00	19	2	-12	6	ENE	Snowing	3.1	N/A
	2	23-Jul-90	11:00	20	21	21	15	NE	Overcast	1.6	N/A
O-3	1	23-Jan-90	11:00	18	5	-2	11	SW	Sun &Cloud	15.0	N/A
	2	31-Jul-90	14:00	21	26	20	20	N	Overcast	14.5	N/A
	3	1-Aug-90	11:00	21	25	25	23	NW	Sunny	11.3	N/A
	4	3-Aug-90	10:00	22	35	27	17	W	Sunny	14.1	N/A
	5	22-Mar-90	15:00	19	15	11	20	SSW	Cloudy	14.0	-
	6	17-Aug-90	11:00	24	38	31	22	SSW	Sun &Cloud	15.3	40
O-4	1	23-Jan-90	14:30	22	9	-2	10	SW	Overcast	6.0	N/A
	2	31-Jul-90	11:00	18	24	16	28	NNW	Overcast	8.3	N/A
	3	1-Aug-90	14:00	26	30	27	24	NW	Sun &Cloud	6.5	N/A
	4	3-Aug-90	13:00	20	48	31	19	W	Sunny	14.0	N/A
	5	22-Mar-90	9:00	19	10	6	15	SSE	Cloudy	13.6	10.2
	6	9-Aug-90	11:00	23	33	26	15	SSW	Sunny	17.0	32
O-5	1	14-Feb-90	15:00	19	6	-7	6	NW	Sunny	14.2	N/A
	2	11-Jul-90	13:00	20	35	24	13	WNW	Sunny	6.2	N/A
O-6	1	13-Feb-90	10:30	18	2	-3	10	S - W	Overcast	5.8	N/A
	2	16-Jul-90	11:30	20	30	25	26	SW	Sun &Cloud	19.0	N/A
O-7	1	14-Feb-90	10:00	20	0	-3	19	NW	Sunny	4.4	N/A
	2	18-Jul-90	14:30	29	42	31	30	SW	Sunny	3.8	N/A
O-8	1	1-Feb-90	12:00	18	7	0	15	S	Overcast	11.7	N/A
	2	1-Jun-90	14:00	22	37	28	30	SW	Sunny	16.8	N/A
	3	13-Jul-90	14:30	24	41	25	9	SE	Sunny	4.3	N/A
	4	18-Jul-90	10:00	21	37	30	20	SSW	Sunny	33.0	N/A
	5	20-Mar-90	14:30	18	11	4	15	N	Cloudy	5.9	11.3
	6	7-Aug-90	11:30	21	24	20	6	W	Cloudy	4.5	7.1
O-9	1	12-Mar-90	11:00	19	11	6	15	ENE	Overcast	8.9	N/A
	2	26-Jul-90	11:00	21	27	26	9	W	Sunny	3.0	N/A
O-10	1	18-Jan-90	12:30	16	7	4	19	SSW	Raining	3.0	N/A
	2	17-Jul-90	11:30	25	35	26	20	SW	Sunny	1.9	N/A
	3	19-Jul-90	10:00	24	40	25	26	W	Sunny	1.6	N/A
	4	20-Jul-90	14:30	21	22	20	11	W	Raining	1.1	N/A
	5	21-Mar-90	12:30	18	21	6	30	W	Sunny	3.5	3.3
	6	2-Aug-90	11:00	20	49	28	17	WSW	Sun &Cloud	1.6	0.9
O-11	1	24-Jan-90	13:00	19	9	5	30	SSW	Raining	11.4	N/A
	2	20-Jul-90	11:00	22	24	19	13	SW	Raining	2.6	N/A
O-12	1	15-Jan-90	14:30	18	2	-11	11	NNE	Snowing	3.7	N/A
	2	17-Jan-90	8:30	18	6	-1	12	ENE	Raining	5.0	N/A
	3	24-Jul-90	15:00	21	47	27	8	SSW	Sun &Cloud	2.8	N/A
	4	25-Jul-90	7:30	20	29	20	11	W	Sunny	1.9	N/A
	5	9-Mar-90	12:00	20	12	4	5	ENE	Sunny	3.2	13.4
	6	30-Jul-90	15:00	20	41	31	22	S	Sunny	6.2	7.3
O-13	1	19-Feb-90	13:00	18	1	-3	37	W	Sun &Cloud	20.3	N/A
	2	19-Jul-90	14:00	24	36	27	24	WSW	Sunny	11.4	N/A
O-14	1	15-Feb-90	12:00	15	-5	-7	26	NE	Snowing	2.2	N/A
	2	25-Jul-90	15:00	20	50	30	13	W	Sunny	1.9	N/A
O-15	1	19-Jan-90	11:00	17	-3	-10	20	W	Sunny	13.4	N/A
	2	14-May-90	12:00	20	39	17	7	NNW-SW	Sunny	7.2	N/A
M-1	1	8-Feb-90	15:00	18	9	-5	15	ENE	Cloudy	2.2	N/A
	2	17-Jun-90	11:00	18	28	25	17	SSW	Sunny	1.2	N/A
M-2	1	8-Feb-90	11:00	19	12	-2	18	NW	Sun &Cloud	2.6	N/A
	2	20-Jun-90	15:00	21	17	15	9	N	Cloudy	2.4	N/A
M-3	1	7-Feb-90	15:00	18	7	-7	22	SSW	Sunny	2.4	N/A
	2	21-Jun-90	14:00	20	16	14	11	N	Overcast	1.9	N/A
M-4	1	9-Feb-90	10:00	19	1	1	22	S	Sun &Cloud	6.7	N/A
	2	17-Jun-90	16:00	18	33	24	15	S	Sunny	2.1	N/A
M-5	1	7-Feb-90	11:00	18	2	-7	11	SSW	Sunny	9.5	N/A
	2	18-Jun-90	14:00	18	27	20	28	SW	Sunny	23.0	N/A

Figure 3.1 **Air Change Rate Distribution**



3.4 Moisture Monitoring Results

The seasonal moisture content profiles for all sensors in each house are presented house by house in Appendix B. As well, the relative humidity profiles for the attic, the house, and the one week, time-averaged samples for the house are posted.

A wood moisture content greater than 30 per cent, combined with a appropriate temperatures and inadequate ventilation, represents conditions conducive to rotting. At the peak of the heating season, many of the test attics had surface sheathing moisture contents above 30 per cent. These attics, however, did not necessarily exhibit elevated moisture content values in the lumber (top truss, webbing, or ceiling joist). Since the sheathing is consistently the coldest surface in the attic during the heating season, it would be the first surface on which condensation would occur and would be anticipated to have elevated readings.

The test group of homes was divided into three categories according to the wetness monitored. 'Wet' attics were considered to have moisture content values above 30 per cent in the sheathing and at least one of the monitored framing members. 'Dry' attics were categorized as having all moisture content values around or below 20 per cent. It was found that three of the fifteen Ottawa area homes and one of the Maritime homes fell into the wet category. These are Homes O-1, O-12, O-13, M-2. Five out of fifteen of the Ottawa area homes and one of the Maritime homes fell into the dry category. These are Homes O-3, O-5, O-9, O-10, O-14 and M-5.

The third category consists simply of those attics neither categorized as wet nor dry. Figure 3.2 contains a sample of moisture curves typical of the wet category and Figure 3.3 contains a sample of the dry category.

Figure 3.2 **Typical Moisture Content, Wet Attic, Seasonal Profile**

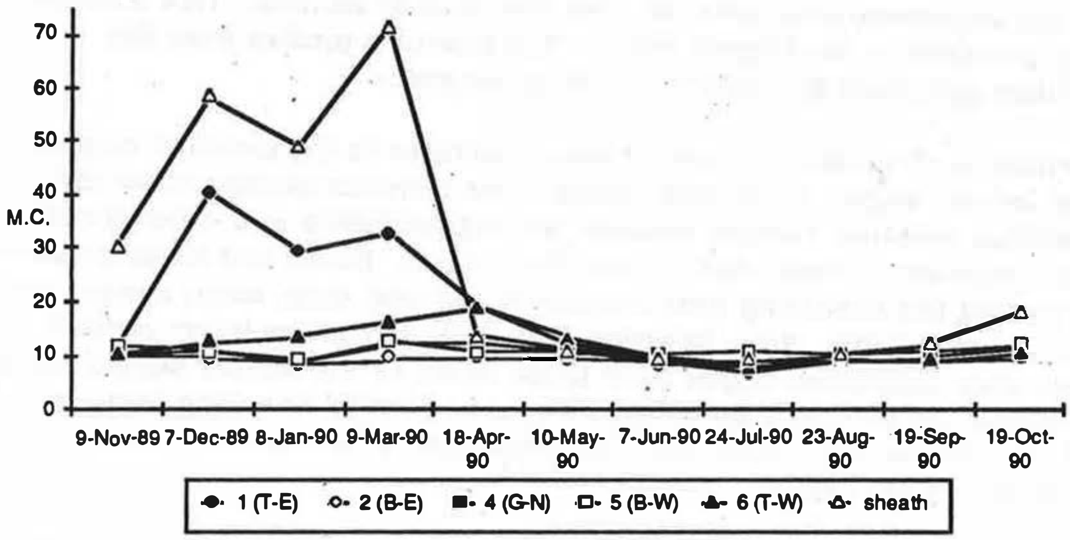
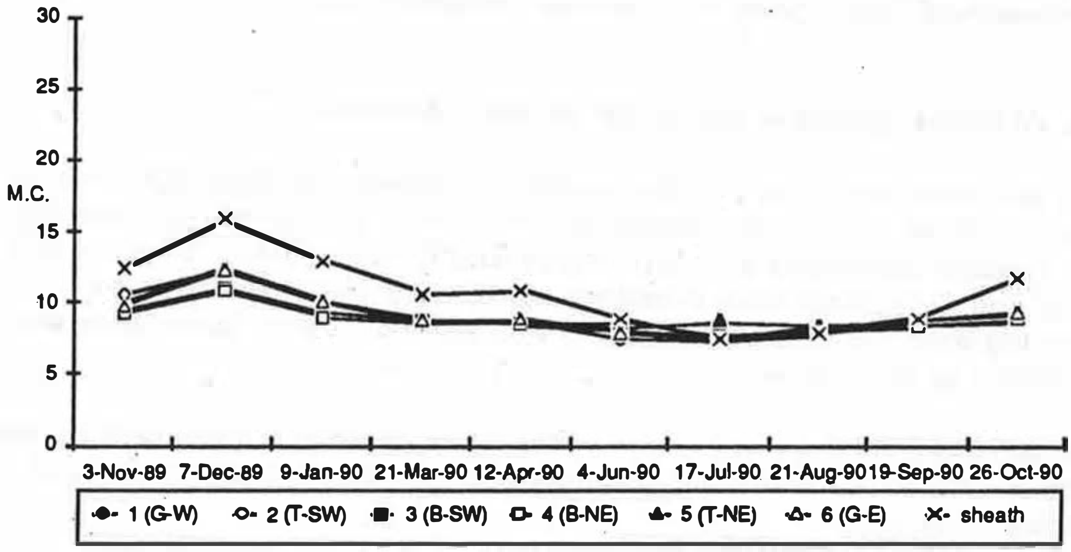


Figure 3.3 **Typical Moisture Content, Dry Attic, Seasonal Profile**



An examination of the characteristics of the wet and dry homes did not reveal any particular aspects of construction or venting common to either classification. The ages of the wet attics ranged from 1970 to 1985. The dry attics were aged between 1960 and 1987. Comments as to the possible causes of the "wet" attics are discussed as individual cases in Section 3.5.

Two distinct trends can be observed from the moisture profiles of each house (Appendix B). Generally, the attic lumber becomes quite moist during the heating season and dries out over the summer months. This trend is most prevalent in the Ottawa group. The moisture profiles from the Maritime group are generally flatter over the year.

Common to all of the test homes was an increase in the moisture content of wood located higher in the attic space. The moisture profiles show that sheathing moisture content reached the highest levels and experienced faster moisture content change than the lumber. Rafter and truss members supporting the sheathing were frequently the next most moist component after the sheathing. Note, however, that gable lumber moisture content levels were sometimes higher than those found in the lumber supporting the sheathing. In all cases, the moisture sensors located in ceiling joists or bottom truss chords (below the top of insulation) detected the lowest moisture content values.

In order to compare moisture content levels among different houses, the monthly readings were averaged across all of the moisture sensors excluding the sheathing values. A maximum value was extracted from each of the resulting sets of moisture readings for each attic. This number was used as a means to gauge the relative overall 'attic wetness' from house to house. A discussion of these values is presented in Section 4.0.

3.5 Observed Effects of Indoor RH on Attic Moisture

The five Maritime attics had house relative humidity profiles (Appendix B) in the top 60 per cent of the sample group. This is not surprising, considering the climatic differences between Ottawa and Charlottetown. In attics M-2, O-12 and O-13 there were occasions when water was observed to be dripping from the attic sheathing. It was also noted that humidifiers were in operation in these houses.

The foregoing confirms the obvious--the living space is a significant source of attic moisture. A few curious anomalies should, however, be pointed out on an individual basis:

House O-1 (wet)

Surprisingly, this house had a house relative humidity profile characteristic of the dry group. An inspection of the moisture and RH data for this house (Appendix B) revealed that only the two gables had lumber moisture contents above 30 per cent. It is also important to note that the gables were more moist than the sheathing.

House 0-7

House O-7 was determined to have average airtightness and air change characteristics relative to the test group. The only aspect in which this house differed from the test group was in its venting strategy. It had only soffit venting. In the attic, infiltration occurred at the eaves, and exfiltration occurred near the ridge at the two gable ends. A possible explanation for the high moisture content at these sites was that exfiltration (and consequently condensation) concentrated there. This was consistent with the observed lack of condensation and lower moisture content associated with the sheathing.

It was generally observed that mushroom type venting was associated with frost collection on sheathing, particularly near the vents.

House O-12 (wet)

This house was characterized as wet because the top-chord east sensor exceeded 30 per cent moisture content in December. During the November site visit, it was noted that the humidistat was set very high. The homeowner promptly reduced the setting. This was reflected in the house relative humidity profile--the humidity was reduced from 60 per cent RH to 30 per cent RH between November to December. The moisture content of this sensor, however, increased. A possible explanation for the attic RH increase was that the low outdoor temperatures had a greater impact on the relative humidity in the attic than the moisture transport into the attic from the house.

House M-5 (dry)

Although House M-5 had one of the most elevated indoor relative humidity profiles of the entire test group, it had generally drier than average lumber moisture content. The low moisture associated with this attic could be attributed to the higher than average attic air change rates observed in the attic. Another possible reason is the Venmar ventilation system (turbine-style) which exhausts air from the attic and results in lower attic moisture.

4.0 ANALYSIS AND DISCUSSION

The preceding section presented the house characterization, airtightness, air change, and moisture content data generated through this survey. Considerable analysis was undertaken in order to account for the moisture levels observed in attic lumber and to see how attic air change affects lumber moisture content.

One approach was to first analyse the data produced from the extended regimen of air change testing in order to determine relationships between the observed air change rates and the various weather factors. This step would allow a normalization of the air change data producing a weather independent data set. The normalized air change data could then be used to investigate effects of construction and attic venting type on air change and, finally, to investigate a possible relationship between attic air change rate and moisture content of the attic lumber.

The following subsections summarize the relationships investigated as part of this process.

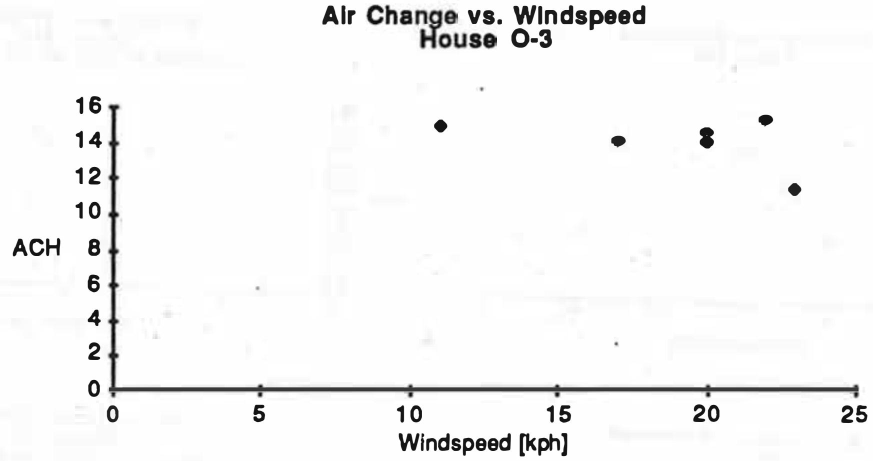
4.1 Air Change Rate and Weather

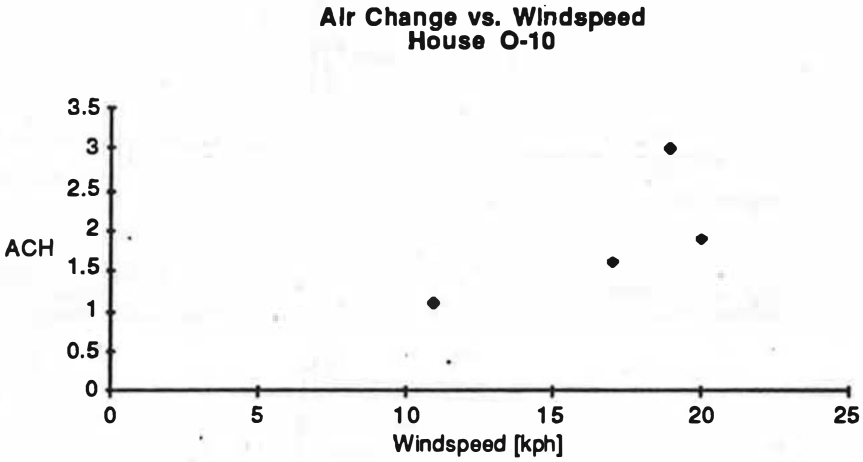
Preliminary testing at the Small Homes Council in Illinois revealed that attic air change rates were very sensitive to wind direction. Table 3.2 indicates that wind speed, as well as attic-to-outdoor temperature drop, impacts on air change rates. These weather related driving forces were separately considered with respect to their effect on air change rate. The air change rates for the five homes in which detailed air change testing took place were plotted against attic-to-outdoor temperature drop, wind speed, and wind speed adjusted for direction and shielding.

The air change rates plotted against the attic to outdoor temperature drop exhibitted a great deal of scatter with very little correlation. For this reason, these plots have not been included in this report.

Roof configurations would be expected to have varying sensitivities to wind speed and direction. A gable-style roof, for example, with a combination of soffit venting and individual vents on one of its faces, would be expected to be more sensitive to wind direction than, for example, a square hip style roof with soffit venting and independent mushroom type vents on each face. Perhaps the most wind independent attic configuration is characterized by House O-3. This house has a roof composed of three gable sections. Venting for this attic is provided by a combination of soffit (in each cardinal direction), gable, and ridge venting. Figure 4.1 shows air change versus windspeed plots for two of the detail homes. Note that House O-3 shows less scatter in the air change values than those for house O-10, which had a gable roof with eave and gable venting.

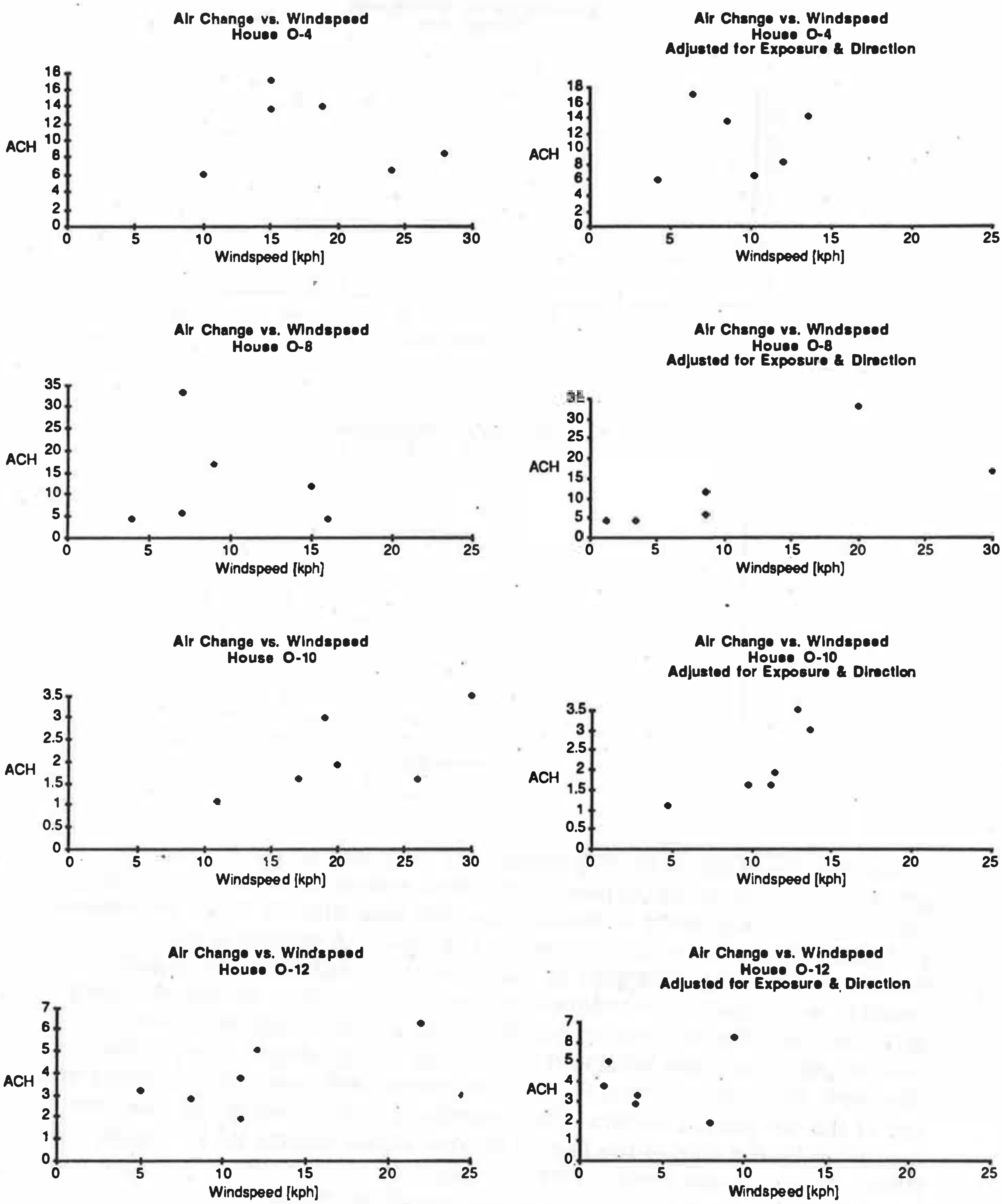
Figure 4.1 **Air Change Versus Windspeed - Detailed Homes**





To explore the effect of wind direction and shielding on air change, an adjusting procedure was applied to the wind speeds of the detailed homes. This procedure consisted of dividing the roof plan into six equal pie shaped sections with the origin at the centre of the roof. A weighting factor between 0 and 5 was assigned to each section--5 reflecting the highest possible anticipated wind induced ventilation. As well, a second shielding factor between 0 and 2 was assigned to each sector--2 indicating no shielding (i.e., an open field) and 0 reflecting a high degree of shielding. The wind direction recorded for that air change test was then classified into one of the pie shaped sectors. The magnitude of the wind speed was then multiplied by the sum of the factors for that sector divided by 7. Figure 4.2 shows the air change versus wind speed and air change versus adjusted wind speed plots for all of the detailed homes except for House O-3.

Figure 4.2 **Air Change Versus Wind Speed - Detailed Homes**

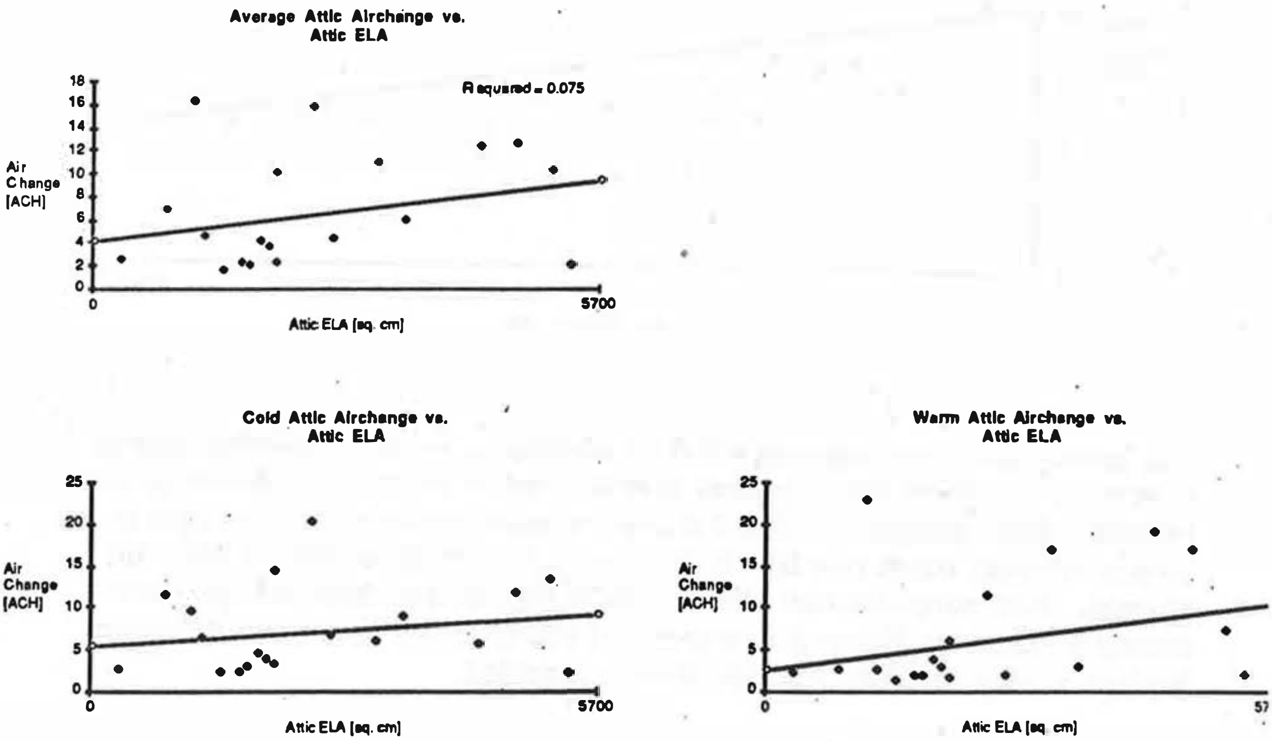


Comparing the plots of air change versus windspeed and air change versus adjusted wind speed, the adjustment has somewhat reduced the scatter for Houses O-8 (gable roof with continuous soffit and mushroom venting) and O-10 (gable roof with soffit and gable venting). The scatter was not reduced for Houses O-4 (gable roof with continuous soffit, gable and mushroom venting) and O-12 (gable roof with continuous soffit and mushroom venting). Examination of the field sheets from the air change tests for House O-12 show that wind directions recorded by field personnel differ from the airport records. This underscores a rather obvious pitfall with using weather station data and extrapolating for the surrounding area.

4.2 Air Change and Equivalent Leakage Area

Figure 4.3 contains cold weather, warm weather, and overall average air change rates for the entire test group were plotted against the attic ELA values measured during the airtightness testing. These plots exhibited a high degree of scatter. Although a good correlation between air change and airtightness was expected, the R squared value for the regression in Figure 4.3 revealed that only 7.5 per cent of the observed positive trend was related to air change variation with ELA. The poor correlation is likely due to the random effects of weather on the air change results.

Figure 4.3 **Air Change Rate Versus Attic ELA**

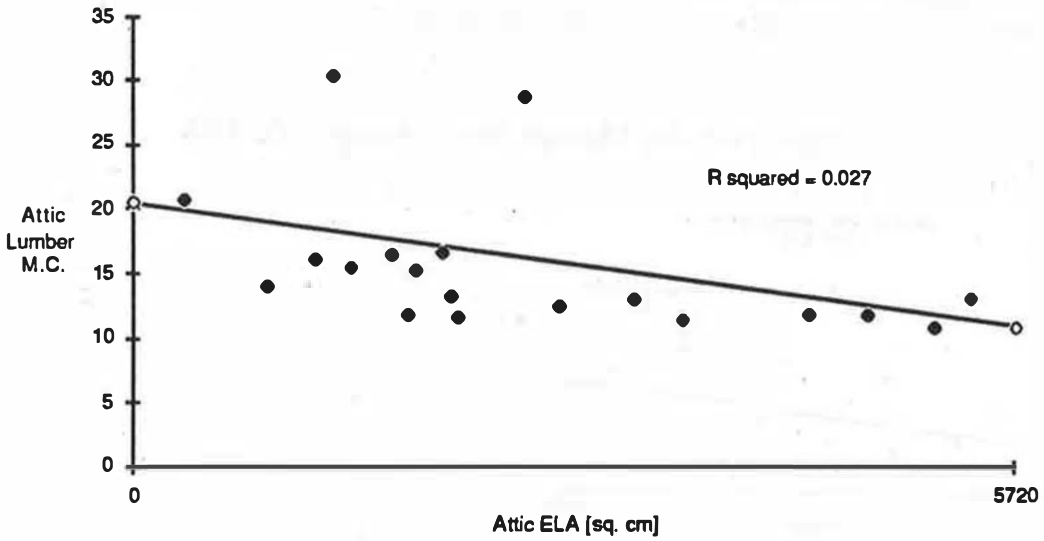


4.3 Lumber Moisture Content

As discussed earlier, the maximum seasonal value of the monthly average lumber moisture content levels was used to compare the overall attic wetness of the houses in the test group. This produced one moisture relating value per house. This quantity, 'attic moisture content,' was then plotted against the average air change rate, measured attic Equivalent Leakage Area, and against interface leakage. There was no observed relationship between overall attic wetness and air change and, therefore, a plot of that relationship has not been included in this report.

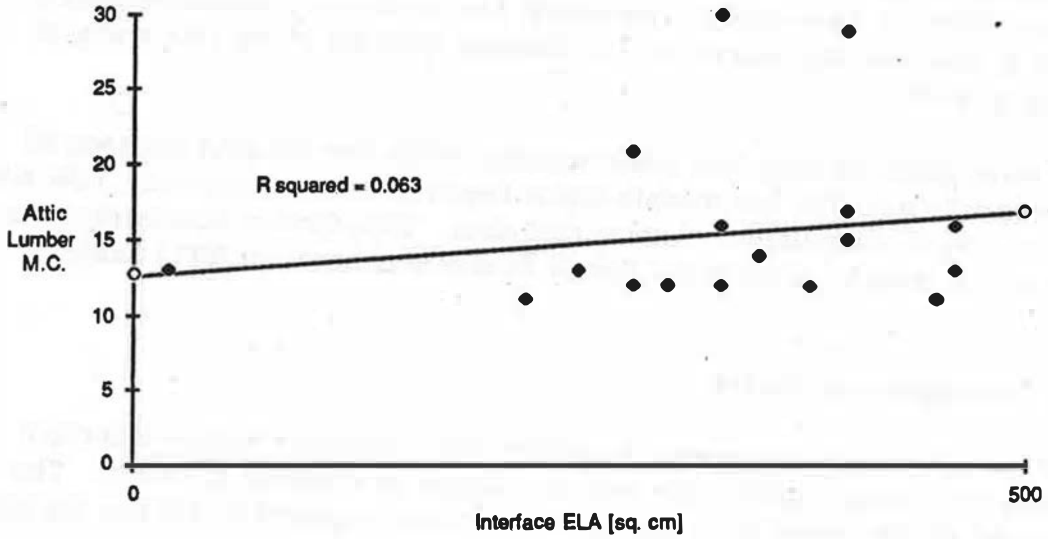
In Figure 4.4, the plots and line fits of the attic moisture content versus attic ELA showed a positive correlation. This plot indicated that, in this survey, attic wetness decreased with increasing attic Equivalent Leakage Area. The four highest points correspond to the four "wet" attics (in descending order; O-1, O-13, M-2, O-12).

Figure 4.4 **Attic Moisture Content versus Attic Equivalent Leakage Area**



The scatter plot and regression line of maximum moisture content versus interface Equivalent Leakage Area is presented in Figure 4.5. Although the interface flows posted in Table 3.3 show a large degree of scatter, this is largely reduced when this flow is expressed as a fraction of total attic air change. This normalization allows comparison of interface leakage flows among houses. In Figure 4.5, a plot and regression of maximum moisture content versus interface leakage flow is provided.

Figure 4.5 Attic Moisture Content versus Interface Equivalent Leakage Area



5.0 ROOF TEMPERATURE AND MOISTURE MODELLING

The FPL Roof Temperature and Moisture Model was provided by Mr. Anton Tenwolde of the United States Department of Agriculture, Forest Service, Forest Products Laboratory. The model has undergone several revisions since it was first introduced by Mr. Thomas Gorman of the University of Idaho in 1987.

The data gathered from the houses subjected to the detailed regimen of testing fully satisfied the model's input requirements. Apparently, this was the first such compilation of measured data. This section summarizes the use of this data to validate the Forest Products Laboratory (FPL) model.

5.1 Description of Model

The model calculates the attic humidity and sheathing moisture content values of a simple gable-style roof (two faces) of specified geometry. The purpose of the model is to provide information required in solving design- and specification-related problems.

The computer implementation of the model was written in FORTRAN, and was provided in a form that runs on IBM and compatible microcomputers. A summary of the model inputs and outputs is presented in Table 5.1.

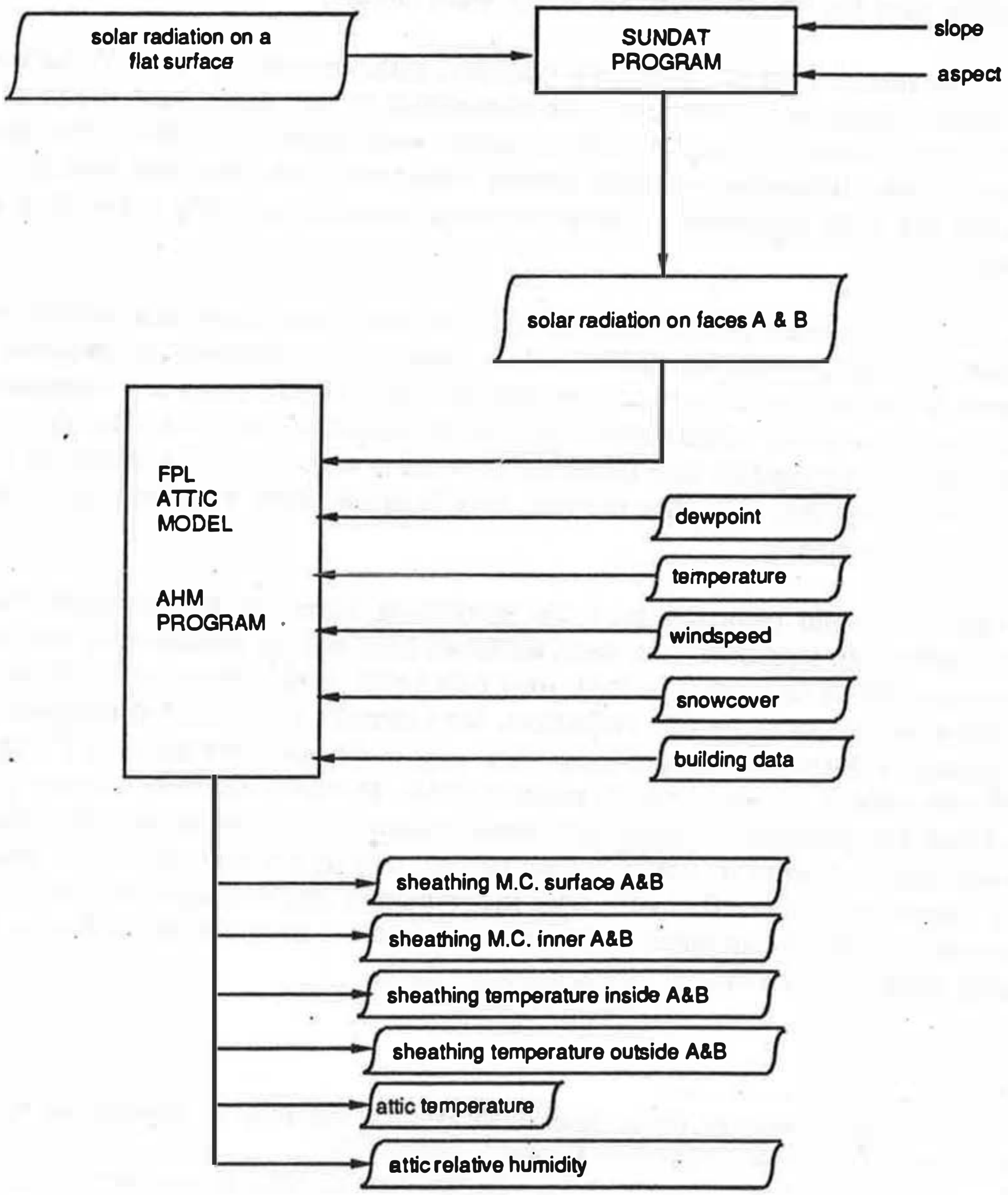
Table 5.1 **FPL Model Inputs and Outputs**

Inputs *Hourly data for:*	**Outputs** *Hourly data for:*
• outdoor temperature [°F]	• sheathing surface moisture content, face A [decimal]
• outdoor dewpoint [°F]	• sheathing surface moisture content, face B [decimal]
• outdoor windspeed [knots]	• sheathing inner moisture content, face A [decimal]
• solar radiation, face A [Langleys]	• sheathing inner moisture content, face B [decimal]
• solar radiation, face B [Langleys]	• sheathing inner temperature, face A [°F]
• snow cover [0 or 1]	• sheathing inner temperature, face B [°F]
• building data	• sheathing outer temperature, face A [°F]
	• sheathing outer temperature, face B [°F]
	• attic air temperature [°F]
	• attic air relative humidity [decimal]

For details on building data and input/output file format, please see Appendix C.

It should be noted that weather offices provide solar data as radiation on a flat surface. A program provided with the model (SUNDAT) uses site specific roof slope and aspect to produce the radiation impinging on roof faces A and B. A flow diagram of the system is provided in Figure 5.1.

Figure 5.1 **Model Flow Diagram**



5.2 Methodology & Limitations

The model was run for four of the five detailed test houses (Houses O-4, O-8, O-10, and O-12). House O-3 was not run because of the highly irregular roof shape of the house. House O-4 was used despite its hip format because two of the faces were deemed dominant.

Weather data was acquired from the Environment Canada Atmospheric Environment Service (AES) spanning the period from February 1,1990 through July 31, 1990. From this data, model input files were created for each house. These files were adjusted so as to commence on the earliest possible date for which monthly visits were made.

From the model output, moisture content, attic temperature and relative humidity values were extracted corresponding to the dates and times of site visits. The measured and modelled values were compared. Note that during the site visits, moisture content values were collected from the roof face nearest the attic hatchway. Model outputs pertaining to the other face were ignored.

The model produced hourly output, and the measured moisture values had a period of roughly one month. For this reason, this comparison exercise cannot be viewed as a rigorous validation. Other limitations are associated with the snow cover observations and solar radiation data. As the collected snow cover information was monthly as well, it was deemed useless as an input to the model. For this reason, hourly snow cover data was set to zero for the entire run.

The data for solar radiation on a flat surface is currently not available from AES. Although this data has been archived and will be available in the future, it is unavailable in digital format, and has never been offered in hard copy. In order to model the solar radiation, Mr Gorman forwarded a computer program for determination of total clear sky radiation by Flint and Childs[6]. AES was able to produce cloud amount data. Buchan, Lawton, Parent Ltd modified the program to read the cloud amount data and produced total cloudy sky radiation in the required units. The approach used was detailed in a paper by Brinsfield et al[7]. The inaccuracies associated with this approach to obtaining solar radiation data cannot be quantified, due to the highly subjective nature of cloud amount data.

---

[6] Alan L. Flint and Stewart W. Childs, **Calculation of Solar Radiation in Mountainous Terrain**, Department of Soil Science, Oregon State University, January 1987. .

[7] Russel Brinsfield and Melih Yaramanoglu and Fredrick Wheaton, **Ground Level Solar Radiation Prediction Model Including Cloud Cover Effects**, Department of Agricultural Engineering, University of Maryland, Feb. 1984.

5.3 Model Performance

Measurements of attic temperature, relative humidity and sheathing moisture content are compared against model predicted values in Table 5.2. The sheathing moisture content results comparisons are repeated graphically in Figure 5.2.

Table 5.2 **Measured vs. Modelled Results**

House O-4

Date	Attic Temperature		Attic Relative Humidity		Sheathing Moisture Content	
	Measured [°C]	Modelled [°C]	Measured [%]	Modelled [%]	Measured [%]	Modelled [%]
21-Mar-90	13	19	42	40	20	20
11-Apr-90	6	6	70	67	20	12
5-Jun-90	16	32	33	25	12	5
29-Jul-90		23		52		6
31-Jul-90	22		61		10	

House O-8

Date	Attic Temperature		Attic Relative Humidity		Sheathing Moisture Content	
	Measured [°C]	Modelled [°C]	Measured [%]	Modelled [%]	Measured [%]	Modelled [%]
1-Feb-90	4	4	60	91	22	22
20-Mar-90	8	7	67	82	13	9
12-Apr-90	4	2	53	52	16	8
1-Jun-90	41	13	15	62	6	6
13-Jul-90		34		34	9	6
29-Jul-90		19		63		6

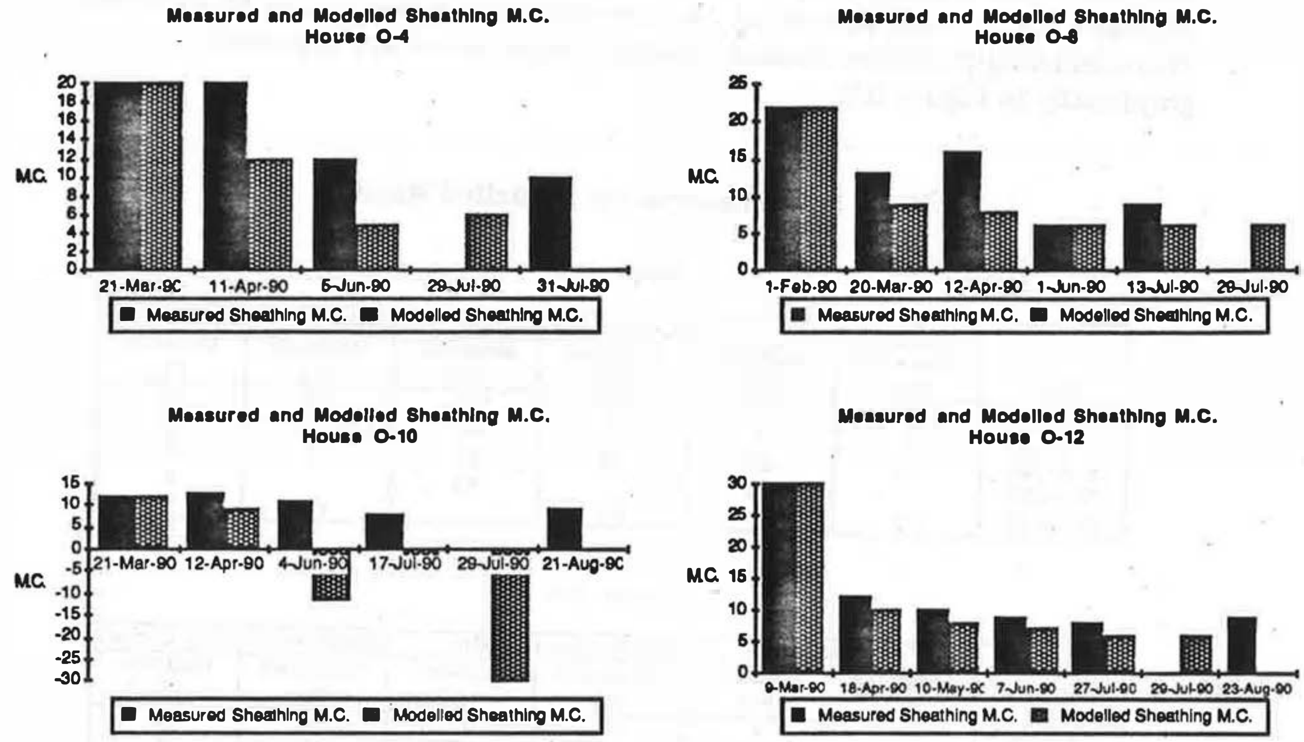
House O-10

Date	Attic Temperature		Attic Relative Humidity		Sheathing Moisture Content	
	Measured [°C]	Modelled [°C]	Measured [%]	Modelled [%]	Measured [%]	Modelled [%]
21-Mar-90	11	19	39	45	12	12
12-Apr-90		5	52	52	13	9
4-Jun-90	21	51		7	11	-12
17-Jul-90	27	32	43	25	8	-2
29-Jul-90		22		95		-30
21-Aug-90	22		56		9	

House O-12

Date	Attic Temperature		Attic Relative Humidity		Sheathing Moisture Content	
	Measured [°C]	Modelled [°C]	Measured [%]	Modelled [%]	Measured [%]	Modelled [%]
9-Mar-90	4	-1	79	60	30	30
18-Apr-90	8	10	22	20	12	10
10-May-90	15	29	32	45	10	8
7-Jun-90	20	13	48	74	9	7
27-Jul-90	38	23	43	52	8	6
29-Jul-90		17		82		6
23-Aug-90	31		51		9	

Figure 5.2 **Measured vs Modelled Moisture Content**



The model-predicted results presented in tabular form in Table 5.2 and graphically in Figure 5.2 were based on data obtained for a six month period from the Atmospheric Environmental Service of Environment Canada. The data covered the period from February 1, 1990 to July 29, 1990. Although measured data was not available for July 29, the modelled values were included in the Table and Figure to provide an indication of how the model changed over the seasons. The closest measured summer data was included for comparison purposes.

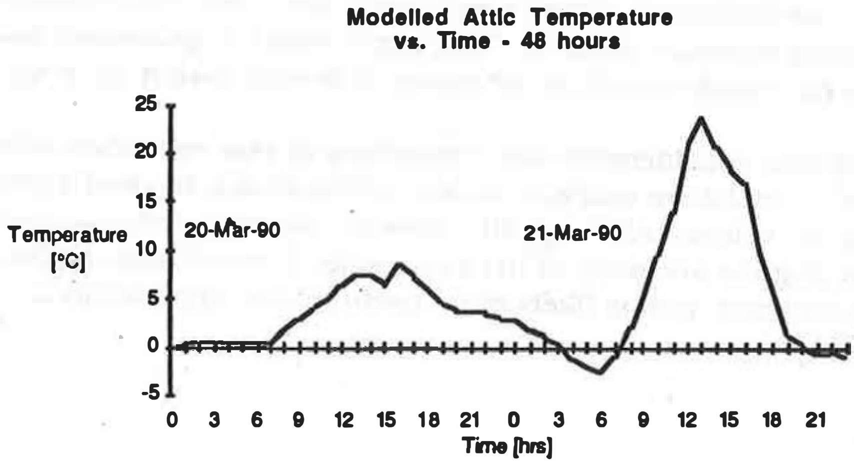
Comparing the modelled sheathing moisture content with the measured results, House O-12 appeared to have excellent agreement, while Houses O8 and O-4 were fair. It should noted that the model consistently under-predicted the moisture content level. This may be related to the over-prediction of the sheathing temperature caused by the assumed zero snow cover.

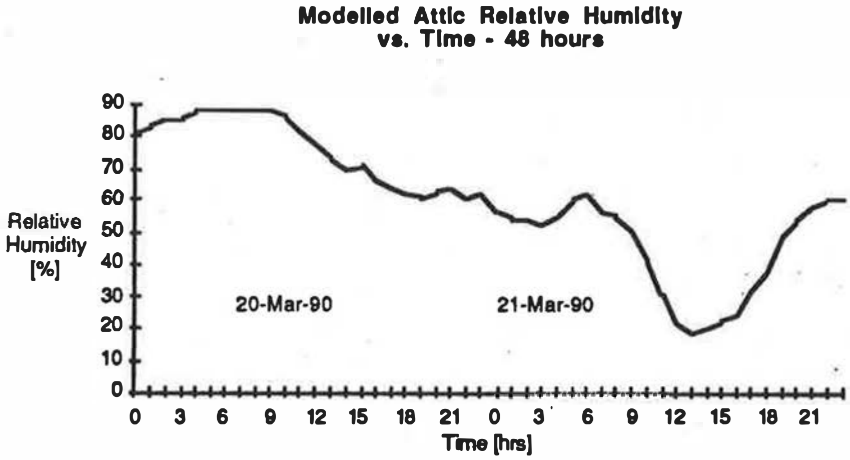
The results for House O-10 appeared to oscillate and produced erroneous negative values. The reason for this was not clear.

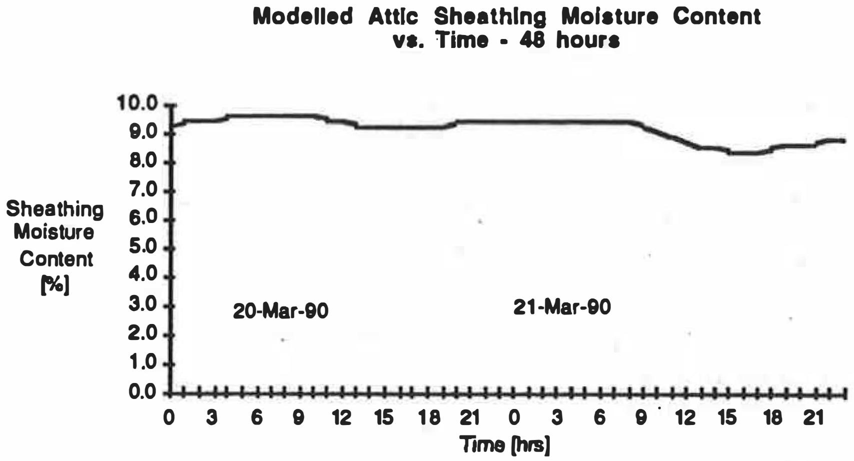
Table 5.2 revealed that the measured attic air temperature and relative humidity values differed significantly from their predicted values. Although the reason for these discrepancies was unknown, it should be pointed out that these quantities varied significantly on a daily cycle compared to sheathing moisture content. This cyclic trend is illustrated in Figure 5.3 where the hourly numbers for house O-8 were posted for a 48-hour interval.

Taking into consideration the limitations of this validation attempt, the predicted moisture content values exhibited fair-to-good agreement with measured values. Although this exercise cannot provide a basis for measuring the accuracy of the FPL model, it would appear that the model is not inaccurate, and is likely quite useful in the application for which it was intended.

Figure 5.3 **House O-8 Model Results--48 hours**







5.0 CONCLUSIONS

The work undertaken in this study must be considered preliminary in nature. The work involved the first major field trial of two new attic testing procedures, one for measuring ELA and a second for measuring air change rate.

The test procedures appeared to be applicable to most houses, however, the physical arrangement of the attic access could significantly complicate the test set up. In addition, houses with very high attic ELAs may exceed the flow capacity of the available fan equipment.

Of the two approaches used in the attic ELA test for measuring the interface ELA, the first approach proved to be far superior. The adjustment of the attic air flow rate, while attempting to maintain a pressure balance between the attic space and the outdoors in the second test, was unreliable.

The house sample size was small and contained a wide variety of construction types and ages of houses in two distinctly different climatic zones, limiting the ability of the data to display trends. A large and more precisely defined sample would help alleviate this problem.

High attic moisture content was not found in the absence of high house humidities.

The venting strategy employed in the attic appeared to have some effect on the concentration of moisture in certain parts of the attic. Although the sample size was too small to draw firm conclusions, observations indicated that venting strategies in which the exfiltration venting area was concentrated resulted in higher localized moisture content in the wood at those sites. A combination of high and low attic venting appeared to facilitate moisture removal.

It is clear that estimating the attic ELA by measuring the venting area is unreliable.

Weather conditions appeared to have a large impact on the air change rates in attics, however, the relationships between the major weather parameters and the air change rate could not be determined from the data gathered. In order to better determine correlations between air change rates and wind parameters, on site, real time wind data recording would be necessary.

As can be expected, there is a definite correlation in some attics between air change rate and wind speed. The hourly airport wind speeds and occasional on-site estimates were insufficient to quantify the effect.

SURVEY OF MOISTURE LEVELS IN ATTICS

APPENDIX A - Methodology Details

APPENDIX B - Results

APPENDIX C - Forest Products Laboratory Detailed Model Inputs

Submitted to:

Research Division
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BLP File No. 2497
March, 1991

Appendix A

METHODOLOGY DETAILS

APPENDIX A-1

AIRTIGHTNESS TEST

APPARATUS

Attic Blower

- Retrotec door fan

House Blower

- Minneapolis blower door

Instrumentation

- 3 four-wall pressure taps with one litre pressure averaging can and capillary tubes
- 2 General Eastern Electronic pressure transducers (0-0.25 inches H_2O output 01-5 V)
- Fluke digital volt meter and switch
- 2 Magnahelic pressure gauges for measuring fan flow pressures

Ductwork

- sheet metal square to round transition piece with flanges weather-stripped with closed cell foam
- 2 adjustable fiberglass extension poles
- 15 and 25 foot lengths of 20" diameter PVC flex duct
- various lengths of 20" diameter lay flat tubing constructed of polyethylene plastic sheet

PROCEDURE

Set-up

- Take instrument case into house and plug in electronic transducers. Place fan controllers beside instrument case.
- Seal intentional openings, close all windows, open interior doors, as per conventional fan test.
- Place four-wall pressure averaging kit in attic, tossing pressure taps towards the eaves and gable ends.
- Run two independent four wall taps outside building, as per conventional fan test.
- Connect attic pressure tap to transition piece. Fit square side of transition into attic. Support transition securely with adjustable

extension poles. Run plastic hose from attic transition to instrument case.

- Connect large flex-duct to transition piece.
- Install attic fan in bottom of doorway.
- Install house fan above attic fan.
- Route two exterior pressure taps through blower door assembly and tape shut. Connect one to the attic zone transducer and the other to the house zone transducer.
- Connect attic zone transducer and house zone transducer. Turn on digital multi-meter. Check transducer calibration. Re-calibrate using oil-filled manometer if necessary.
- Connect flex duct to attic blower.
- Connect fan flow pressure gauges and fan controllers.
- Close fan apertures on both blowers. Record initial transducer output for attic zone. Toggle transducer switch to house zone and record initial output.
- Calculate target transducer output values corresponding to 10, 20 and 30 Pa for house transducer and attic transducer. Recalculate target pressures for the second part of the test.
- Record target transducer values for first and second parts of test on field data sheet.

1-Pressurize Attic

- Open attic fan aperture to full or nearly full configuration. Open house fan aperture to a medium configuration. Toggle transducer switch to attic zone, turn on attic fan. Pressurize attic until target transducer output is achieved (10 Pa). Wait until transducer output is stable.
- Toggle transducer switch to house zone, turn on house blower ands de-pressurize house. Adjust blower speed until target transducer output is reached (initial transducer output recorded during set-up).
- Toggle transducer switch to attic blower and readjust attic flow.
- Repeat last two steps until stable target transducer outputs have been achieved.
- Repeat last three steps for 20 and 30 Pa; attic fan capacity permitting.

2-Depressurize House

- Go outside, close attic fan aperture to a nearly closed configuration.
- Toggle transducer switch to house, turn on house fan. Adjust fan speed until target transducer output is achieved (-10 Pa).
- Toggle between zones until stable targeted transducer outputs have been achieved as in the first part of the test.

APPENDIX A-2

AIR CHANGE TEST

APPARATUS

Tracer Gas

- pressurized canister 0.01% SF_6, balance air
- regulator
- electronic mass flow meter

Injection Apparatus

- one 10 manifold constructed of 0.25" diameter copper tubing sections connected to 1" copper tubing vessel
- outlets connected by PVC hose of varying lengths to spray nozzles (oil furnace type)

Sampling Apparatus

- four aquarium-type air pumps
- four long PVC hoses
- four 60 litre sampling bags (garbage bags)
- 10 cc evacuated blood collection tubes ('vacu-tainers')
- 35 ml syringes

PROCEDURE

Sample and Injection Location

- Four sample pumps to be located at centroid of attic quadrants.
- Injection nozzles to be evenly distributed around the four sampling pumps.

Set-Up

- Hang sample pumps from rafters. Gang pump plug-in ends together and run one extension cord through attic hatch to floor of house.
- Run hoses from pumps through attic hatch to floor of house.
- Locate injection nozzles throughout attic. Route feed hose to injection manifold through attic hatch.
- Fit temporary attic hatch made of cardboard and seal with tape.

- Plug in extension cord feeding pumps and check each of four sampling hoses to ensure pumps are functioning. Correct if necessary. Unplug extension cord feeding pumps.
- Connect manifold injection hose to mass flow meter and mass flow meter to tracer gas tank.
- Open tank, adjust flow rate to 1900 cc/min. Note start time of injection.
- Record outdoor temperature, indoor temperature, attic temperature.
- Evacuate sampling bags and fit bags with PVC hose and hose connector. Plug connector, arrange all bags nearby sampling hoses.
- After period of one hour from start of injection, plug in sampling pumps and allow 1-2 minutes to bleed lines.
- Unplug sampling bags and connect to sampling tubes.
- Make sketch of attic plan with pump numbers and locations, injection point locations and 2 sets of air sample identification numbers per pump.
- One-half hour after connecting bags to pumps, purge sampling syringe several times and draw 17 ml sample from each bag. Inject 17 ml sample into corresponding vacu-tainer.
- Disconnect each bag from tube, evacuate bag of air and reconnect bag to tube.
- One half hour after reconnecting tube, draw second set of samples.

Dual Zone Tracer Gas

- Set up attic sampling and injection apparatus as for conventional test substituting 99.5 per cent CO_2 tracer gas for attic. Use rotameter-type flow metering.
- Add fifth sampling pump to centre of attic volume.
- Add 1 per cent SF_6 mixture and mass flow meter set up to provide single point injection into return air grille of heating system. Optionally, use multi-point injection to various rooms.
- Measure CO_2 concentration in attic prior to test.
- Route all sampling lines outside to sampling stations.
- Inject CO_2 at approximately 15000 cc/min., and SF_6 at 1500 cc/min.

- Connect fifth sampling hose to CO_2 analyser during stabilization period, adjust CO_2 flow rate to target steady-state concentration of approximately 4000 ppm. Commence filling sample bags.
- Using timing similar to conventional test, draw SF_6 samples from bags; connect bags to CO_2 analyser; take readings. Deduct from readings background CO_2 concentration recorded prior to test.
- Analyse samples for SF_6 concentration.

APPENDIX A-3

MOISTURE MONITORING

APPARATUS

Moisture Sensor

- Delmhorst moisture pins with 6 m extension wires
- T-type thermocouples with 6 m extension leads

Instrumentation

- Delmhorst moisture meter with surface probe and adapter for permanent pin connectors
- T-type thermocouple reader
- electric psychrometer
- BLP humidity samplers
- terminal block mounting connectors for all moisture sensors installed in attic

SENSOR INSTALLATION DETAILS

The majority of the attics were instrumented with six moisture sensors. The sensors were placed in lumber on the gables (if applicable), in the rafters (or upper truss member) supporting the sheathing, and in the joists (beneath the insulation). A typical installation would include one sensor in each gable, two sensors located in the top truss at opposite ends of the attic and two sensors in the bottom joists located directly below the upper sensors. All moisture pins were driven to a depth of 1/4 lumber thickness. The pins were inserted parallel to plank grain, spaced at 2 cm according to the manufacturer's directions. Exposed T-type thermocouples were mounted on the lumber adjacent to the pins. These were fastened by covering the thermocouple junction with a thin piece of foam and stapling the foam to the lumber. Each thermocouple and moisture pin was equipped with approximately six metres of lead wire. A labelled terminal block was mounted to the attic lumber in close proximity to the attic hatch. The leads from the various sensors were routed through this panel and connected to screw-type connectors exposed for easy measurement with the moisture meter adapter probe and thermocouple reader. Figures A-3.1 and A-3.2 show the sensor mounting detail and terminal block assembly respectively.

Figure A-3.1 Moisture Sensor Installation Details

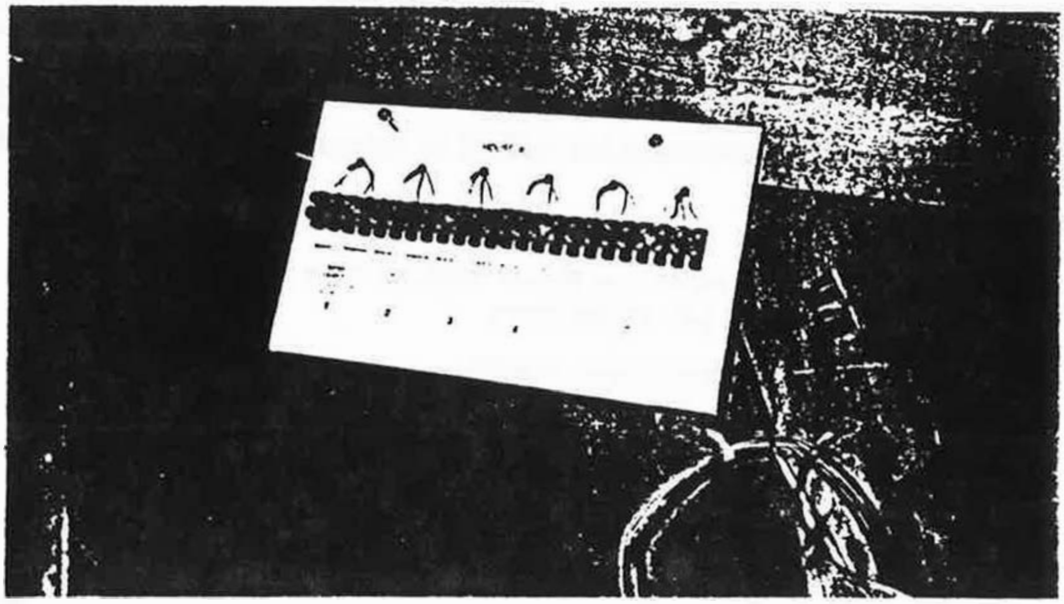
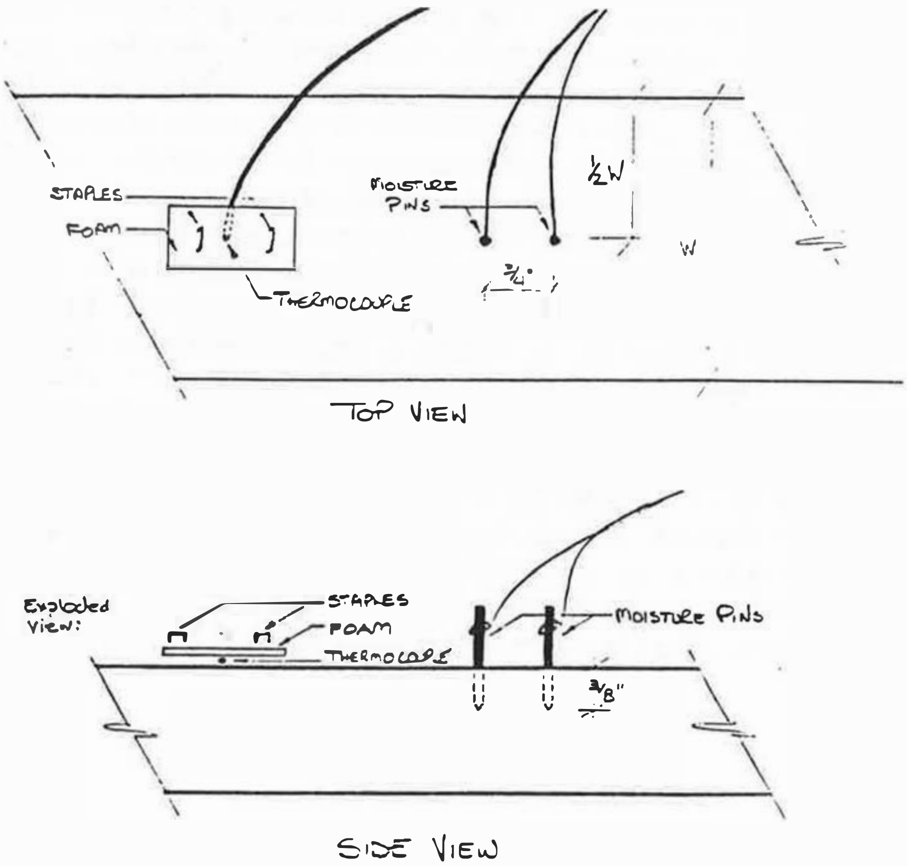


Figure A-3.2 Example Terminal Block



MONTHLY SITE VISIT PROCEDURES

Humidity Measurements

- Measure relative humidity of attic air with minimum disturbance of attic by placing a functioning psychrometer in attic and closing attic hatch. Allow time for psychrometer to stabilize.
- Retrieve previous month's humidity sampler from house space and re-deploy new humidity sampler.
- Retrieve psychrometer from attic. Record attic wet bulb and dry bulb temperature and calculate relative humidity.
- Record house wet bulb and dry bulb temperatures and calculate relative humidity.

Moisture Monitoring

- Using the moisture meter equipped with terminal leads, probe all moisture pins at the terminal block from the attic hatch and record moisture values.
- Using the thermocouple reader, read all the thermocouple outputs on the terminal connection block.
- Using the Delmhorst moisture meter with surface probe, record average moisture levels for sheathing, top truss, webbing and bottom joist lumber.
- Close attic hatch.
- Record date, time, snow cover on roof and humidity sampler I.D.

APPENDIX A-4

ERROR CALCULATIONS

House Characterization

Venting Area:

Generally,

$$A = n L_1 L_2 p$$

where
- n = number of vents
- $L_{1,2}$ = dimensions [cm]
- p = percentage open (0.6)

As the shape of openings were very rough and vents were blocked to varying degrees by insulation, the following estimates of the component errors were made:

$$\delta L_{1,2} = \pm 10\%$$
$$\delta p = \pm 10\%$$

The component errors were summed in quadrature to yield the accuracy, dA:

$$dA = \sqrt{(0.1^2 + 0.1^2 + 0.1^2)}$$
$$dA = 0.17 \text{ or } 17\%$$

Air Tightness - Accuracy

Equivalent Leakage Area:

Generally,

$$ELA = 0.0013\, Cr\, 10^{n-0.5}$$

$$= \frac{0.0013}{\sqrt{(10)}} Cr\, 10^{n}$$

$$= \frac{0.0013}{\sqrt{(10)}} Q_{10}$$

$$= 0.0004\, Q_{10} \quad [m^2]$$

where
- Cr, n = flow coefficient and exponent of depressurized volume.
- Q_{10} = flow through depressurized volume @ 10 Pa [L/s]

ventilation ELA, (also applies to house ELA results)

	VELA	=	$4\,(Qa - Qh)$
		=	$4\,(Ca\ p_a^{na} - Ch\ p_h^{nh})$
where	$C_{a,\,h}$ & $N_{a,\,h}$	:	calibration data for attic and house zone fans.
	$p_{a,\,h}$	:	how pressures measured through attic and house fans.
	dVELA	=	$\sqrt{([\delta a^2 + \delta p_a^2] + [\delta h^2 + \delta p_h^2])}$
where	$\delta_{a,\,h}$	:	manufacturer's stated fan calibration accuracies for the attic and house fans.
	$\delta p_{a,\,h}$	:	accuracies of flow pressure gauges for attic and house fans.
	δ_a	=	0.05 (Retrotec)
	δ_h	=	0.10 (Minneapolis)
	$\delta p_{a,\,h}$	=	0.05 (Magnahelic, based on mean flow pressure of 50 Pa)
	dVELA	=	$\sqrt{([0.05^2 + 05^2]) + ([0.1^2 + 0.05^2])}$
		=	$\sqrt{0.005 + 0.0125}$
		=	0.13 or 13%

Interface ELA

In part 1 of the test, interface ELA was measured with the house fan:

$$dIELA_1 = \sqrt{(0.125)} = .11 \text{ or } 11\%$$

Air Tightness - Measurement Error

Considerable measurement error was prevalent when trying to measure the pressure difference of 10 Pa between the house and attic zones. The sources of this error were the transducers, their calibration, and the effects of wind-induced pressure fluctuations.

Including wind effects, the pressure drop was measured as follows:

$$dp_{ha} = dp_{ho} - dp_{ao} + dpw$$

where	h	:	house zone
	a	:	attic zone
	o	:	outdoor zone
	w	:	wind effects

The measurement error,

$$dp_{ha} = \sqrt{(\delta ph^2 + \delta pa^2 + \delta pw^2)}$$

Estimating the component errors:

The general eastern transducers had an error ±2 per cent of full-scale which was 0.25 inches H_2O. This corresponded to ±2 Pa, or ±10 per cent in the applied range. An additional calibration error of ±0.2 per cent was also included.

$$\delta h = \pm 12\%$$

$$\delta a = \pm 12\%$$

$$\delta w = \pm 10\% \text{ (estimate of } \pm 1 \text{ Pa)}$$

The components were summed in quadrature to yield the measurement error, dELA

$$dELA = \sqrt{(0.12^2 + 0.12^2 + 0.1^2)} = 0.2 \text{ or } 20\%$$

Air Change Measurement

Air Change Rate:

$$I = \frac{Q \times 1\,000\,000}{Cs \times V} \quad \text{[a.c.h.]}$$

where	Q	=	the gas injection rate [L/h]
	C_s	=	the steady state concentration of tracer gas [p.p.m.]
	V	=	the volume of the attic [L]

For the above variables, the component errors were taken as:

δQ	=	±1% (Matheson mass flow meter specifications)
δC_s	=	±3% (G.C. lab estimate)
δV	=	±10% (based on ±5% estimated error in length measurements)

$$dI = \sqrt{(0.01^2 + 0.03^2 + 0.1^2)}$$

$$= \pm 11\%$$

Interface Leakage:

$$I_1 = \frac{Th}{Ta} \quad \frac{Ca}{Ch} \quad Qa$$

where	$T_{h,a}$	=	absolute house and attic temperature [K]
	$C_{h,a}$	=	steady state house and attic tracer gas concentrations [p.p.m.]
	Q_a	=	flow rate through attic

Compiling the component errors, δQ_a followed the exact same analysis as above, but δQ and δC_s values were modified for the use of rotameters and the Nova absorption equipment.

$$\delta Q = \sqrt{(0.05^2 + 0.05^2 + 0.1^2)}$$
$$= \pm 12\%$$

$\delta T_{h,a}$	=	±1% (thermocouple reader specifications)
δC_h	=	±3% (as before)
δC_a	=	±5% (from Nova specifications)

Summing Component Errors:

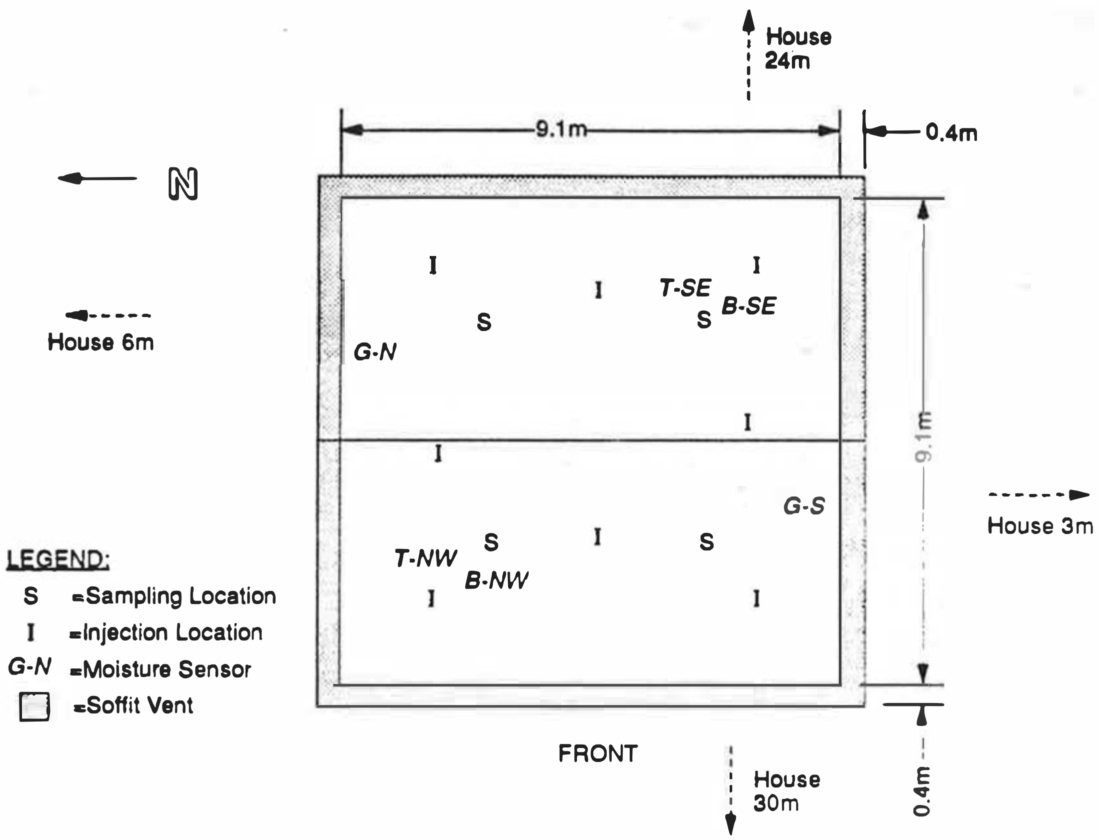
$$\delta I_1 = \sqrt{(0.12^2 + 0.01^2 + 0.03^2 + 0.05^2)}$$
$$= \pm 14\%$$

Appendix B

RESULTS

HOUSE O-1
HOUSE CHARACTERISTICS

Site Plan



House Data

General		*Attic*		*Venting*	
Location:	Ottawa	Ceiling to ridge height:	1.3 m	Types:	soffit
Age:	1970	Volume:	53 m^3	Free venting area (approx.):	2300 cm^2
Type:	2 storeys	Ceiling area:	84 m^2		
Roof		Insulation:	RSI 3.3 glass fibre batts		
Type:	gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	fir				

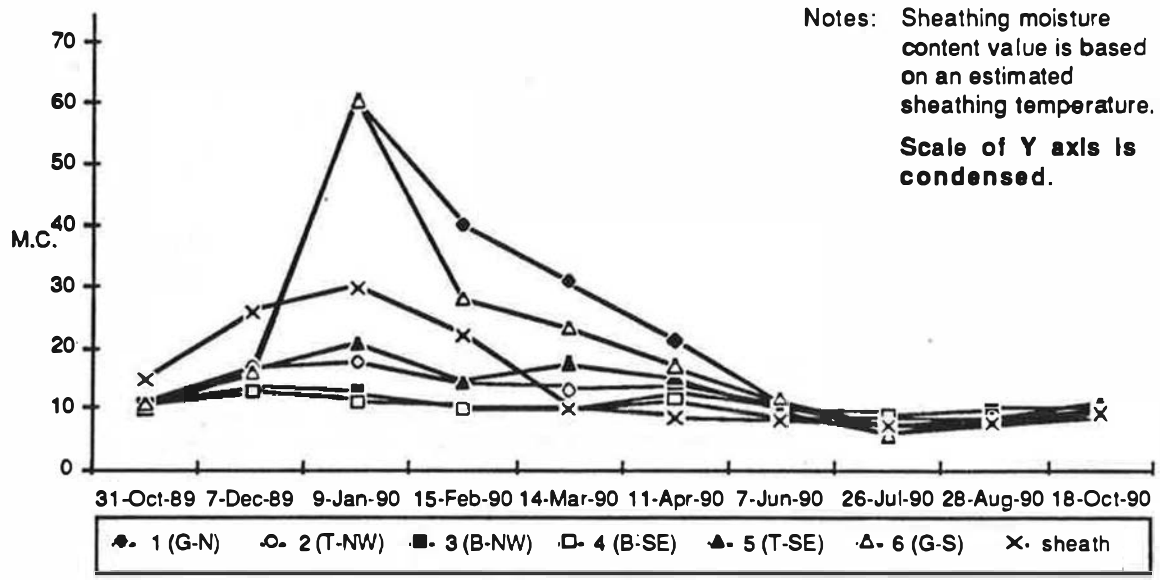
Air Change Data

Test	*Date*	*Average Wind Speed (kph)*	*Wind Direction*	*Outside Temp (T_o) (°C)*	*Attic Temp (T_a) (°C)*	*House Temp (°C)*	*Attic Air Change (ACH)*	*Average Interface Leakage (L/s)*
1	24-Jan-90	24	S	5	10	20	6.5	N/A
2	26-Jul-90	7	W	31	52	26	2.6	N/A

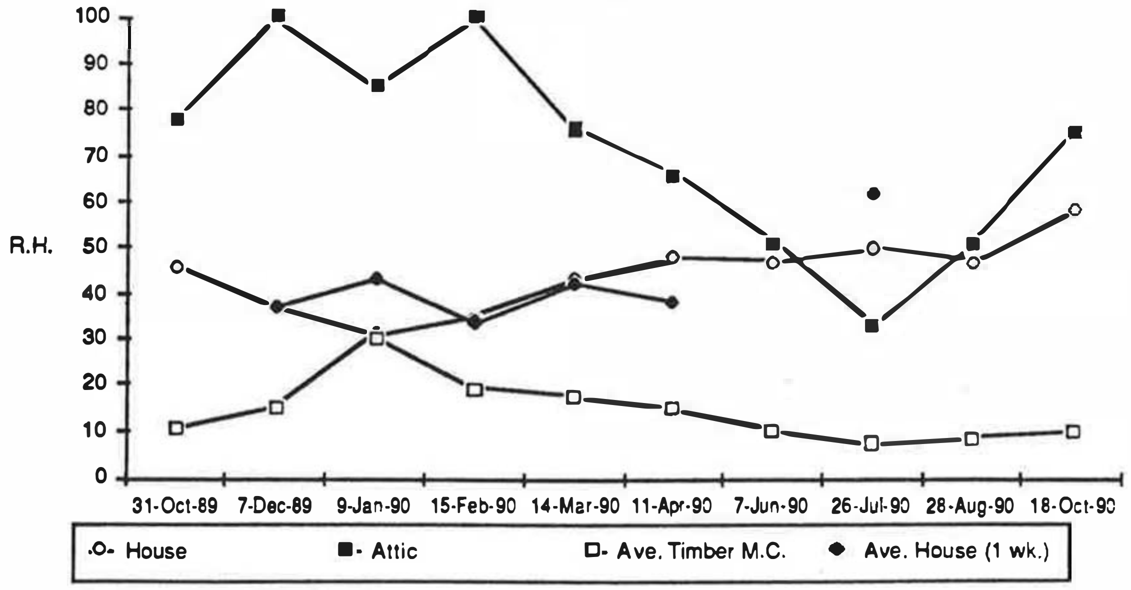
Attic Air Tightness Data

Wind Speed During Test kph	*Attic Ventilation ELA cm^2*	*Interface ELA cm^2*
18	1700	330

Moisture Curves: House O-1

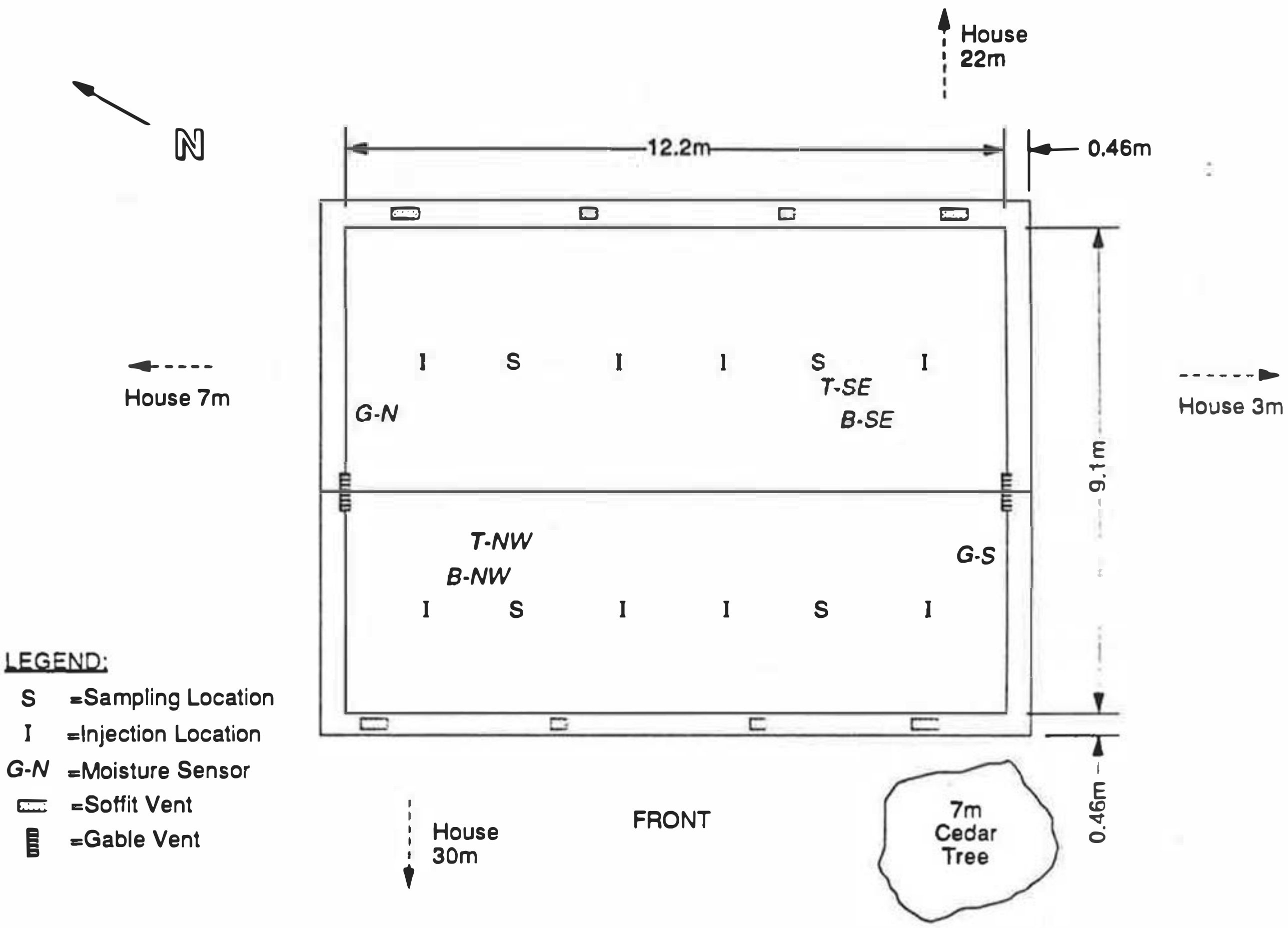


Relative Humidity and Average Lumber Moisture Content Curves: House O-1



HOUSE O-2
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.4 m	Types:	soffit, gable
Age:	1968	Volume:	82 m^3	Free venting area (approx.):	2700 cm^2
Type:	1 storey	Ceiling area:	112 m^2		
Roof		Insulation:	RSI 2.8 glass fibre roof board		
Type:	gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

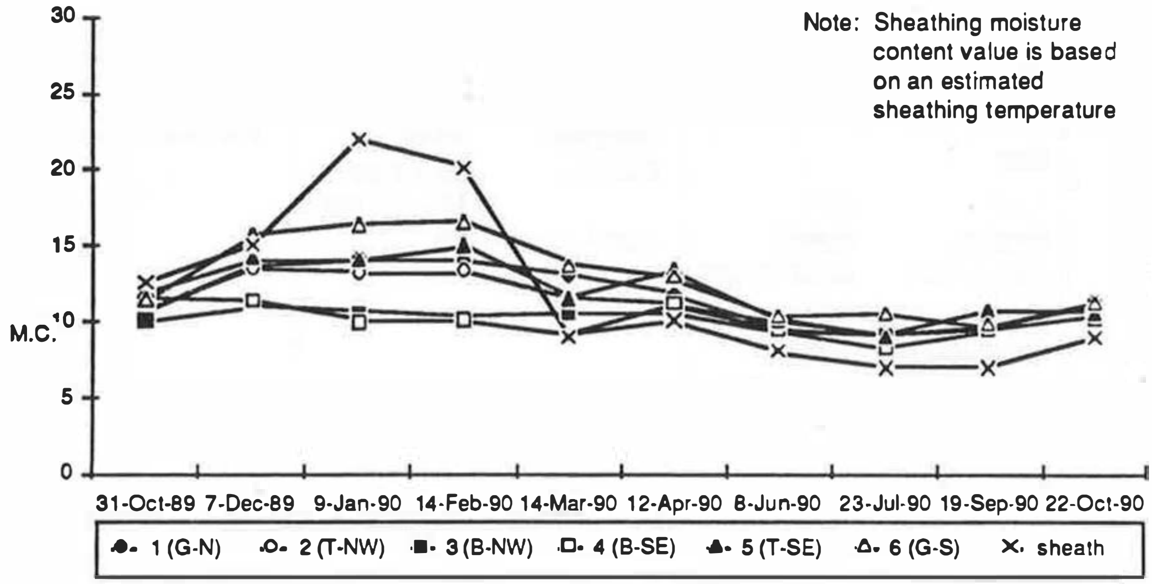
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	22-Jan-90	6	ENE	-12	2	19	3.1	N/A
2	23-Jul-90	15	NE	21	21	20	1.6	N/A

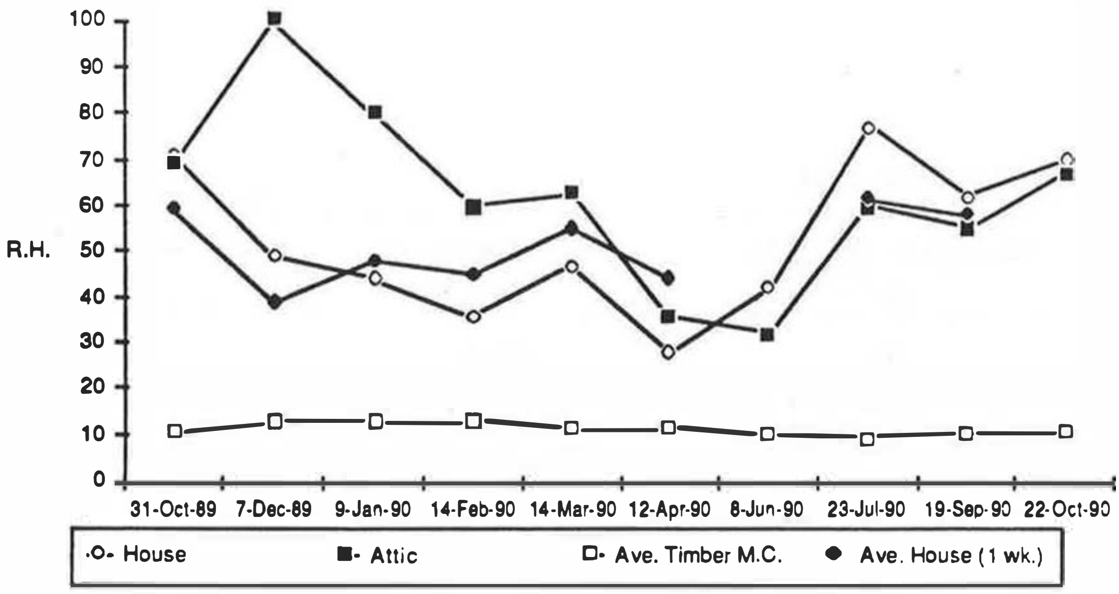
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
11	2500	460

Moisture Curves: House O-2

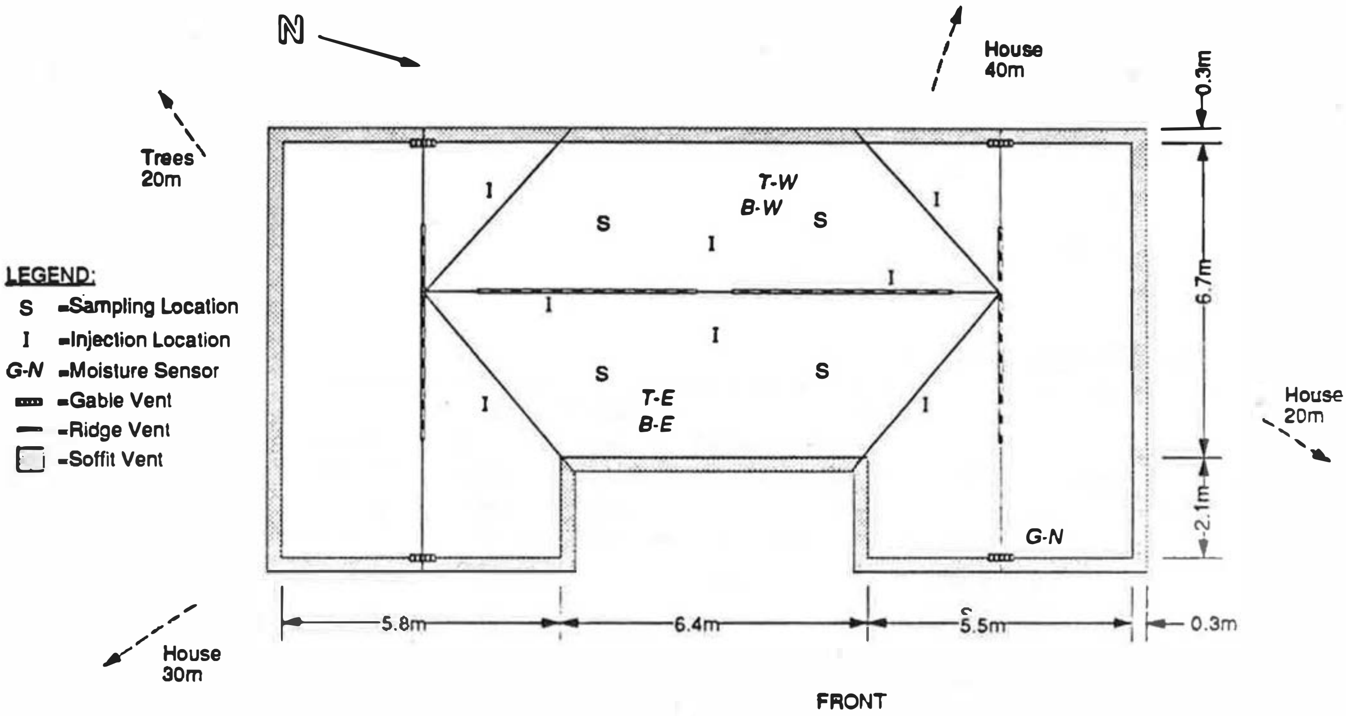


Relative Humidity and Average Lumber Moisture Content Curves: House O-2



HOUSE O-3
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	3.0 m	Types:	soffit, gable, ridge
Age:	1987	Volume:	202 m^3	Free venting area (approx.):	29,000 cm^2
Type:	1 storey	Ceiling area:	149 m^2	**Further Relevant Information**	
Roof		Insulation:	RSI 5.0 blown glass fibre		House built to the R-2000 Specifications
Type:	H gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

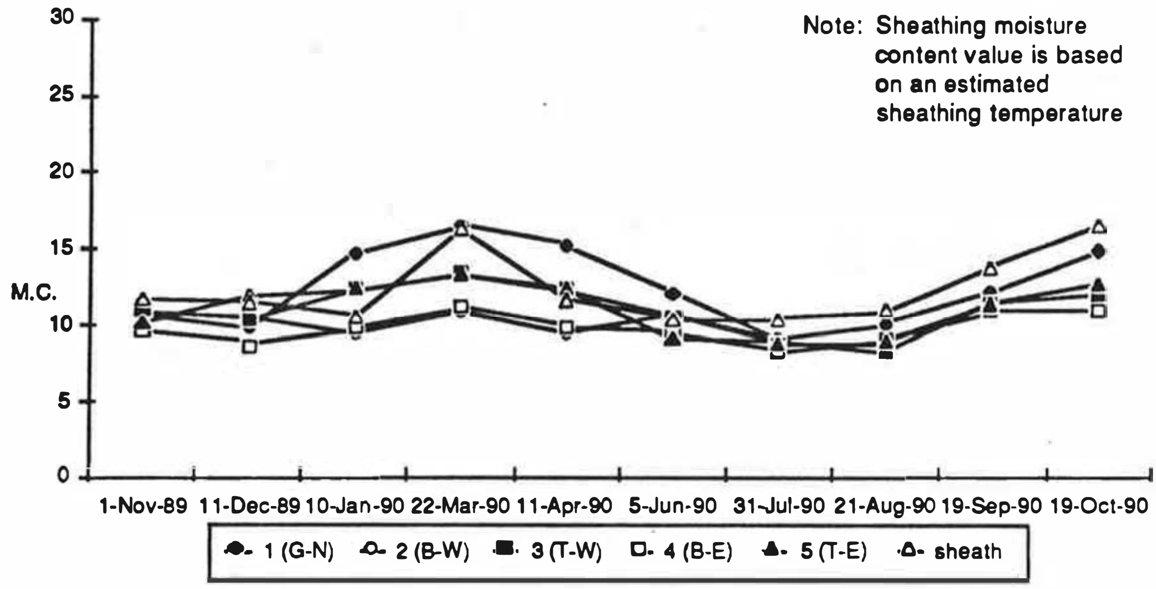
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH	L/s)	Average Interface Leakage (L/s)
1	23-Jan-90	11	SW	-2	5	18	15	840	N/A
2	31-Jul-90	20	N	20	26	21	14.5	812	N/A
3	1-Aug-90	23	NW	25	25	21	11.3	633	N/A
4	3-Aug-90	17	W	27	35	22	14.1	789	N/A
5	22-Mar-90	20	SSW	11	15	19	14	784	-
6	17-Aug-90	22	SSW	31	38	24	15.3	857	40

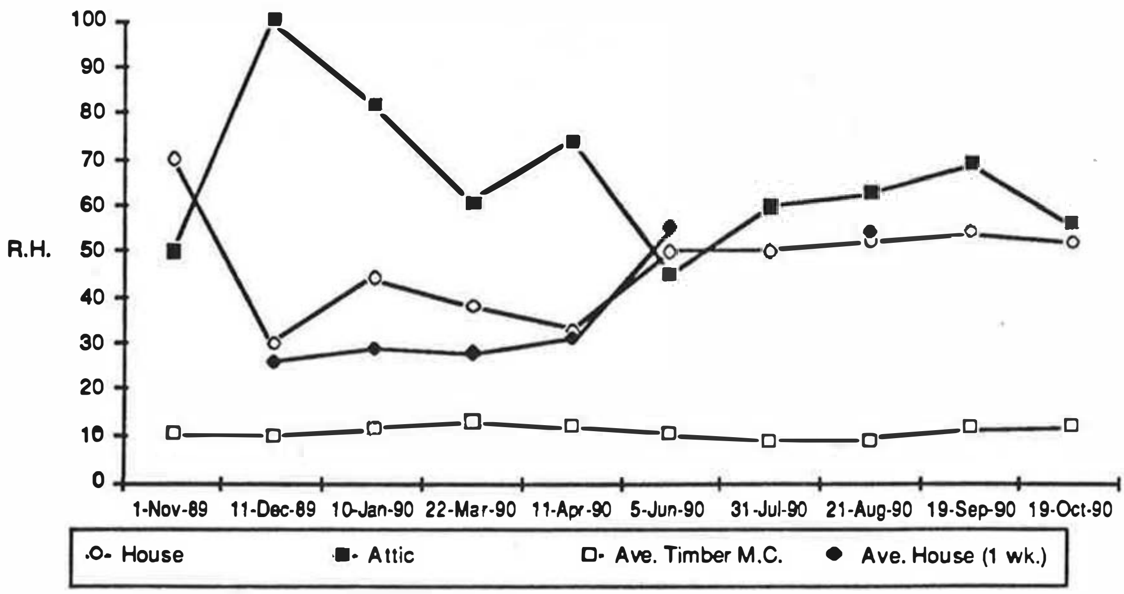
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
27	attic test not done -- unable to pressurize	

Moisture Curves: House O-3

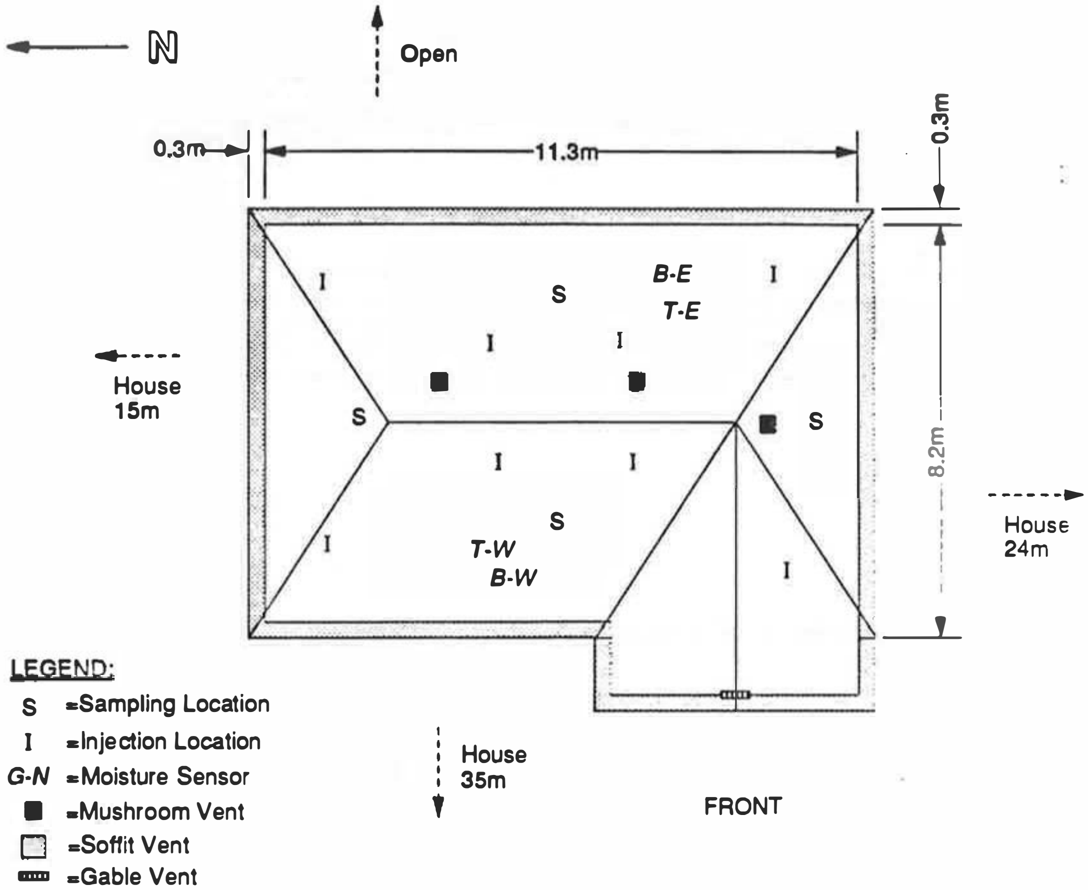


Relative Humidity and Average Lumber Moisture Content Curves: House O-3



HOUSE O-4
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.8 m	Types:	soffit 3 mushroom gable
Age:	1987	Volume:	70 m^3	Free venting area (approx.):	3900 cm^2
Type:	2 storeys	Ceiling area:	89 m^2		
Roof		Insulation:	RSI 5.0 blown glass fibre		
Type:	hip, gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

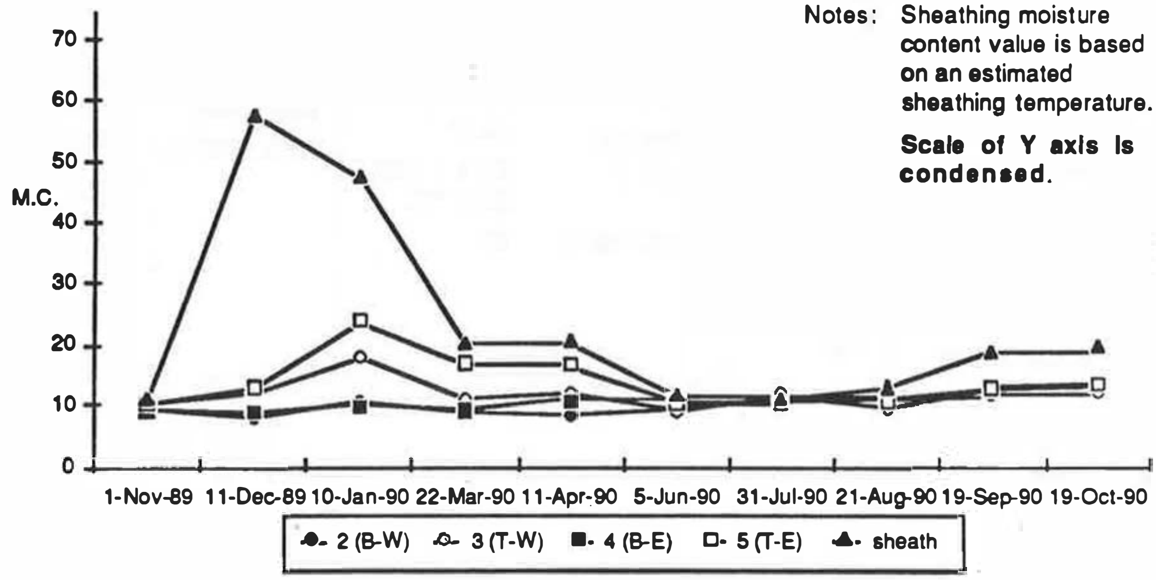
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH	L/s)	Average Interface Leakage (L/s)
1	23-Jan-90	10	SW.	-2	9	22	6	115	N/A
2	31-Jul-90	28	NNW	16	24	18	8.3	159	N/A
3	1-Aug-90	24	NW	27	30	26	6.5	125	N/A
4	3-Aug-90	19	W	31	48	20	14	268	N/A
5	22-Mar-90	15	SSE	6	10	19	13.6	261	10.2
6	9-Aug-90	15	SSW	26	33	23	17	326	32

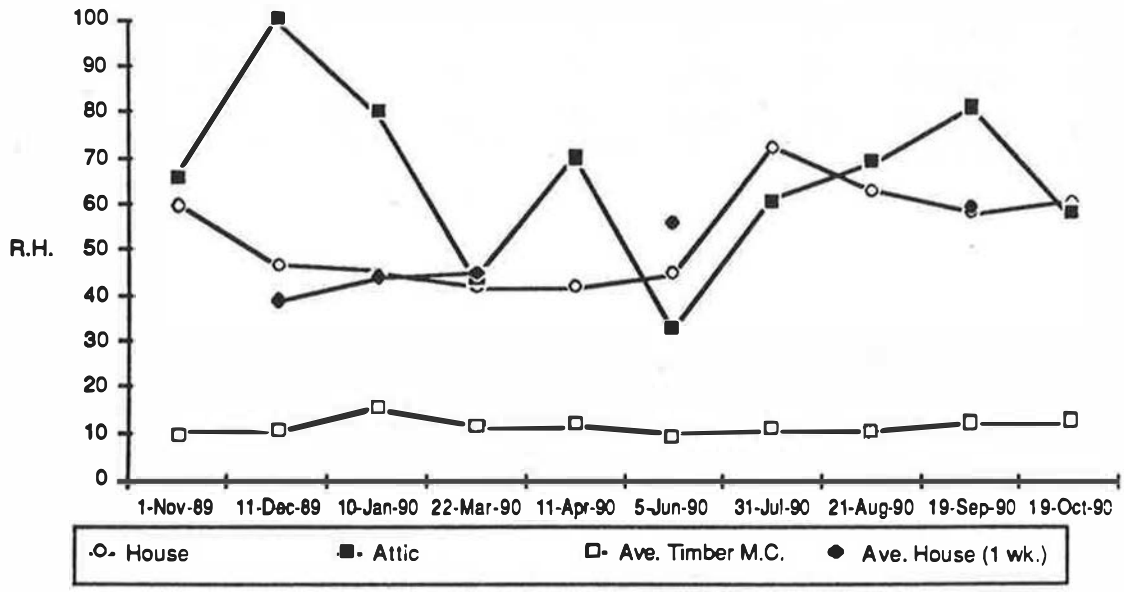
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
27	3600	250

Moisture Curves: House O-4

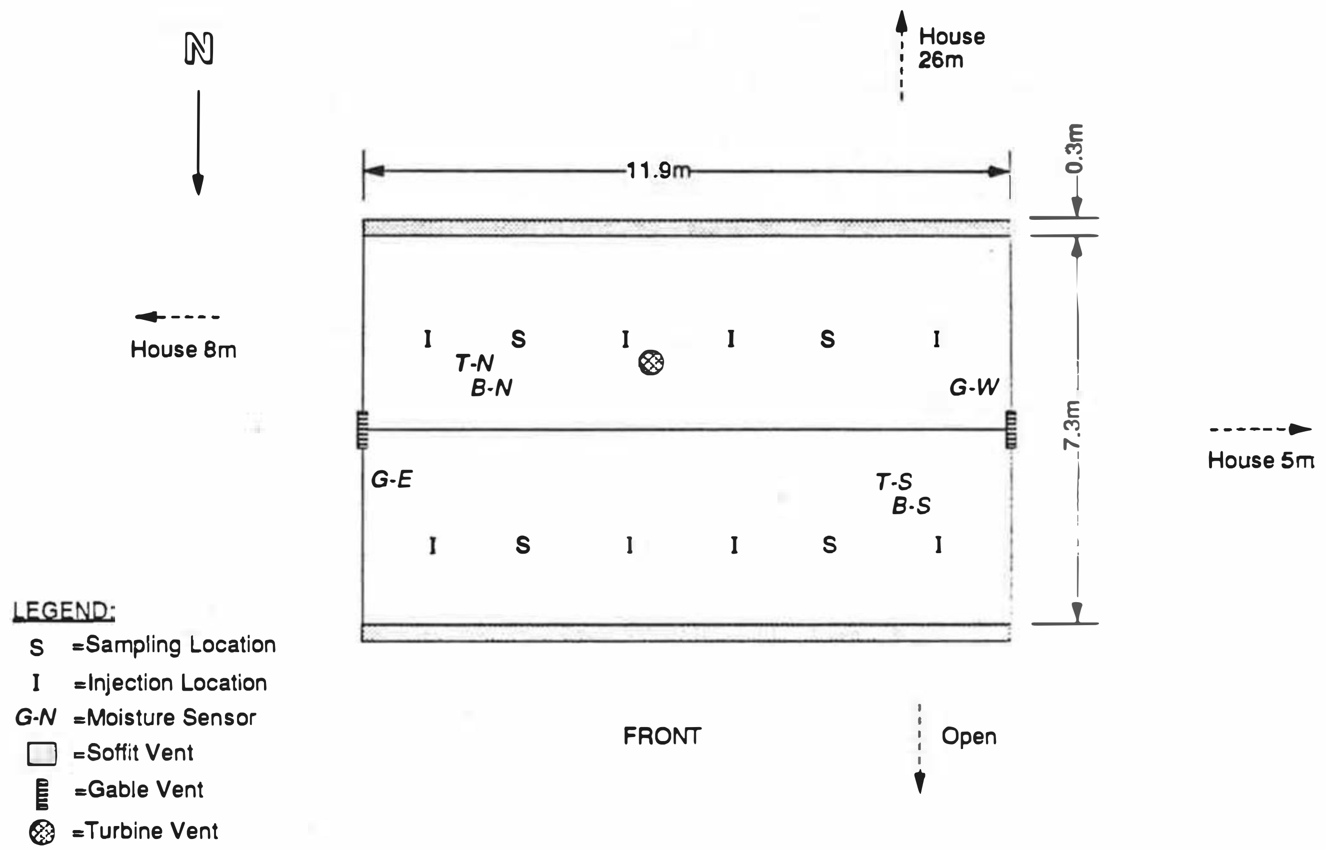


Relative Humidity and Average Lumber Moisture Content Curves: House O-4



HOUSE O-5
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.3 m	Types:	soffit, gable, turbine
Age:	1972	Volume:	61 m^3	Free venting area (approx.):	3400 m^2
Type:	1 storey	Ceiling area:	87 m^2		
Roof		Insulation:	RSI 3.3 glass fibre batt	**Further Relevant Information**	
Type:	gable, mansard	Vapour barrier:	yes		Bathroom fan vented into attic
Sheathing:	waferboard				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

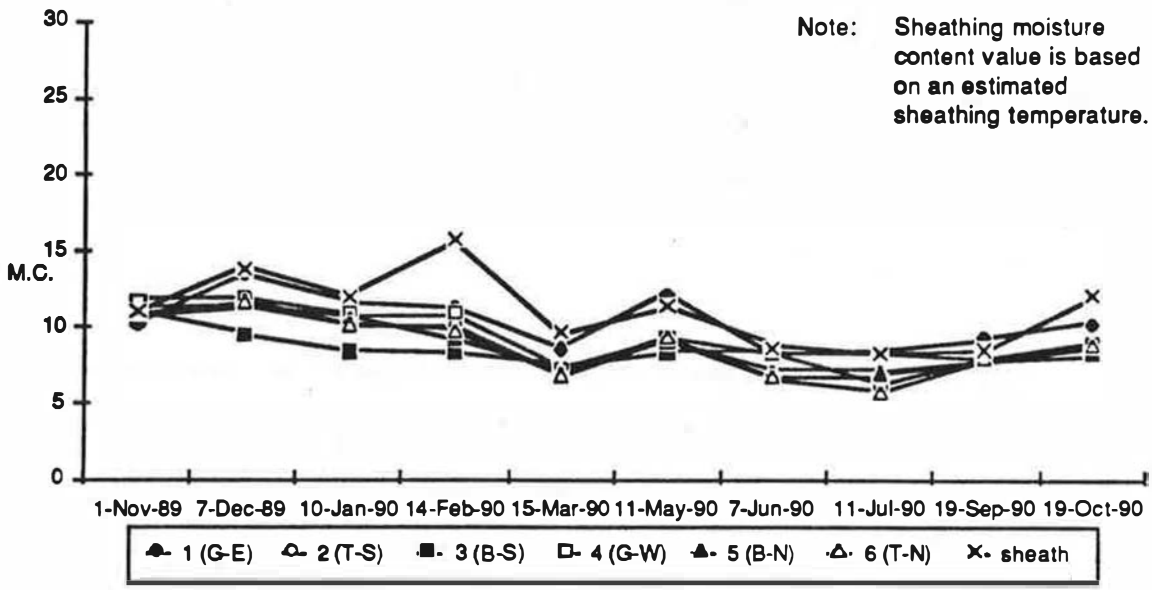
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	14-Feb-90	6	NW	-7	6	19	14.2	N/A
2	11-Jul-90	13	WNW	24	35	20	6.2	N/A

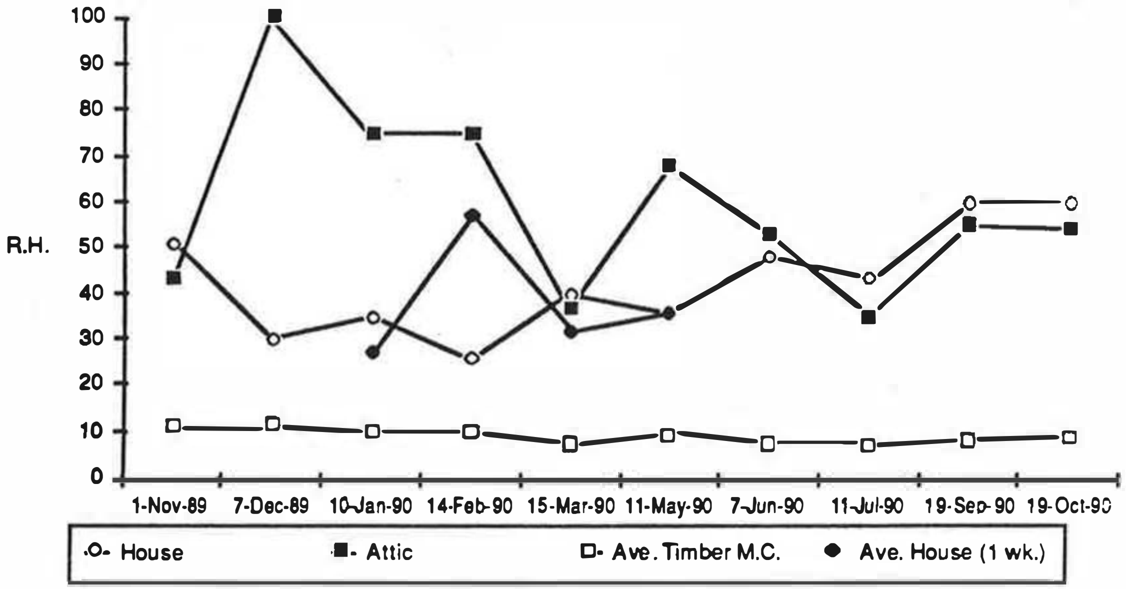
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
12	2500	300

Moisture Curves: House O-5

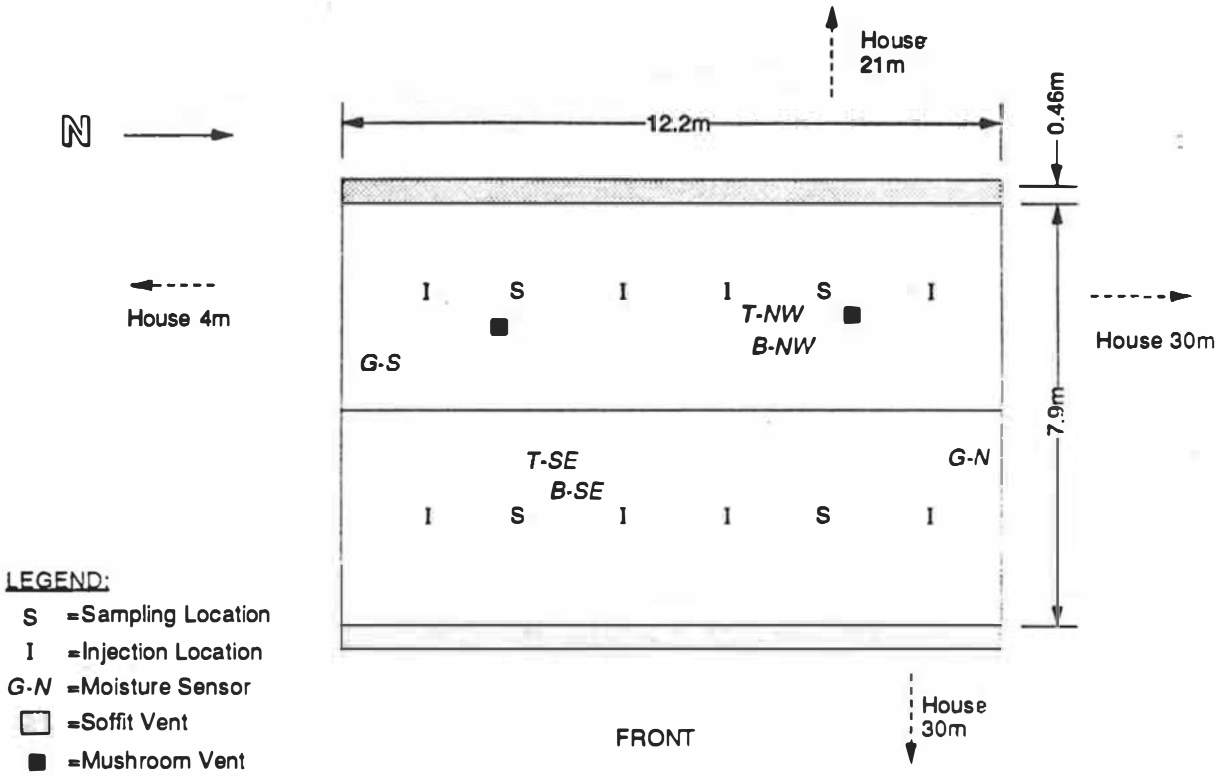


Relative Humidity and Average Lumber Moisture Content Curves: House O-5



HOUSE O-6
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.5 m	Types:	soffit 2 mushroom
Age:	1988	Volume:	79 m^3	Free venting area (approx.):	6100 cm^2
Type:	2 storeys	Ceiling area:	97 m^2		
Roof		Insulation:	RSI 7.6 blown glass fibre		
Type:	gable	Vapour barrier:	yes		
Sheathing:	waferboard				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

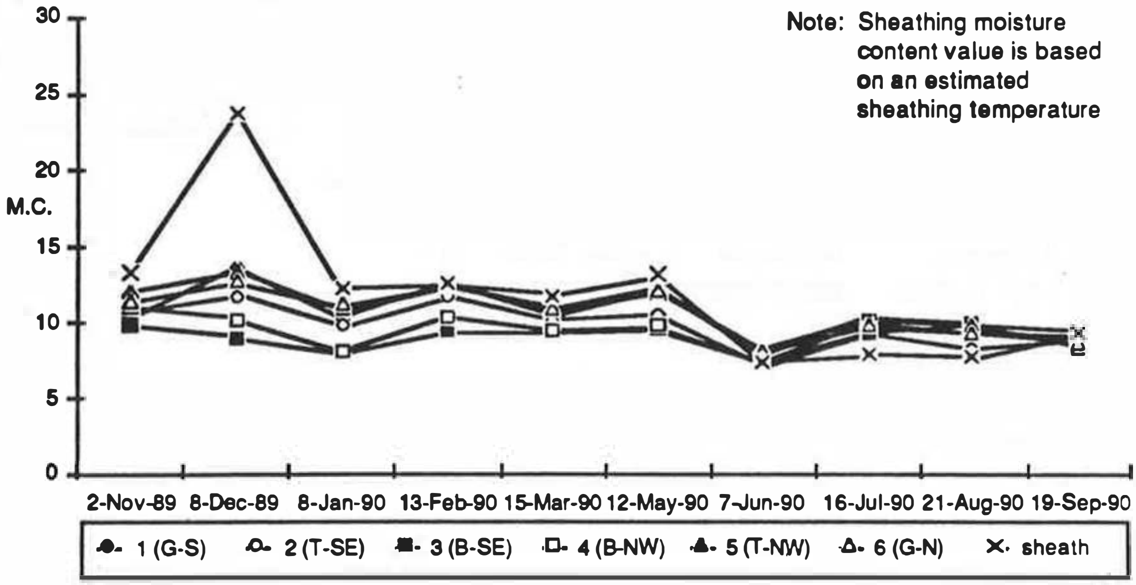
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	13-Feb-90	10	S-W	-3	2	18	5.8	N/A
2	16-Jul-90	26	SW	25	30	20	19	N/A

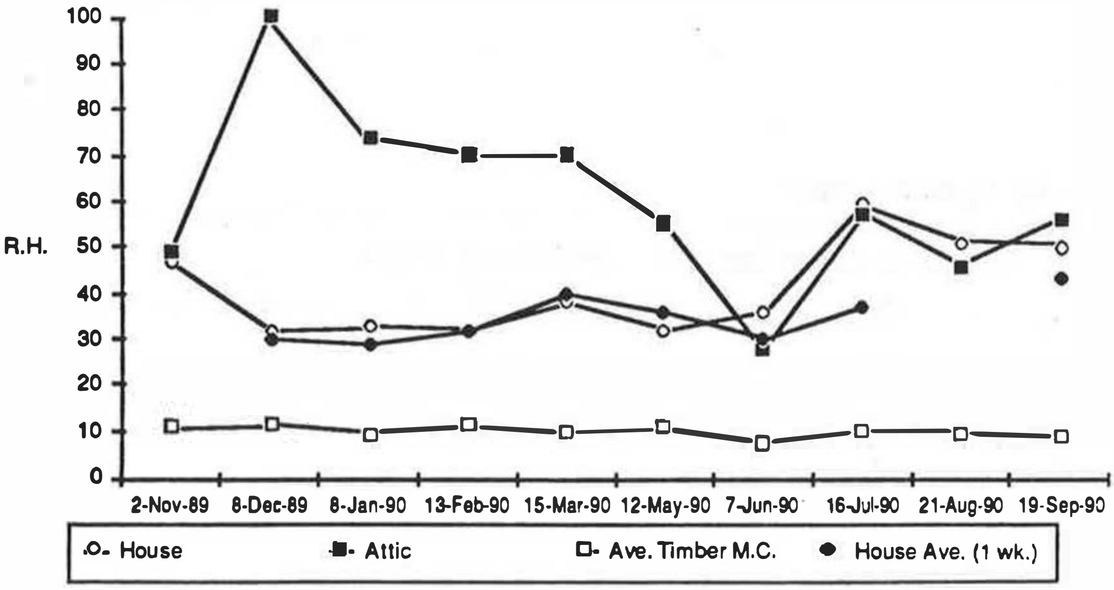
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
12	4700	330

Moisture Curves: House O-6

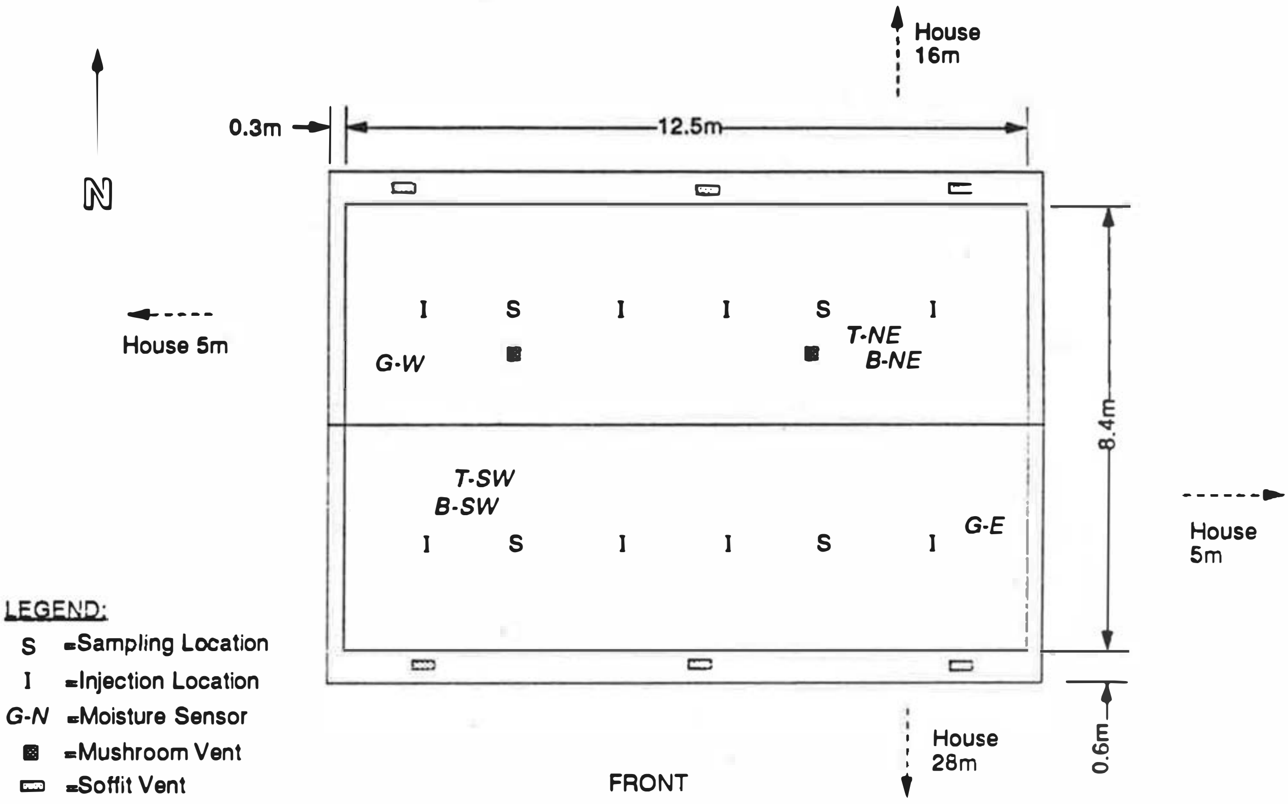


Relative Humidity and Average Lumber Moisture Content Curves: House O-6



HOUSE O-7
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.4 m	Types:	6 soffit 2 mushroom
Age:	1968	Volume:	82 m^3	Free venting area (actual.):	1500 cm^2
Type:	1 storey	Ceiling area:	105 m^2		
Roof		Insulation:	RSI 3.1 glass fibre batt		
Type:	gable	Vapour barrier:	yes		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

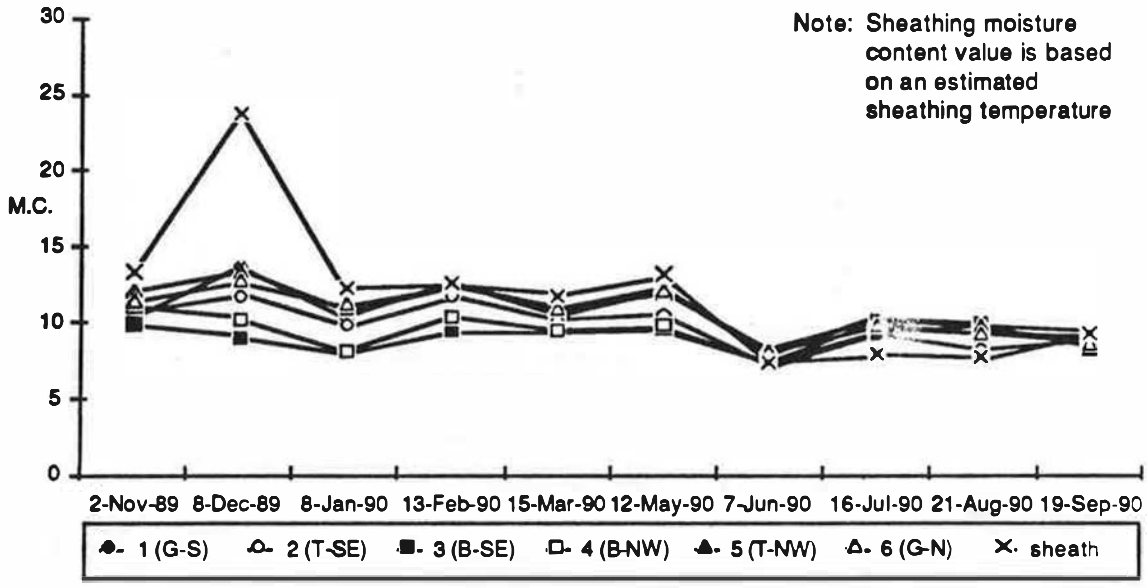
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	14-Feb-90	19	NW	-3	0	20	4.4	N/A
2	18-Jul-90	30	SW	31	42	29	3.8	N/A

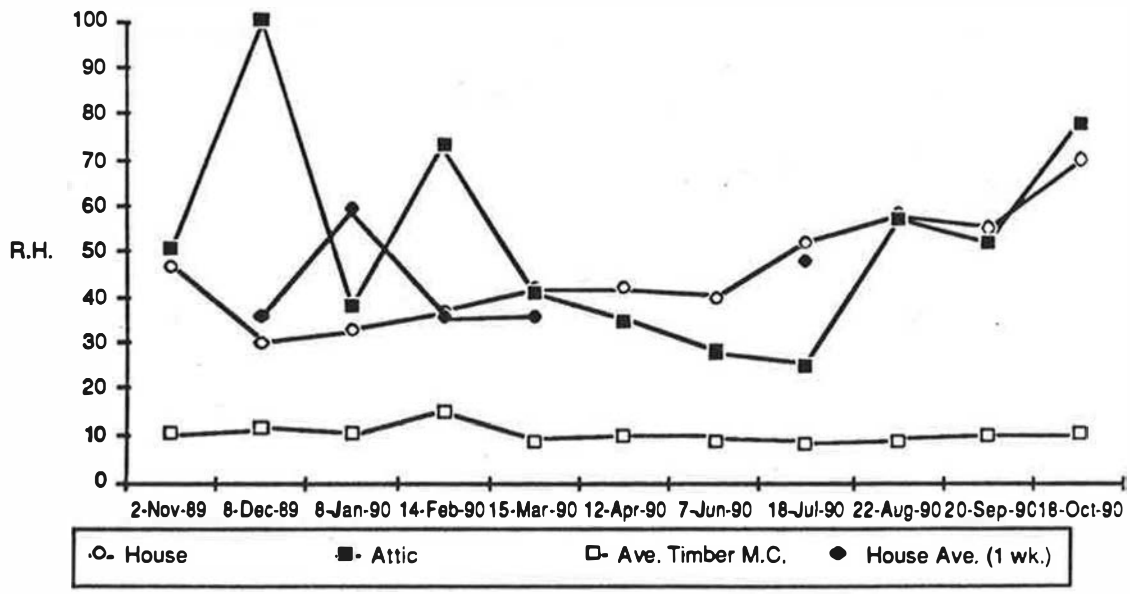
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
6	2300	400

Moisture Curves: House O-7

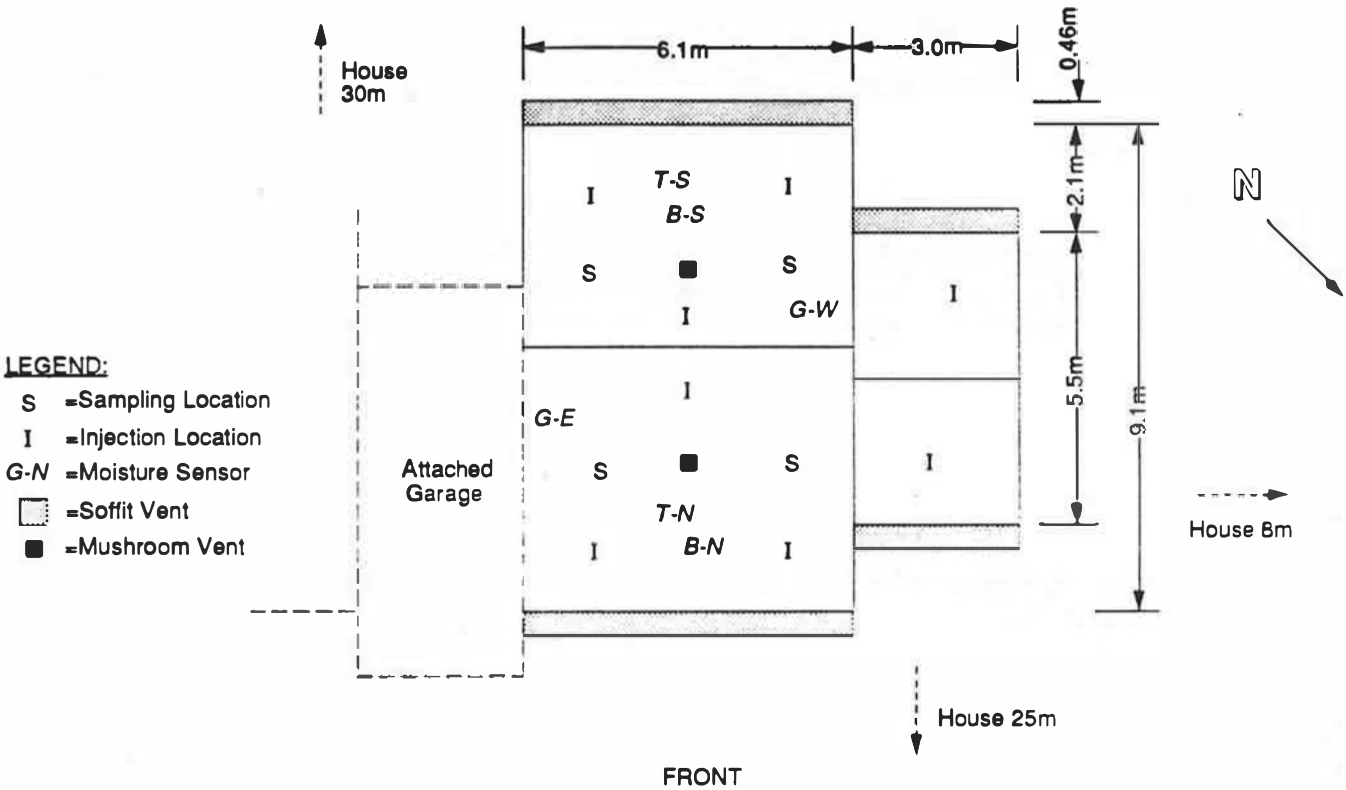


Relative Humidity and Average Lumber Moisture Content Curves: House O-7



HOUSE O-8
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.6 m	Types:	soffit 2 mushroom
Age:	1971	Volume:	56 m^3	Free venting area (approx.):	2500 cm^2
Type:	2 storeys	Ceiling area:	74 m^2		
Roof		Insulation:	RSI 5.5 glass fibre batt		
Type:	gable	Vapour barrier:	no		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

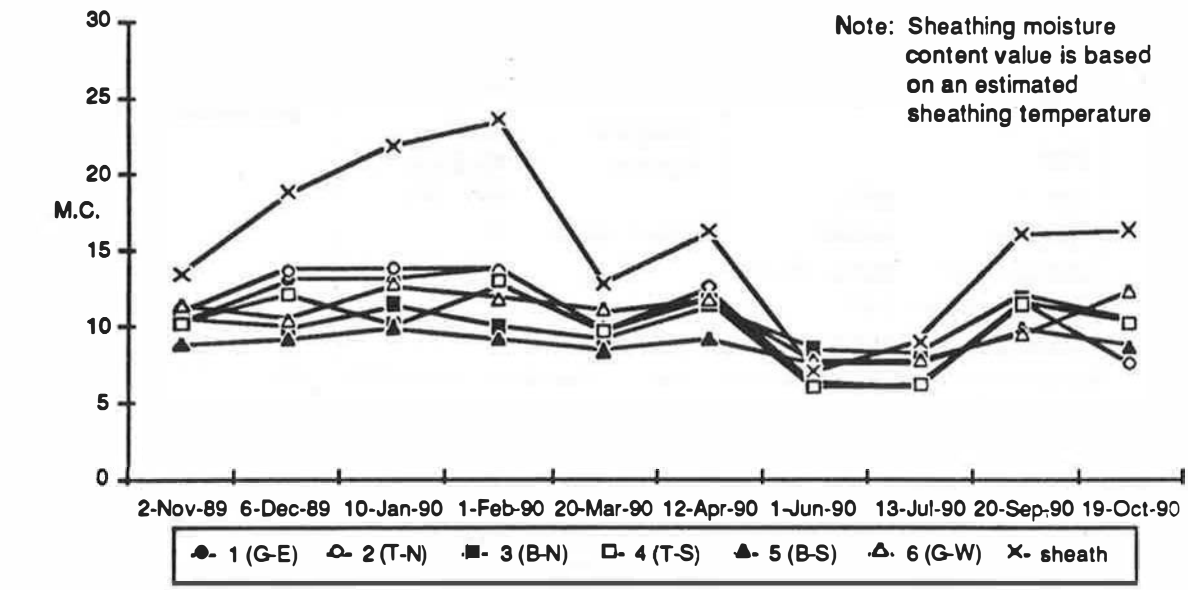
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH	L/s)	Average Interface Leakage (L/s)
1	1-Feb-90	15	S	0	7	18	11.7	184	N/A
2	1-Jun-90	30	SW	28	37	22	16.8	264	N/A
3	13-Jul-90	9	SE	25	41	24	4.3	67	N/A
4	18-Jul-90	20	SSW	30	37	21	33	518	N/A
5	20-Mar-90	15	N	4	11	18	5.9	93	11.3
6	7-Aug-90	6	W	20	24	21	4.5	71	7.1

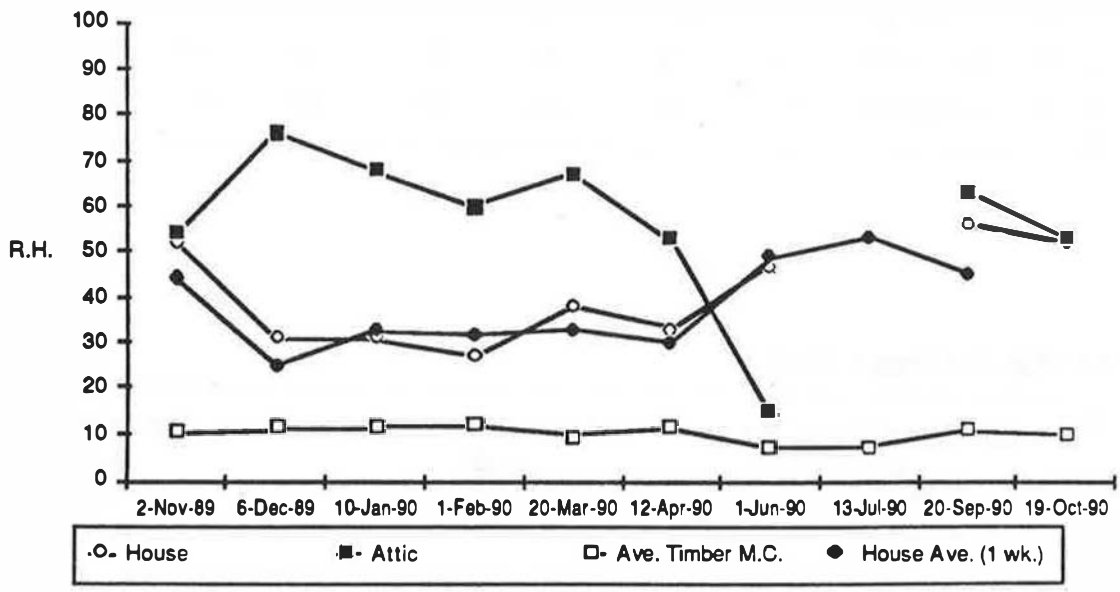
Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
10	5100	280

Moisture Curves: House O-8

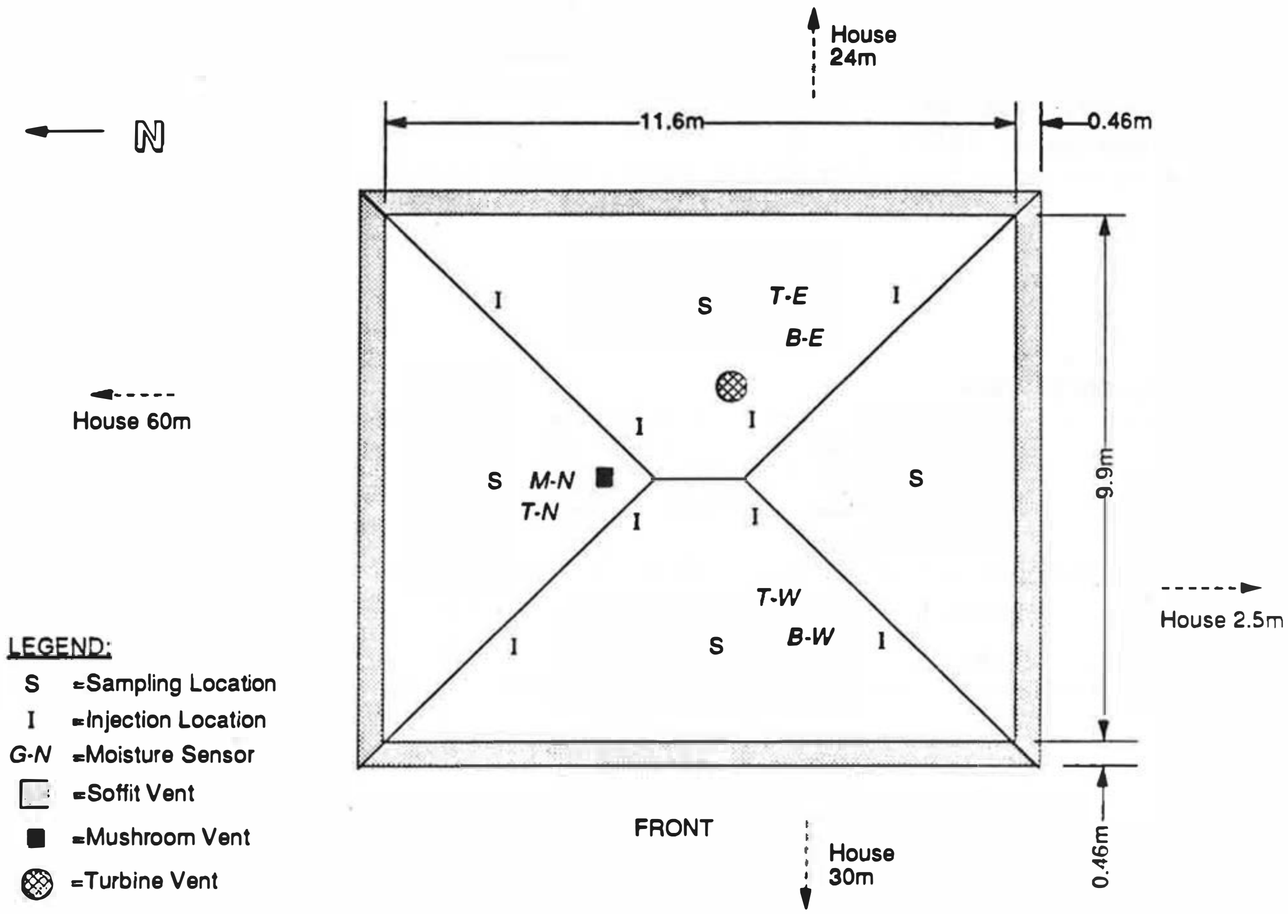


Relative Humidity and Average Lumber Moisture Content Curves: House O-8



HOUSE O-9
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.8 m	Types:	soffit
Age:	1960	Volume:	78 m^3		mushroom
Type:	1 storey	Ceiling area:	111 m^2		turbine
Roof		Insulation:	RSI 3.3 glass fibre with RSI 3.1 blown cellulose	Free venting area (approx.):	6200 cm^2
Type:	hip	Vapour barrier:	none		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

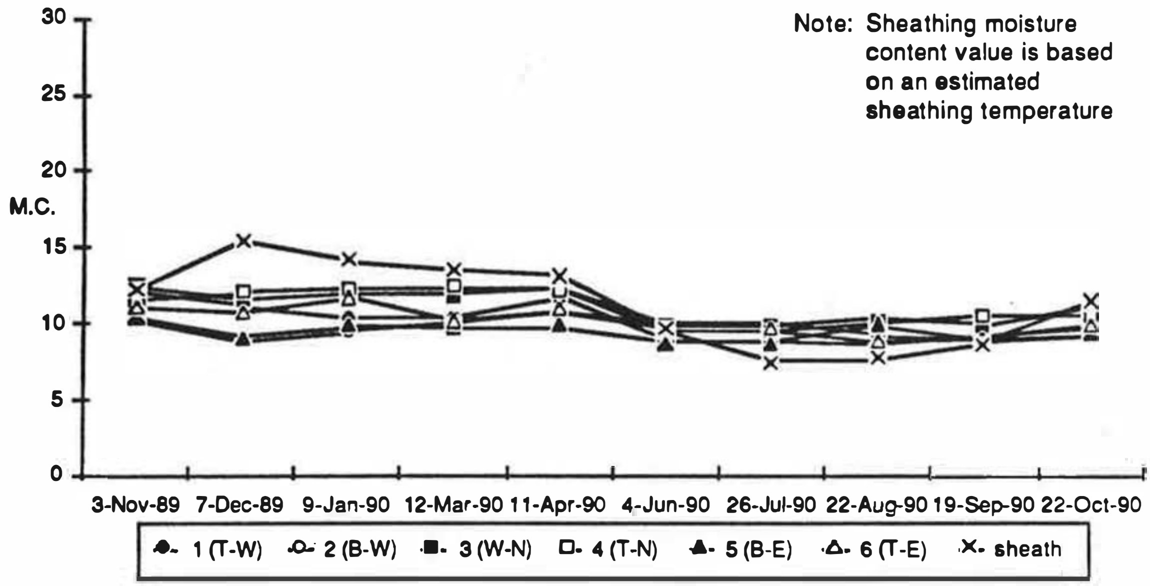
Air Change Data

Test	*Date*	*Average Wind Speed (kph)*	*Wind Direction*	*Outside Temp (T_o) (°C)*	*Attic Temp (T_a) (°C)*	*House Temp (°C)*	*Attic Air Change (ACH)*	*Average Interface Leakage (L/s)*
1	12-Mar-90	15	ENE	6	11	19	8.9	N/A
2	26-Jul-90	9	W	26	27	21	3	N/A

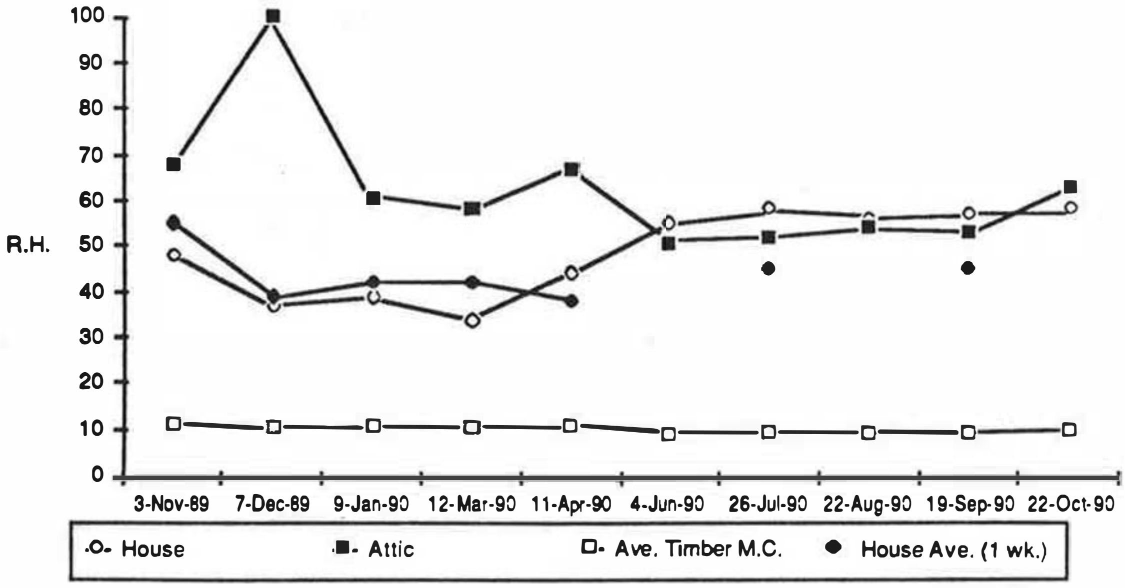
Attic Air Tightness Data

Wind Speed During Test kph	*Attic Ventilation ELA cm^2*	*Interface ELA cm^2*
8	3900	450

Moisture Curves: House O-9

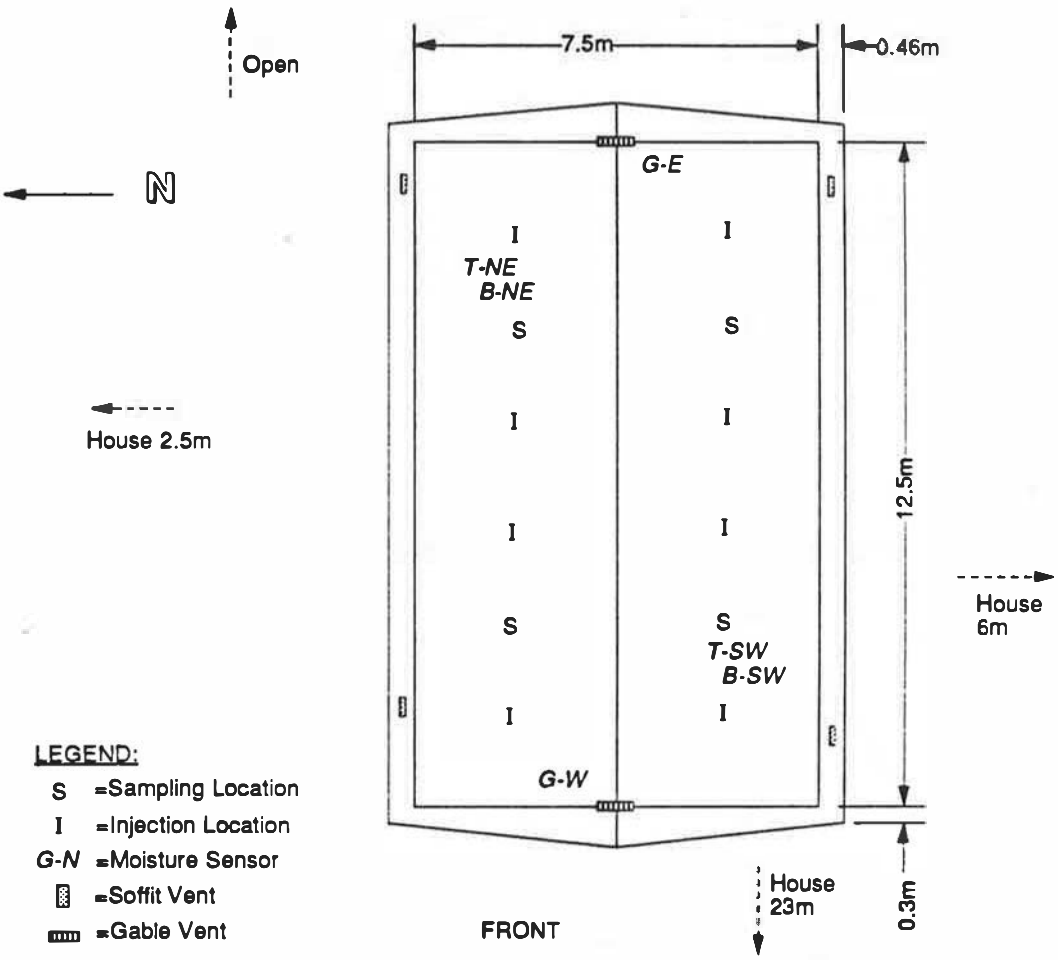


Relative Humidity and Average Lumber Moisture Content Curves: House O-9



HOUSE O-10
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.8 m	Types:	soffit gable
Age:	1960	Volume:	92 m^3	Free venting area (actual.):	1900 cm^2
Type:	1 storey	Ceiling area:	93 m^2		
Roof		Insulation:	RSI 5.0 blown cellulose loose fill		
Type:	gable	Vapour barrier:	none		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

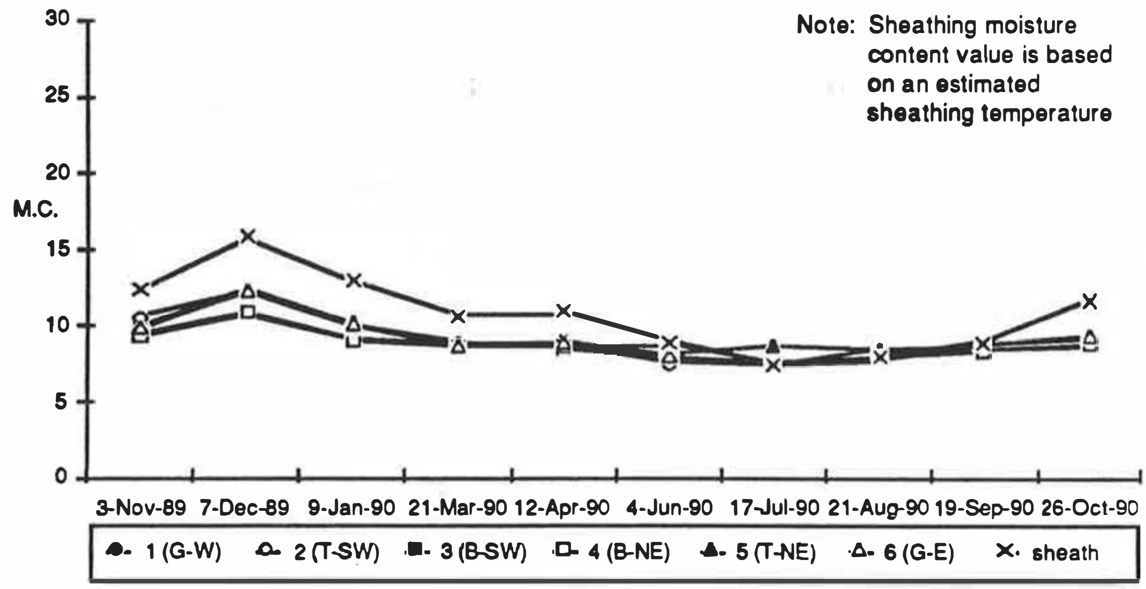
Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH	L/s)	Average Interface Leakage (L/s)
1	18-Jan-90	19	SSW	4	7	16	3	77	N/A
2	17-Jul-90	20	SW	26	35	25	1.9	48	N/A
3	19-Jul-90	26	W	25	40	24	1.6	41	N/A
4	20-Jul-90	11	W	20	22	20	1.1	28	N/A
5	21-Mar-90	30	W	6	21	18	3.5	89	3.3
6	2-Aug-90	17	WSW	28	49	20	1.6	41	0.9

Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
15	2200	280

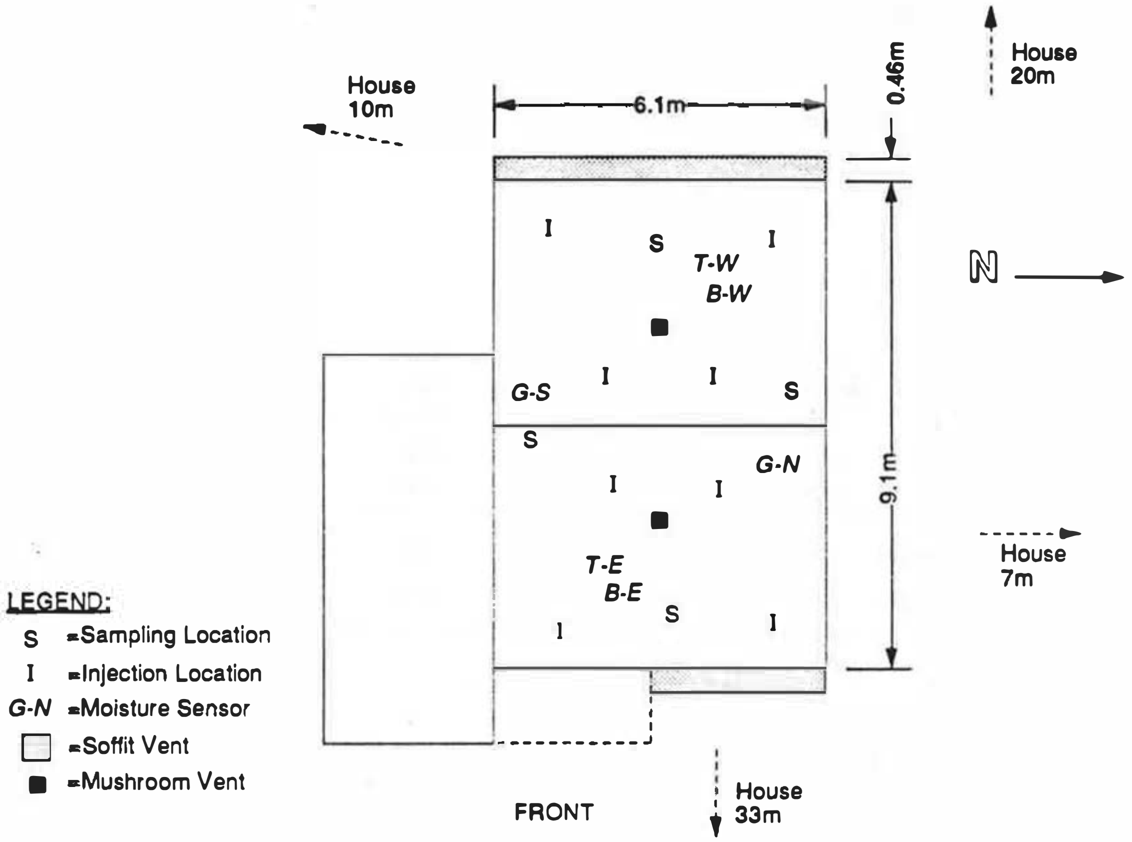
Moisture Curves: House O-10



Relative Humidity and Average Lumber Moisture Content Curves: House O-10

HOUSE O-11
HOUSE CHARACTERISTICS

Site Plan



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.6 m	Types:	soffit 2 mushroom
Age:	1985	Volume:	50 m^3	Free venting area (approx.):	2300 cm^2
Type:	2 storeys	Ceiling area:	55.7 m^2		
Roof		Insulation:	RSI 5.0 blown glass fibre		
Type:	hip	Vapour barrier:	yes		
Sheathing:	waferboard				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

Air Change Data

Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	24-Jan-90	30	SSW	5	9	19	11.4	N/A
2	20-Jul-90	13	SW	19	24	22	2.6	N/A

Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
32	1300	350

BUILDING DATA

Building length	[ft]
Building width	[ft]
Grade to ceiling height	[ft]
Roof overhang	[ft]
Roof pitch	[rise/run]
Interface flow/house exfiltration	[h^{-1}]
Windshade factor	[0-1]
Absorptivity	(0.9)
House air change rate	[ach]
R ceiling	[h.ft sq F/BTU]
R end walls	[h.ft sq F/BTU]
R roof	[h.ft sq F/BTU]
House temperature	[R]
RH house	[%]
Sheathing M.C. "A"	[%]
Sheathing M.C. "B"	[%]
Attic exhaust fan rate	[cfm]
Attic air change	[ach]
Vent area/ceiling area	[ft^2]

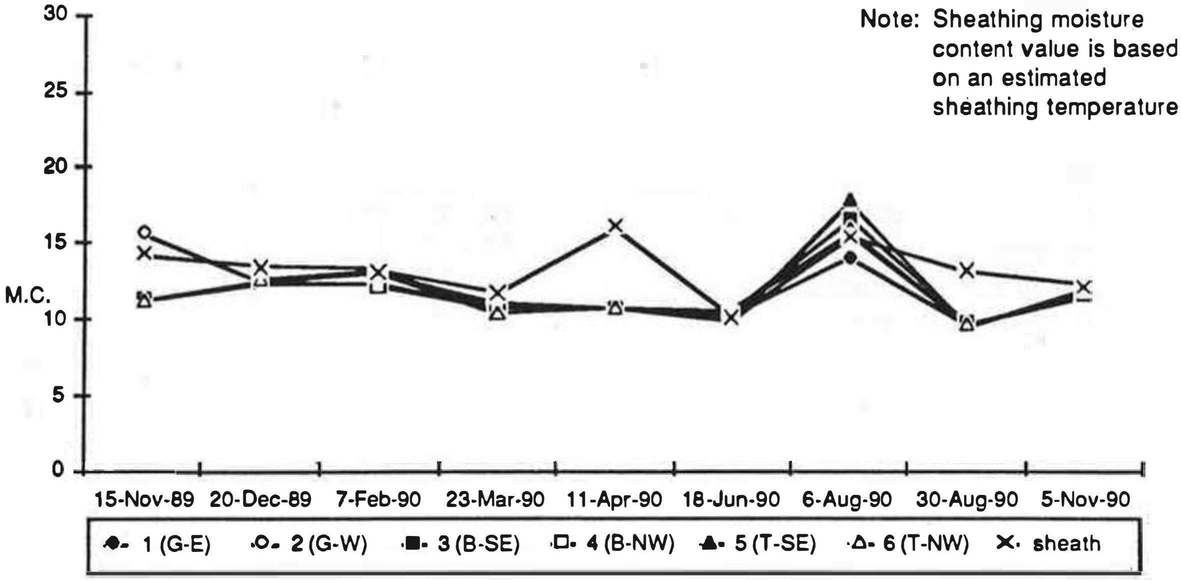
FILE FORMATS

All input files ASCII format. Records 24 numbers, comma separated. Records delimited by a CR/LF sequence. No file name convention required.

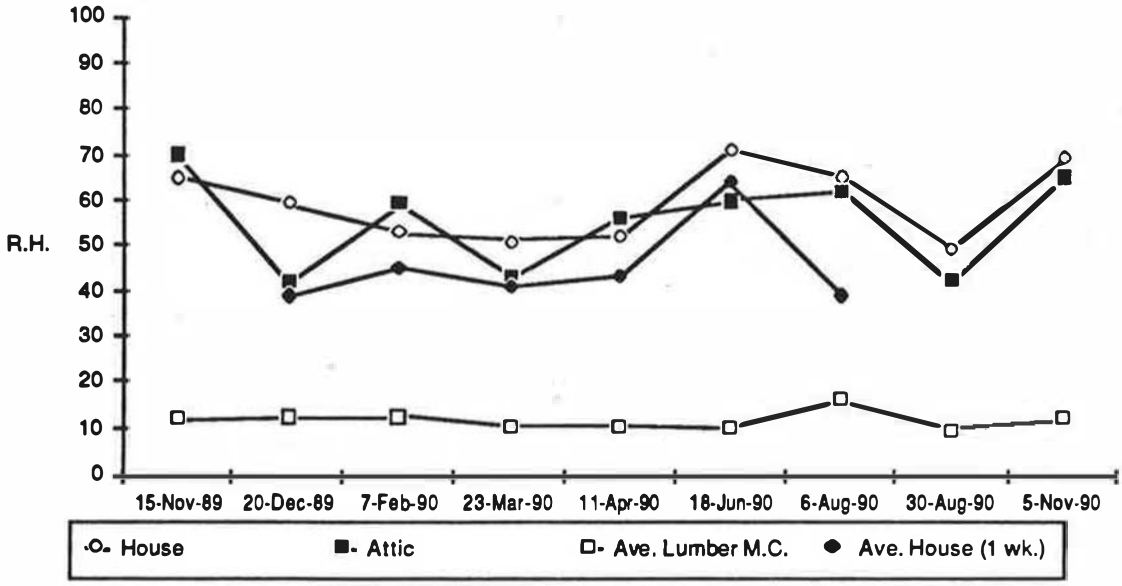
Appendix C

FOREST PRODUCTS LABORATORY DETAILED MODEL INPUTS

Moisture Curves: House M-5



Relative Humidity and Average Lumber Moisture Content Curves: House M-5



House Data

General		Attic		Venting	
Location:	Charlottetown	Ceiling to ridge height:	1.2 m	Types:	gable, turbine
Age:	1975	Volume:	67 m^3	Free venting area (actual):	1600 cm^2
Type:	1 storey	Ceiling area:	101 m^2		
Roof		Insulation:	RSI 3.3 glass fibre batts with RSI 3.0 rock wool loose fill		
Type:	gable	Vapour barrier:	4 mil poly		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	spruce				
Lumber species:	spruce				

Air Change Data

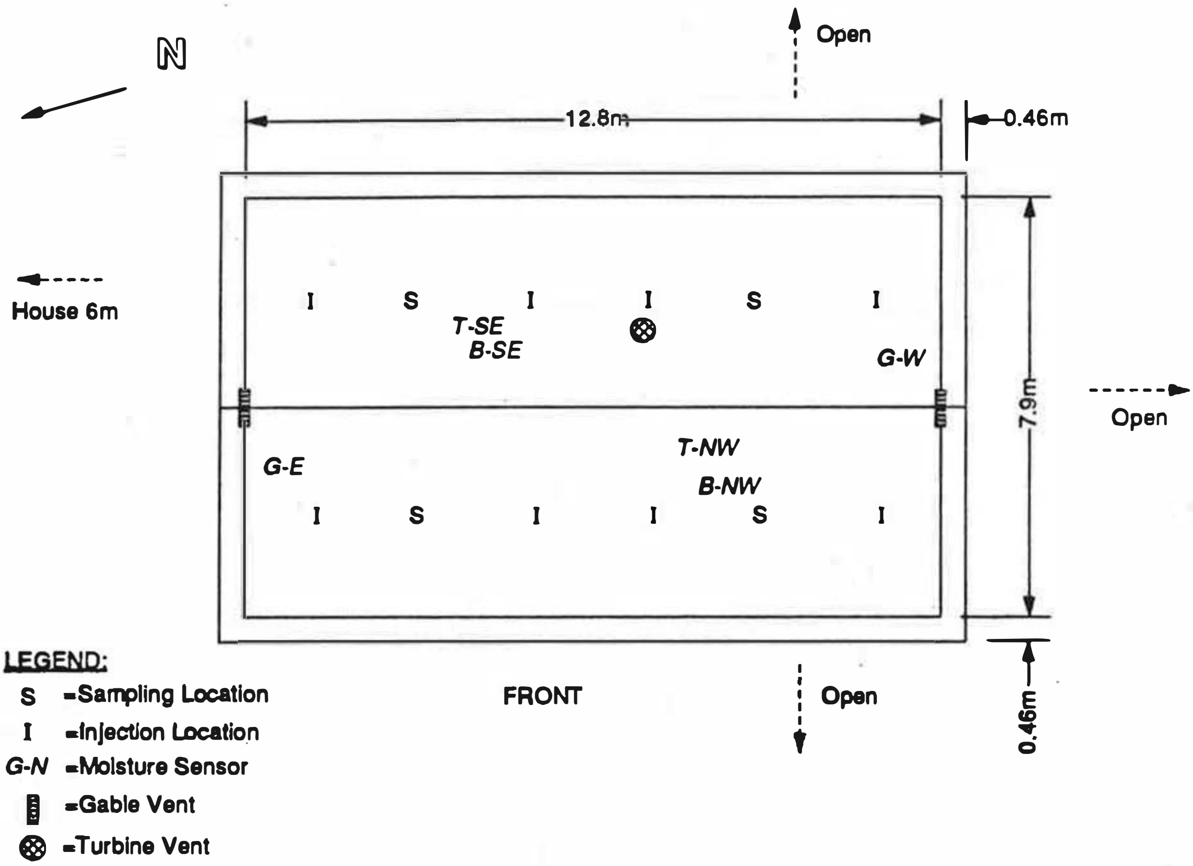
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	7-Feb-90	11	SSW	-7	2	18	9.5	N/A
2	18-Jun-90	28	SW	20	27	18	23	N/A

Attic Air Tightness Data

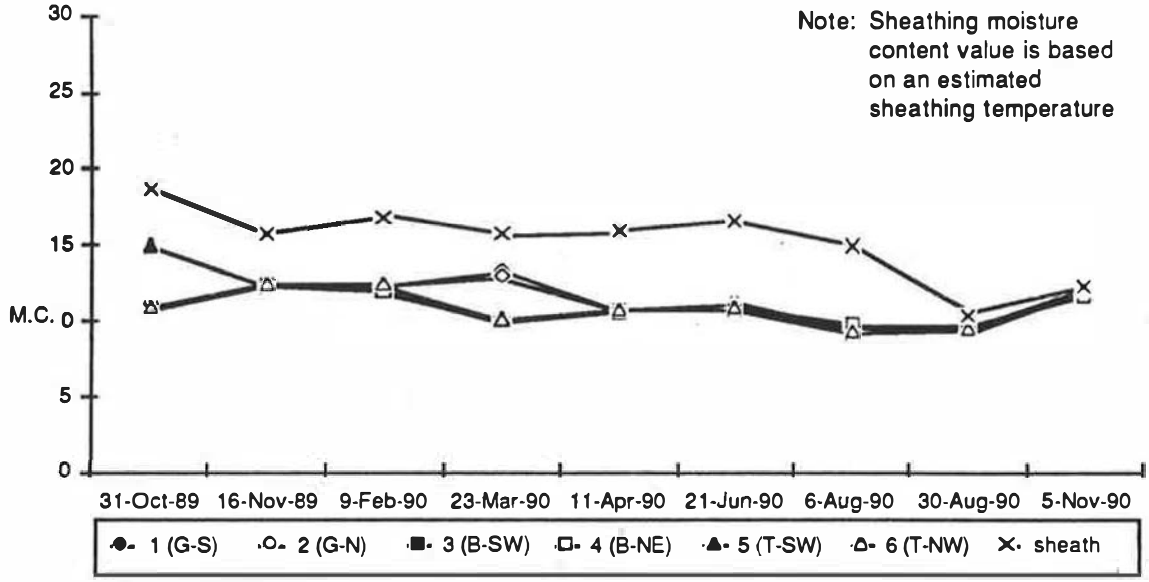
Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
25	1600	460

HOUSE M-5
HOUSE CHARACTERISTICS

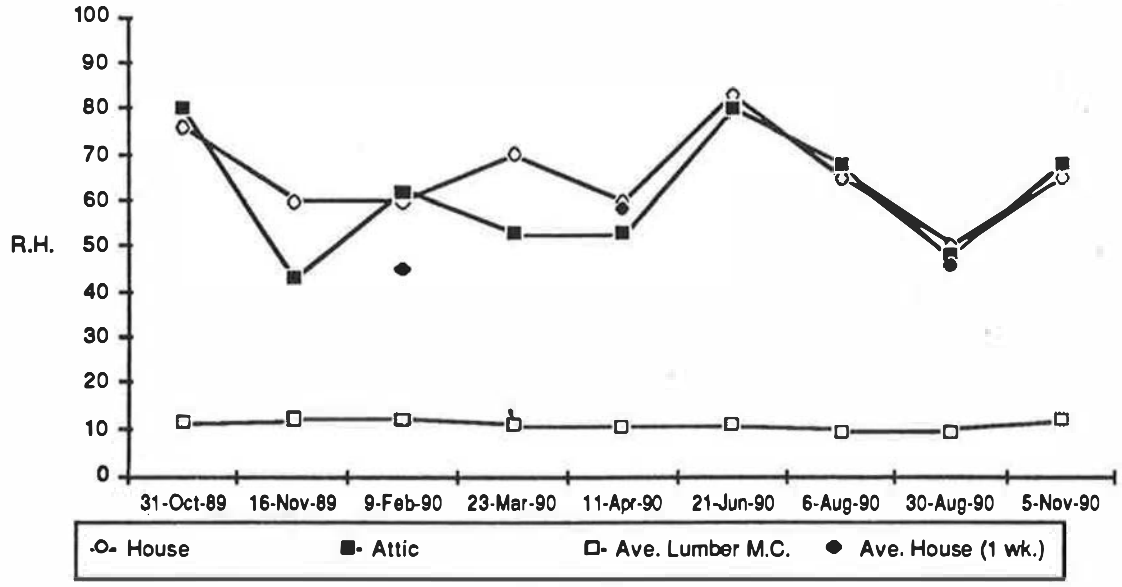
Site Plan



Moisture Curves: House M-4



Relative Humidity and Average Lumber Moisture Content Curves: House M-4



House Data

General		Attic		Venting	
Location:	Charlottetown	Ceiling to ridge height:	1.5 m	Types:	gable
Age:	1964	Volume:	113 m^3	Free venting area (actual):	1000 cm^2
Type:	1 storey	Ceiling area:	136 m^2		
Roof		Insulation:	RSI 3.0 rock wool loose fill		
Type:	gable	Vapour barrier:	4 mil poly		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	spruce				
Lumber species:	spruce				

Air Change Data

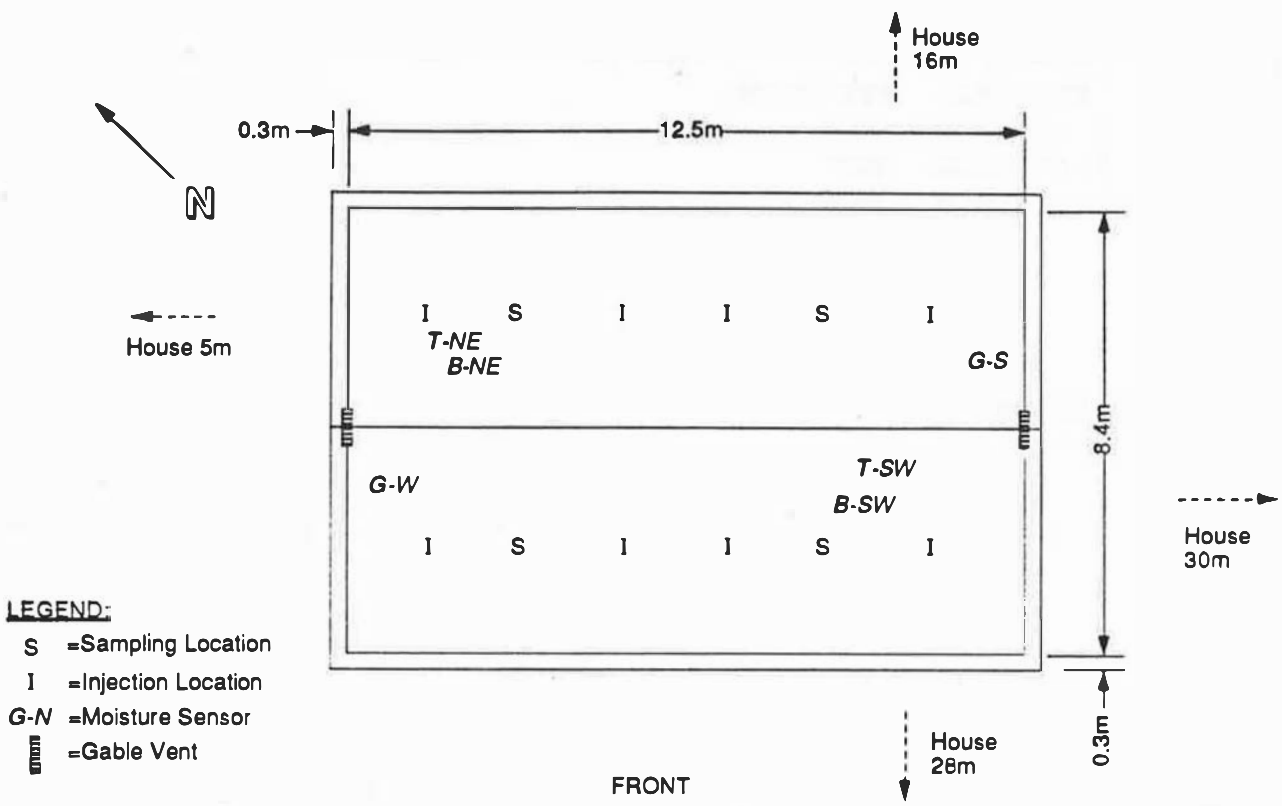
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	9-Feb-90	22	S	1	1	19	6.7	N/A
2	17-Jun-90	15	S	24	33	18	2.1	N/A

Attic Air Tightness Data

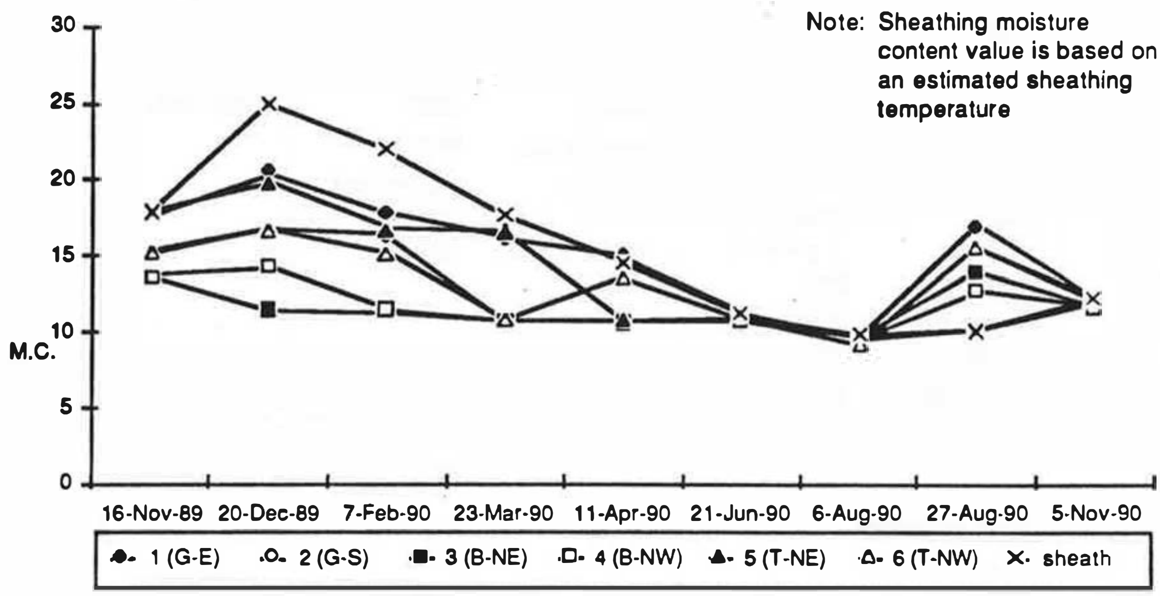
Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
13	3100	380

HOUSE M-4
HOUSE CHARACTERISTICS

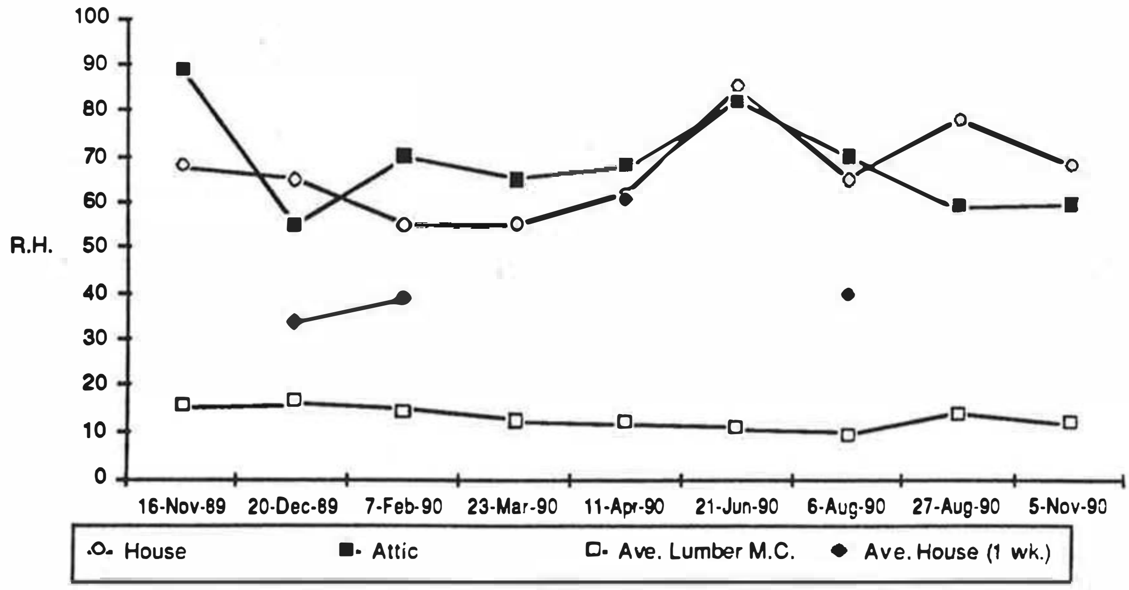
Site Plan



Moisture Curves: House M-3



Relative Humidity and Average Lumber Moisture Content Curves: House M-3



House Data

General		Attic		Venting	
Location:	Charlottetown	Ceiling to ridge height:	2.0 m	Types:	gable
Age:	1956	Volume:	85 m^3	Free venting area (actual):	320 cm^2
Type:	1 storey	Interface area:	97 m^2		
Roof		Insulation:	RSI 4.0 rock wool loose fill		
Type:	gable & hip (L-shaped)	Vapour barrier:	none		
Sheathing:	plank				
Exterior finish:	asphalt shingles				
Sheathing species:	spruce				
Lumber species:	spruce				

Air Change Data

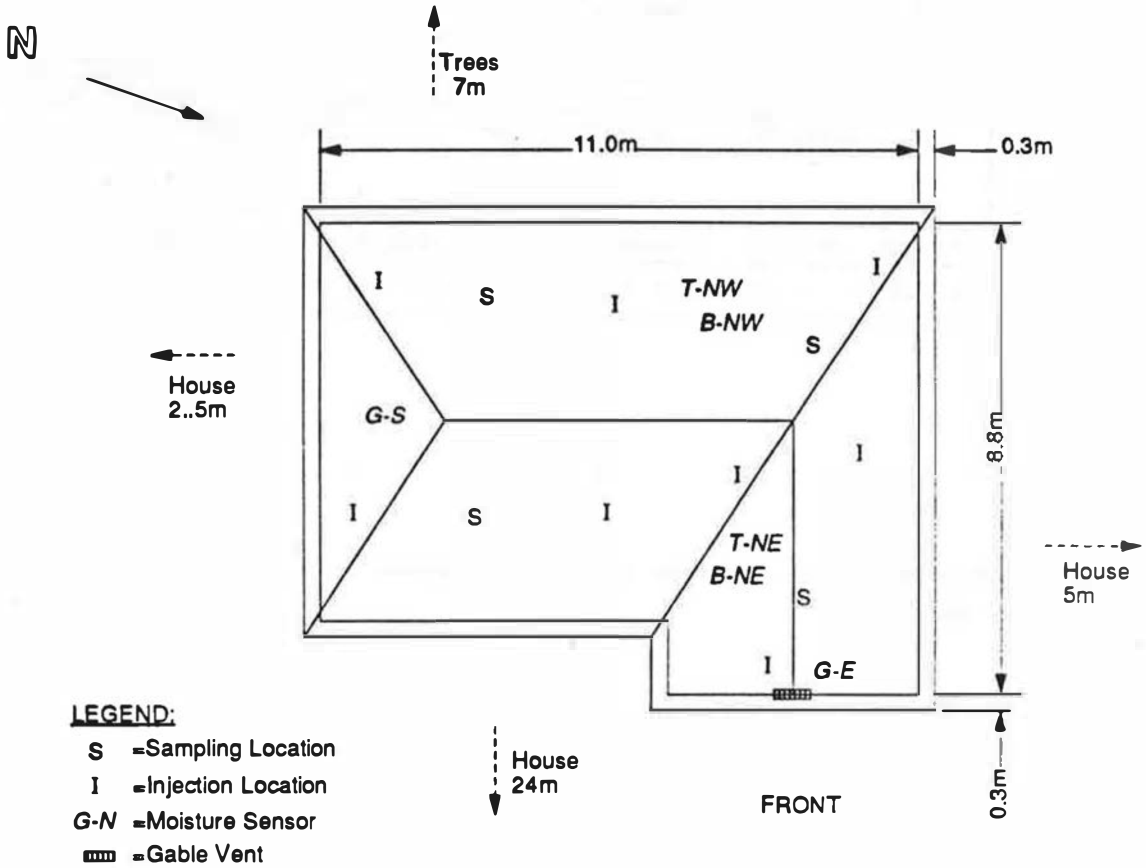
Test	*Date*	*Average Wind Speed (kph)*	*Wind Direction*	*Outside Temp (T_o) (°C)*	*Attic Temp (T_a) (°C)*	*House Temp (°C)*	*Attic Air Change (ACH)*	*Average Interface Leakage (L/s)*
1	7-Feb-90	22	SSW	-7	7	18	6.2	N/A
2	21-Jun-90	11	N	14	16	20	1.9	N/A

Attic Air Tightness Data

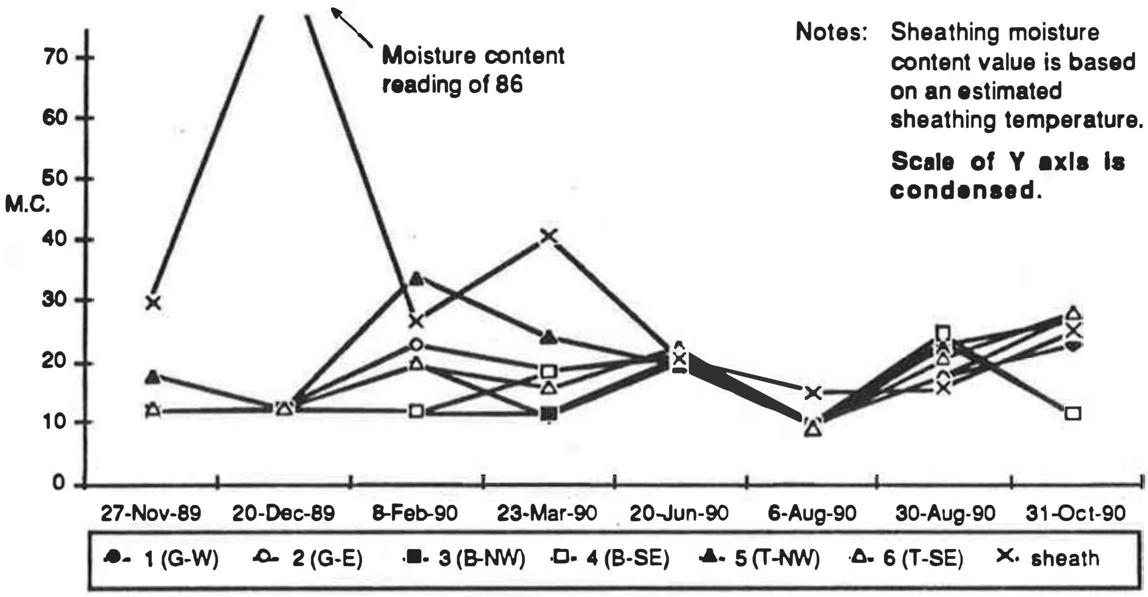
Wind Speed During Test kph	*Attic Ventilation ELA cm^2*	*Interface ELA cm^2*
13	2100	400

HOUSE M-3
HOUSE CHARACTERISTICS

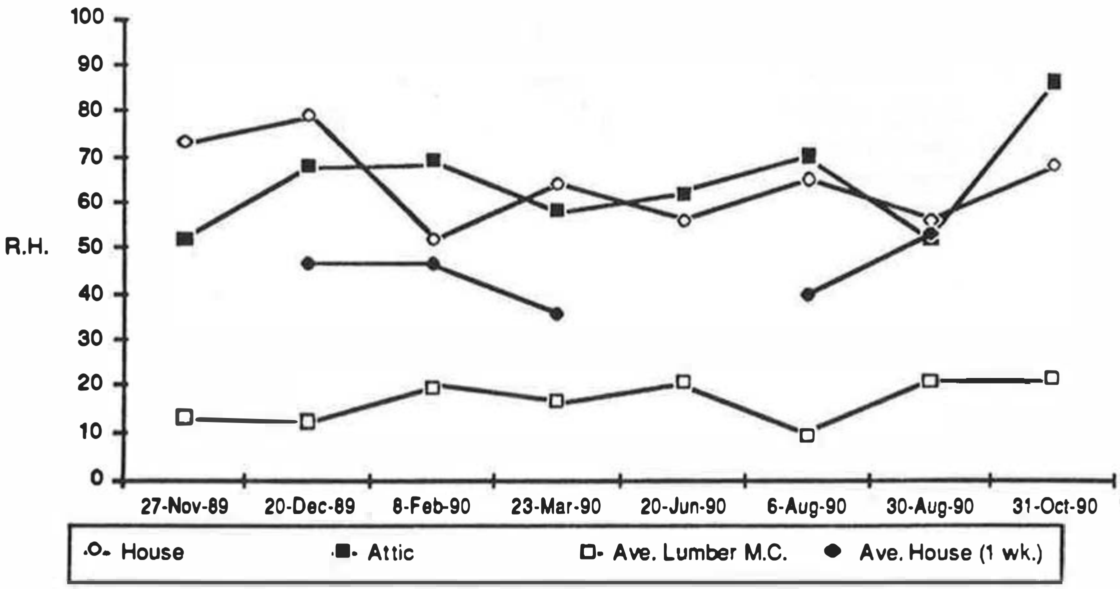
Site Plan



Moisture Curves: House M-2



Relative Humidity and Average Lumber Moisture Content Curves: House M-2



House Data

General		Attic		Venting	
Location:	Charlottetown	Ceiling to ridge height:	1.6 m	Types:	gable
Age:	1979	Volume:	57 m^3	Free venting area (actual.):	570 cm^2
Type:	split level	Ceiling area:	60 m^2		
Roof		Insulation:	RSI 5.0 glass fibre batts		
Type:	gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	fir				
Lumber species:	spruce				

Air Change Data

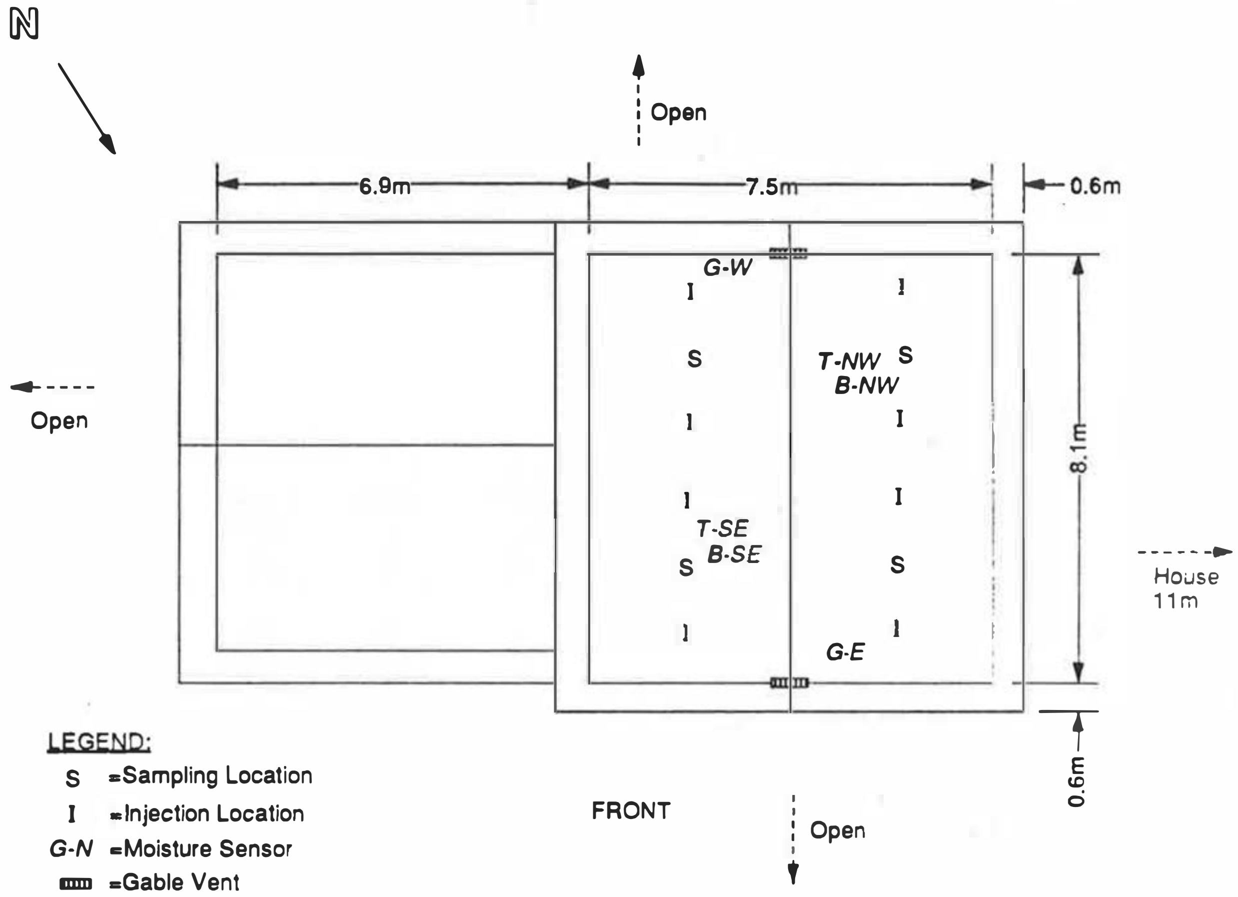
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	8-Feb-90	18	NW	-2	12	19	2.6	N/A
2	20-Jun-90	9	N	15	17	21	2.4	N/A

Attic Air Tightness Data

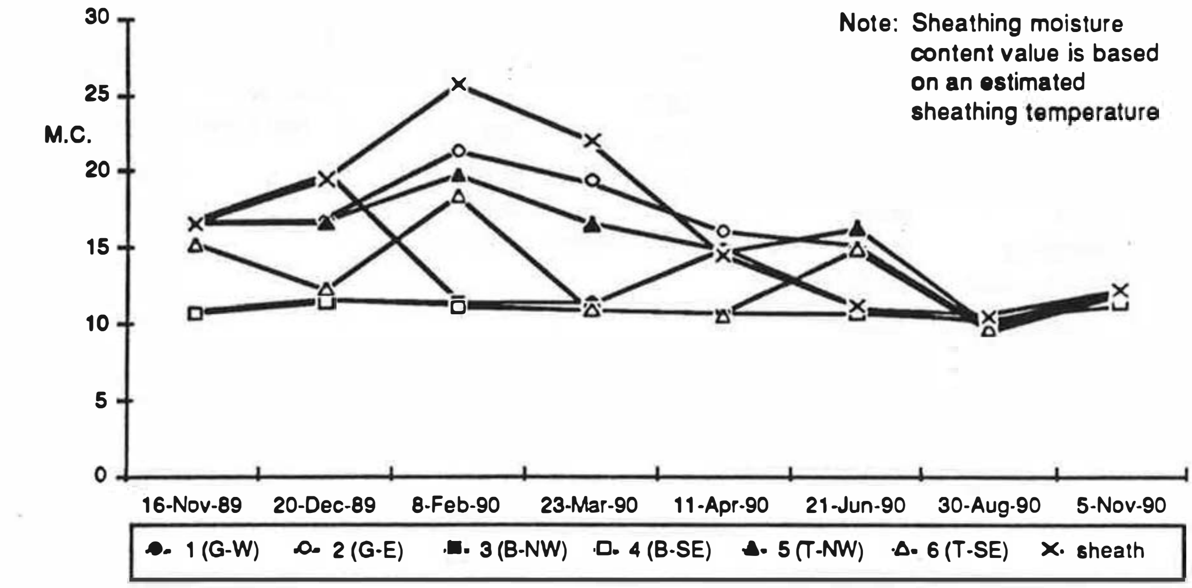
Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
10	820	280

HOUSE M-2
HOUSE CHARACTERISTICS

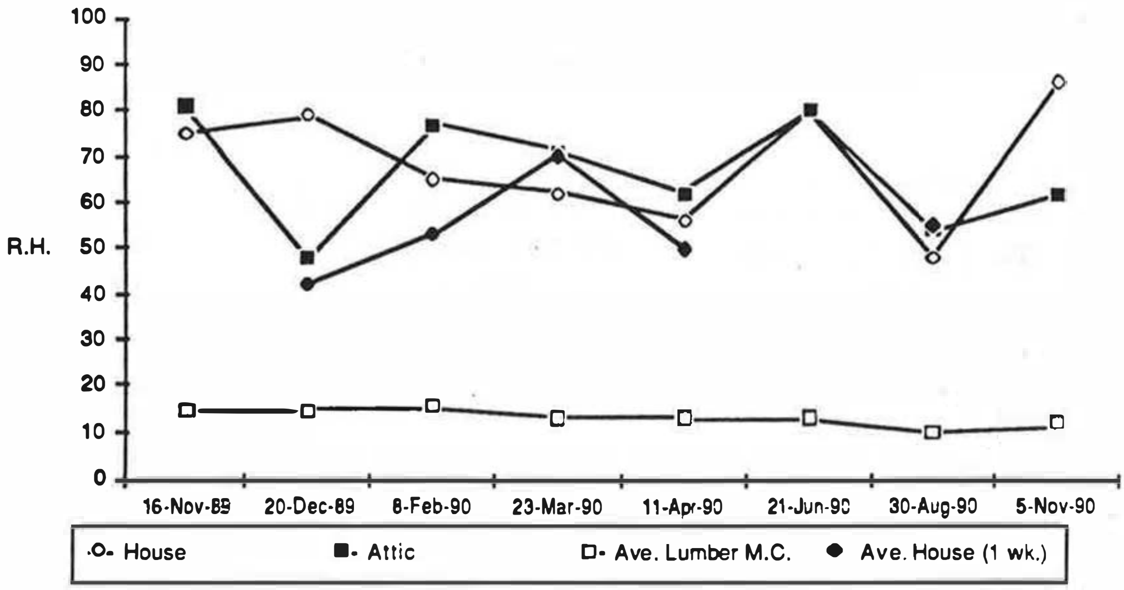
Site Plan



Moisture Curves: House M-1



Relative Humidity and Average Lumber Moisture Content Curves: House M-1



House Data

General		Attic		Venting	
Location:	Charlottetown	Ceiling to ridge height:	1.4 m	Types:	soffit gable
Age:	1971	Volume:	124 m^3	Free venting area (actual.):	1400 cm^2
Type:	1 storey	Ceiling area:	157 m^2		
Roof		Insulation:	RSI 5.0 blown cellulose fibre		
Type:	gable	Vapour barrier:	4 mil poly		
Sheathing:	tongue & groove				
Exterior finish:	asphalt shingles				
Sheathing species:	spruce				
Lumber species:	spruce				

Air Change Data

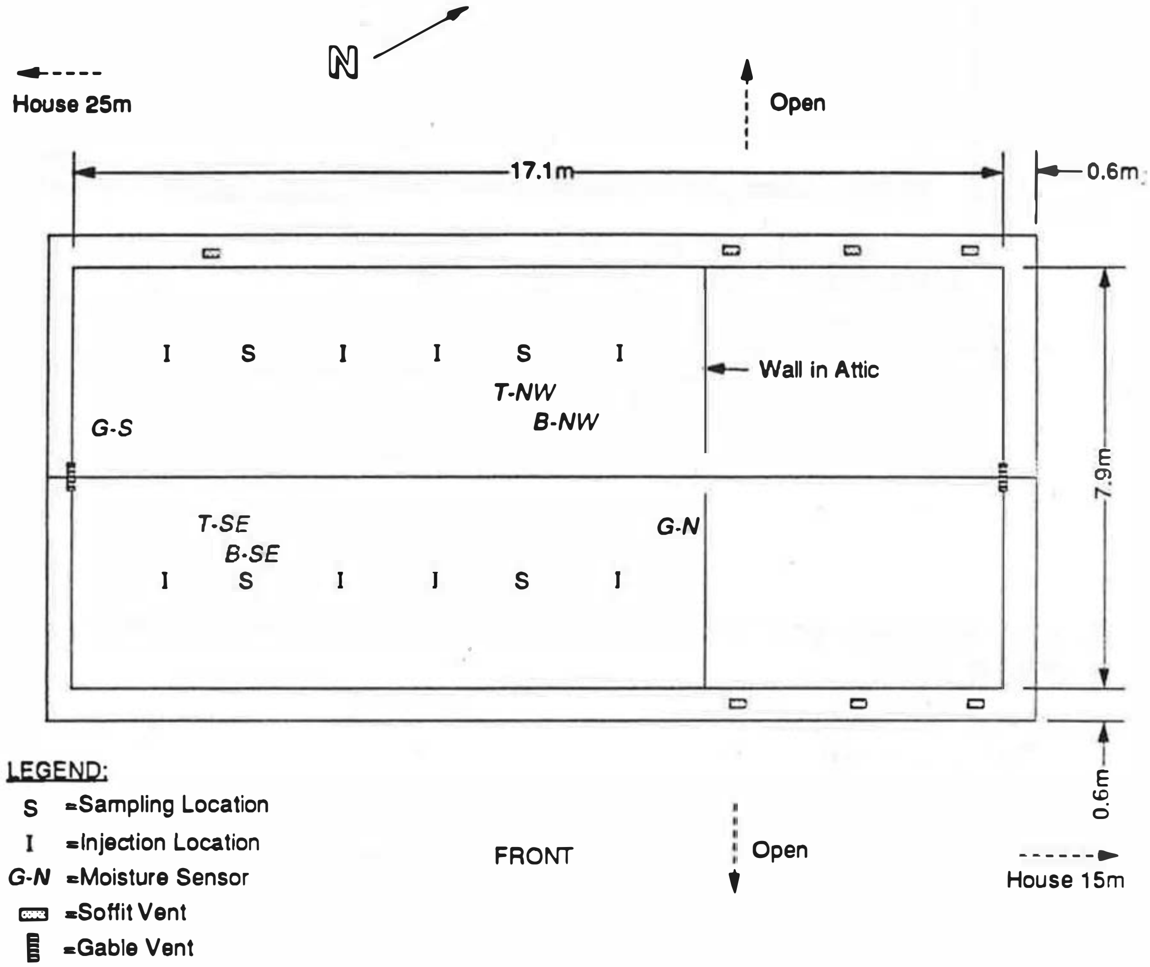
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	8-Feb-90	15	ENE	-5	9	18	2.2	N/A
2	17-Jun-90	17	SSW	25	28	18	1.2	N/A

Attic Air Tightness Data

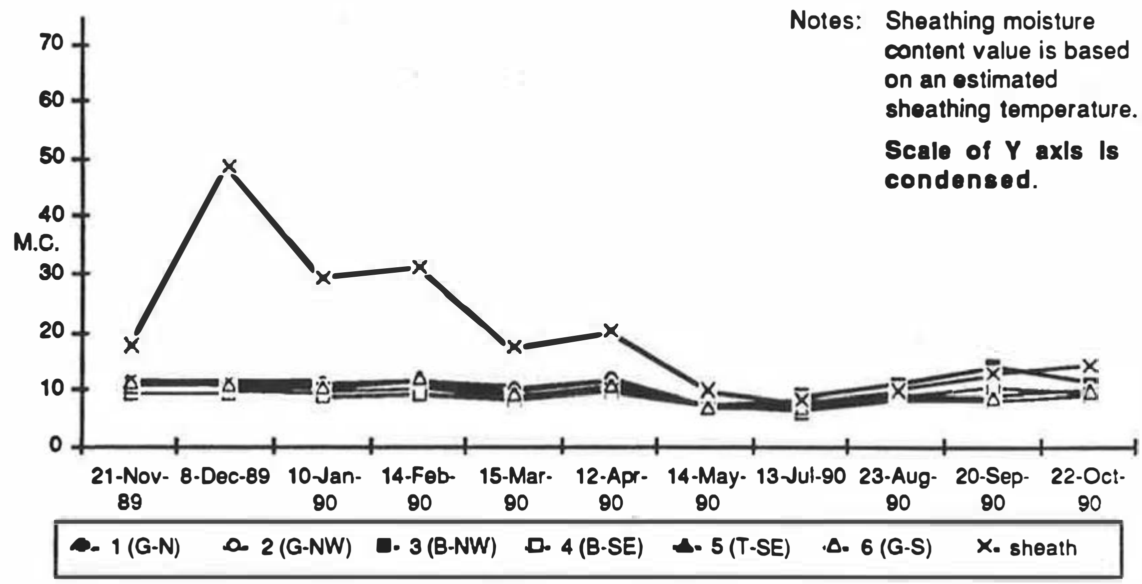
Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
25	1900	330

HOUSE M-1
HOUSE CHARACTERISTICS

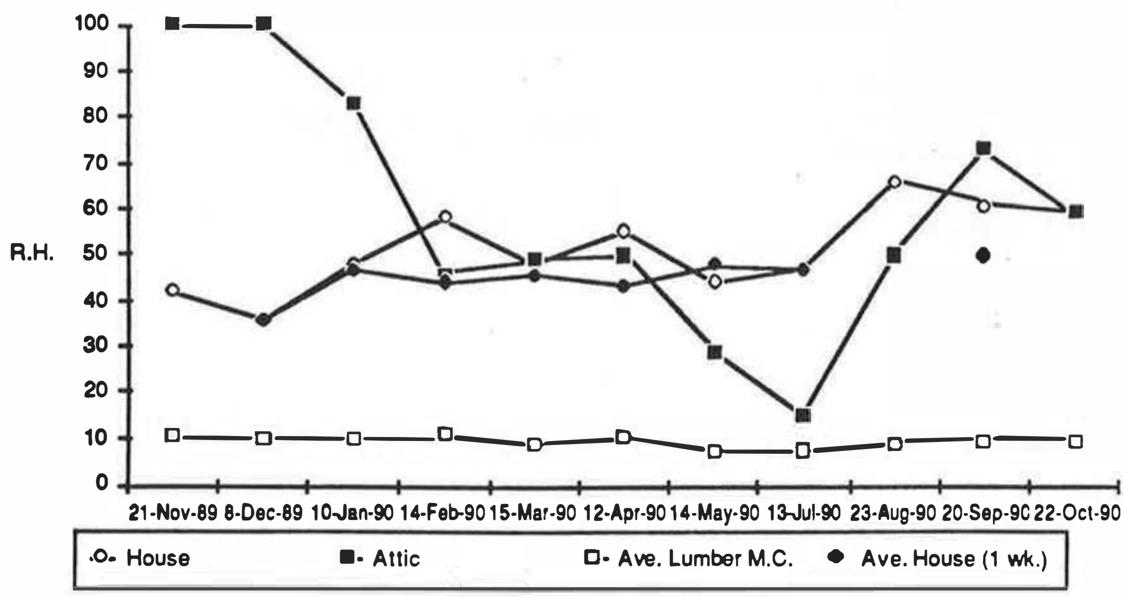
Site Plan



Moisture Curves: House O-15



Relative Humidity and Average Lumber Moisture Content Curves: House O-15



House Data

General		*Attic*		*Venting*	
Location:	Ottawa	Ceiling to ridge height:	1.5 m	Types:	soffit
Age:	1968	Volume:	63 m^3	Free venting area (approx.):	3600 cm^2
Type:	2 storeys	Ceiling area:	77 m^2		
Roof		Insulation:	RSI 3.3 glass fibre batt		
Type:	gable	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

Air Change Data

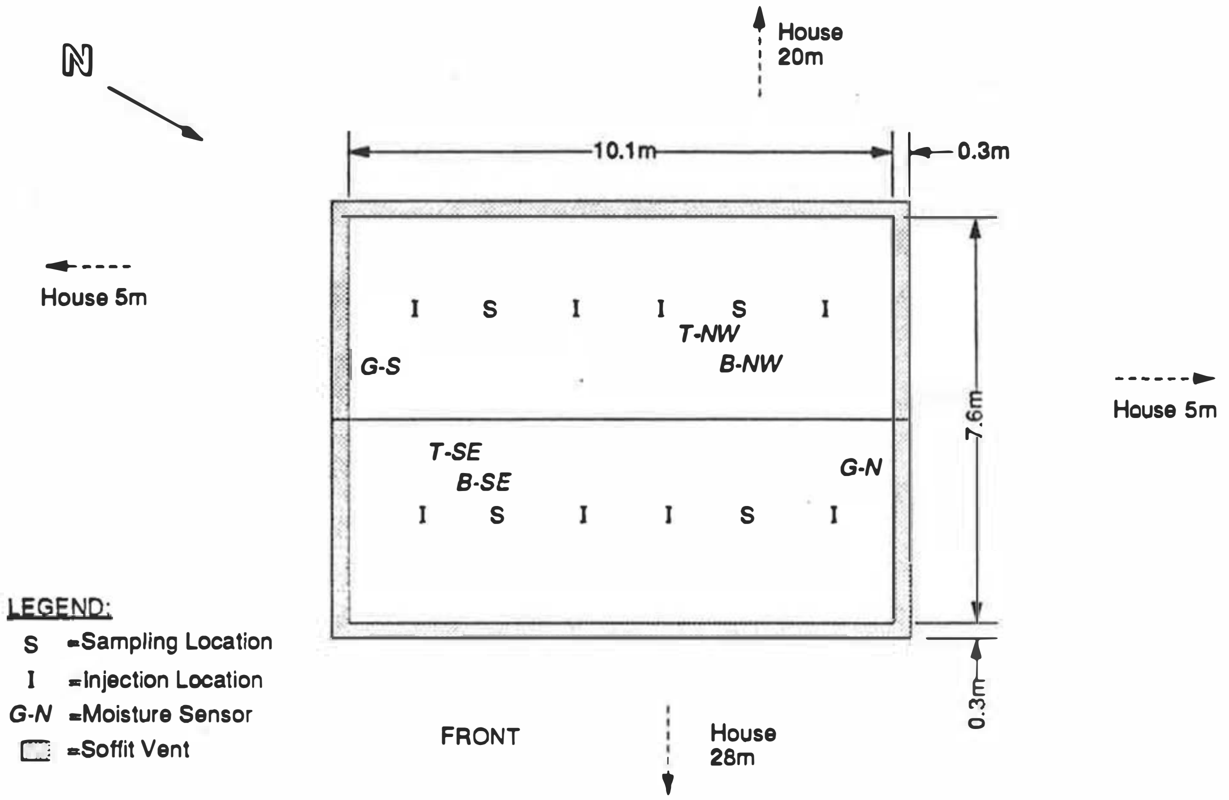
Test	*Date*	*Average Wind Speed (kph)*	*Wind Direction*	*Outside Temp (T_o) (°C)*	*Attic Temp (T_a) (°C)*	*House Temp (°C)*	*Attic Air Change (ACH)*	*Average Interface Leakage (L/s)*
1	19-Jan-90	20	W	-10	-3	17	13.4	N/A
2	14-May-90	7	NNW-SW	17	39	20	7.2	N/A

Attic Air Tightness Data

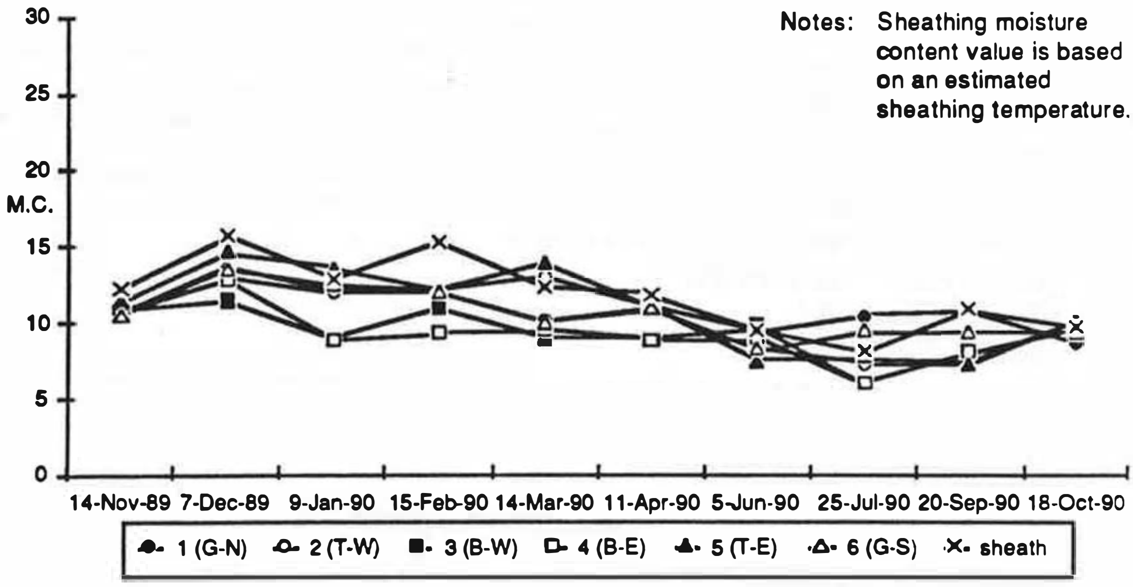
Wind Speed During Test kph	*Attic Ventilation ELA cm^2*	*Interface ELA cm^2*
11	5500	220

HOUSE O-15
HOUSE CHARACTERISTICS

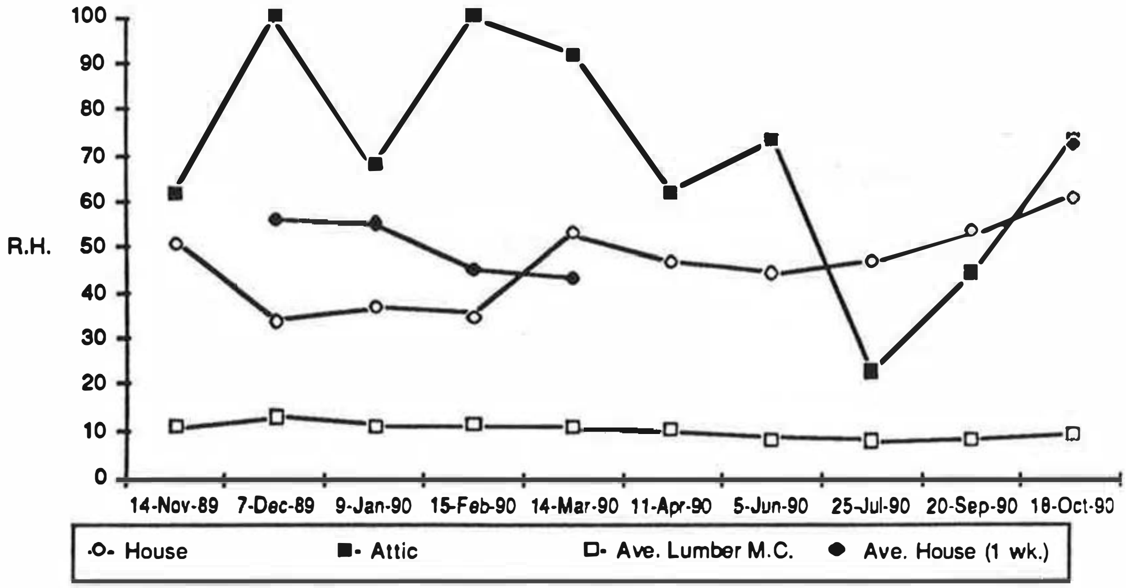
Site Plan



Moisture Curves: House O-14



Relative Humidity and Average Lumber Moisture Content Curves: House O-14



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	2.2 m	Types:	soffit gable
Age:	1987	Volume:	237 m^3	Free venting area (approx.):	7000 cm^2
Type:	1 storey	Ceiling area:	212 m^2	**Further Relevant Information**	
Roof		Insulation:	RSI 7.0 blown cellulose fibre		Building built to the R-2000 Specifications
Type:	gable	Vapour barrier:	yes		
Sheathing:	waferboard				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

Air Change Data

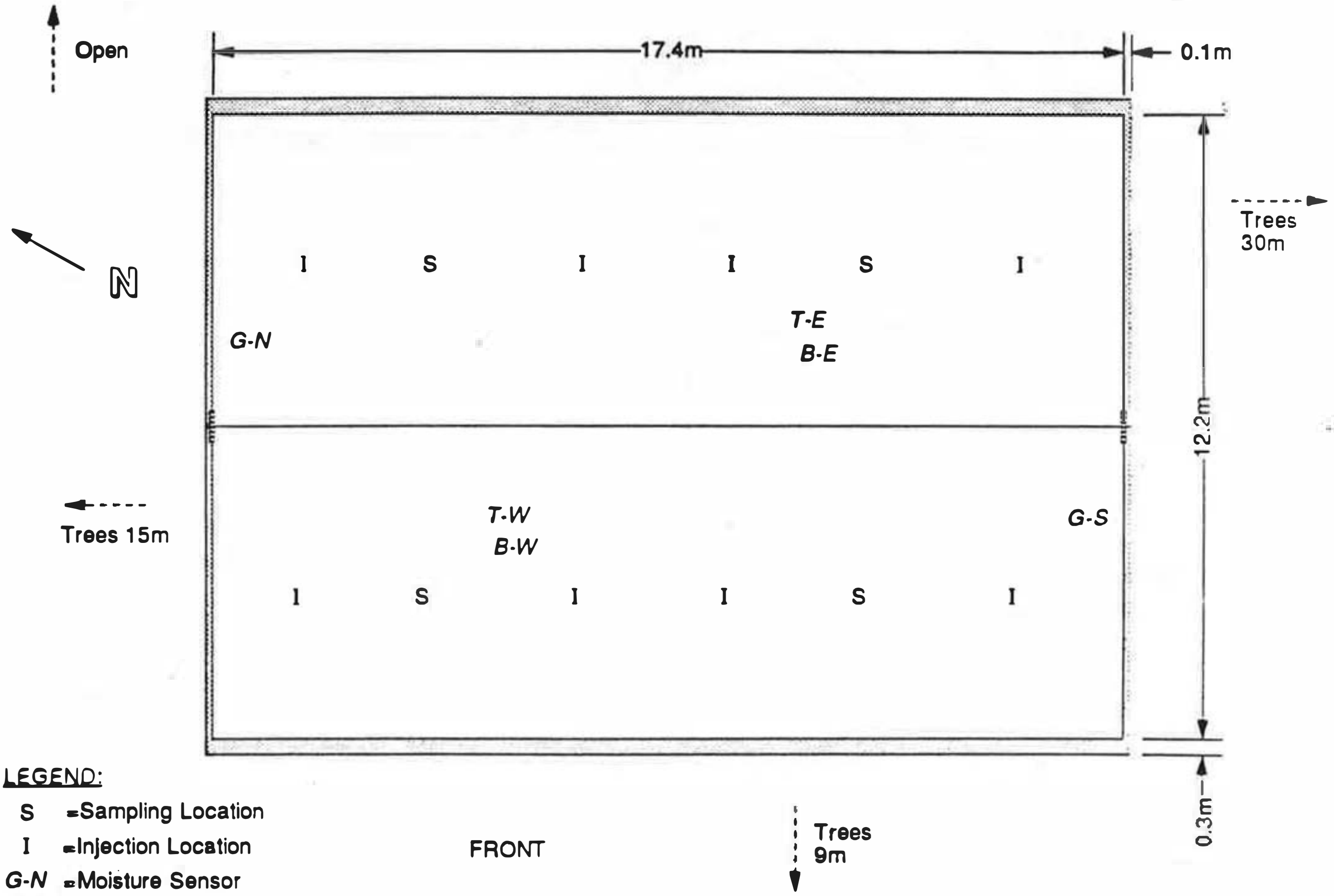
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	15-Feb-90	26	NE	-7	-5	15	2.2	N/A
2	25-Jul-90	13	W	30	50	20	1.9	N/A

Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
15	5700	20

HOUSE O-14
HOUSE CHARACTERISTICS

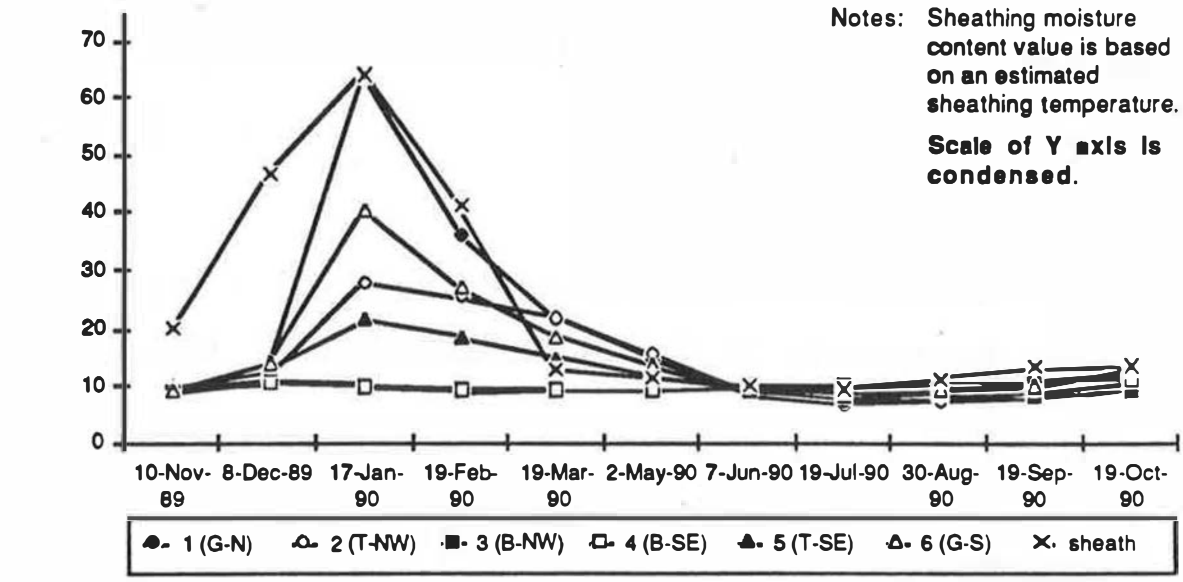
Site Plan



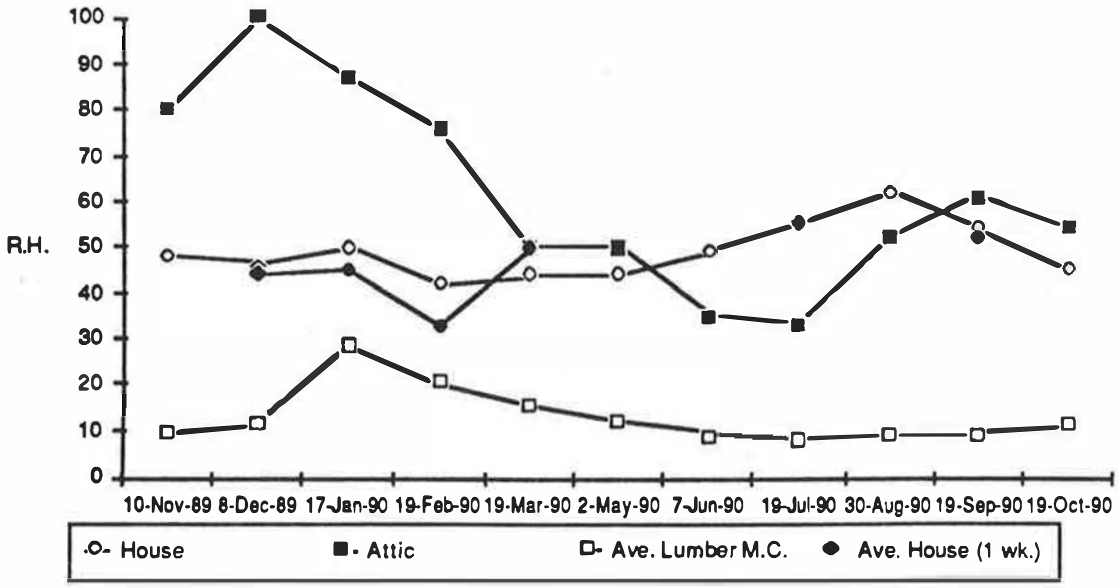
LEGEND:

S =Sampling Location
I =Injection Location
G-N =Moisture Sensor
=Soffit Vent
=Gable Vent

Moisture Curves: House O-13



Relative Humidity and Average Lumber Moisture Content Curves: House O-13



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.9 m	Types:	soffit ridge
Age:	1985	Volume:	116 m^3	Free venting area (approx.):	8500 cm^2
Type:	2 storeys	Ceiling area:	114 m^2		
Roof		Insulation:	RSI 7.0 glass fibre batt		
Type:	hip	Vapour barrier:	yes		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

Air Change Data

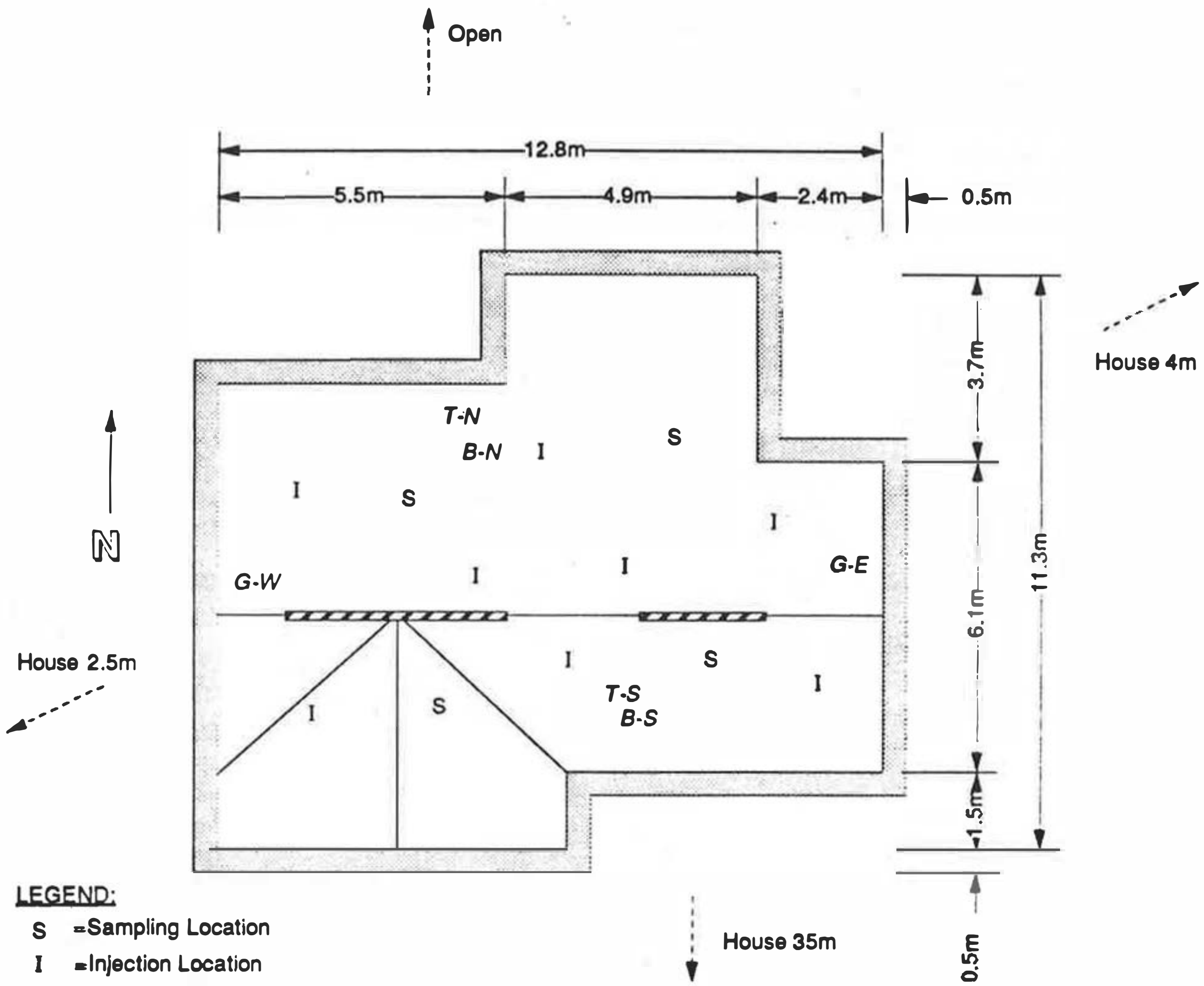
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH)	Average Interface Leakage (L/s)
1	19-Feb-90	37	W	-3	1	18	12.6	N/A
2	19-Jul-90	24	WSW	27	36	24	11.4	N/A

Attic Air Tightness Data

Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
8	2900	400

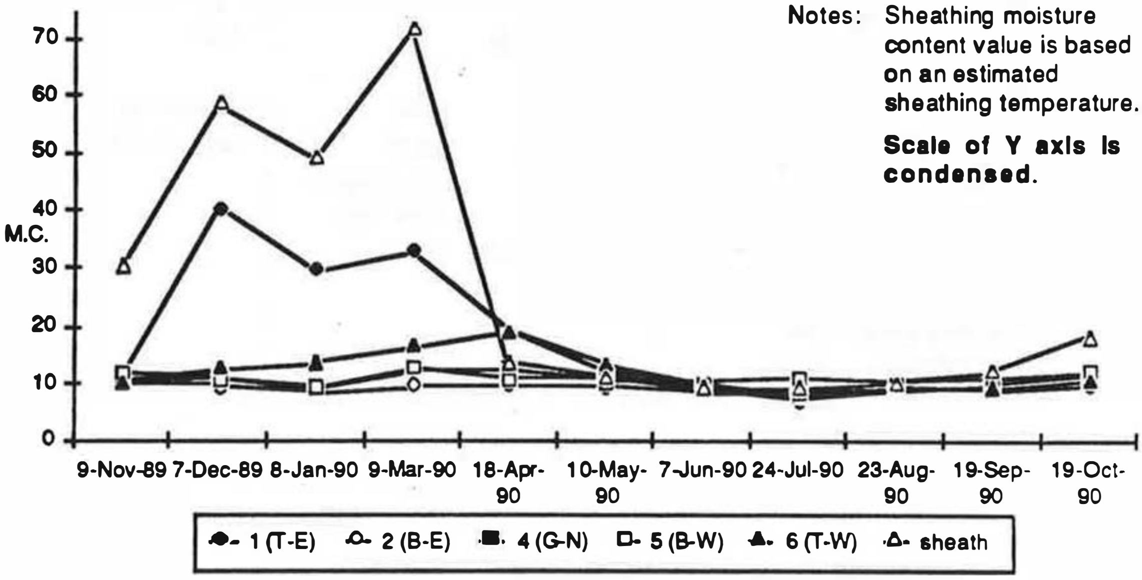
HOUSE O-13
HOUSE CHARACTERISTICS

Site Plan

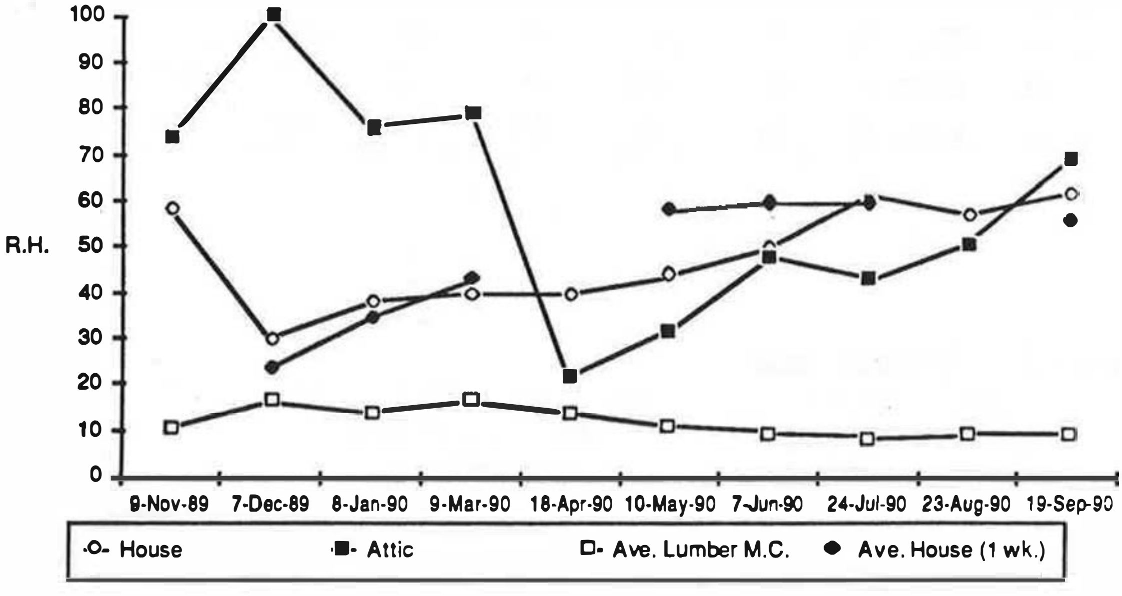


LEGEND:
- S =Sampling Location
- I =Injection Location
- *G-N* =Moisture Sensor
- =Soffit Vent
- =Ridge Vent

Moisture Curves: House O-12



Relative Humidity and Average Lumber Moisture Content Curves: House O-12



House Data

General		Attic		Venting	
Location:	Ottawa	Ceiling to ridge height:	1.75 m	Types:	soffit 2 mushroom
Age:	1972	Volume:	56 m^3	Free venting area (approx.):	2200 cm^2
Type:	2 storey	Ceiling area:	56 m^2		
Roof		Insulation:	RSI 3.3 glass fibre batt		
Type:	gable	Vapour barrier:	none		
Sheathing:	plywood				
Exterior finish:	asphalt shingles				
Sheathing species:	CSP				
Lumber species:	S-P-F				

Air Change Data

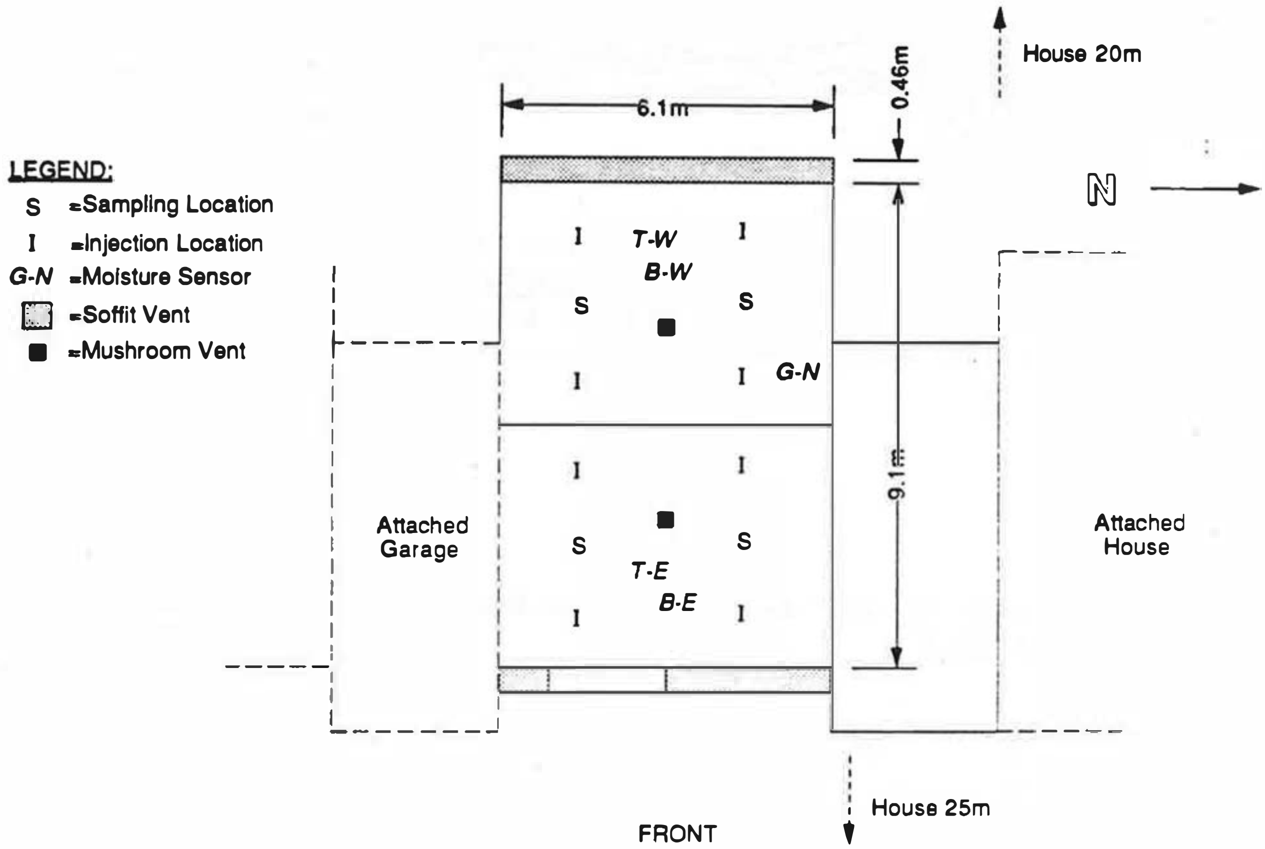
Test	Date	Average Wind Speed (kph)	Wind Direction	Outside Temp (T_o) (°C)	Attic Temp (T_a) (°C)	House Temp (°C)	Attic Air Change (ACH	L/s)	Average Interface Leakage (L/s)
1	15-Jan-90	11	NNE	-11	2	18	3.7	58	N/A
2	17-Jan-90	12	ENE	-1	6	18	5	78	N/A
3	24-Jul-90	8	SSW	27	47	21	2.8	44	N/A
4	25-Jul-90	11	W	20	29	20	1.9	30	N/A
5	9-Mar-90	5	ENE	4	12	20	3.2	50	13.4
6	30-Jul-90	22	S	31	41	20	6.2	97	7.3

Attic Air Tightness Data

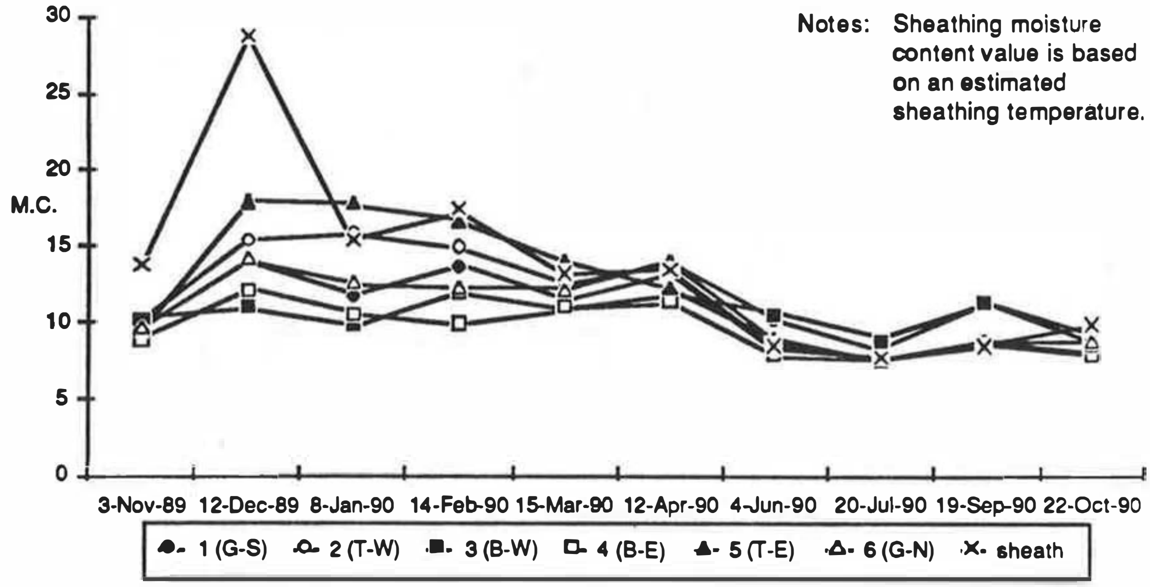
Wind Speed During Test kph	Attic Ventilation ELA cm^2	Interface ELA cm^2
28	2400	-

HOUSE O-12
HOUSE CHARACTERISTICS

Site Plan



Moisture Curves: House O-11



Relative Humidity and Average Lumber Moisture Content Curves: House O-11