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ATTIC VENTILATION
AND MOISTURE

NOTE: **DISPONIBLE AUSSI EN FRANÇAIS SOUS LE**
HUMIDITÉ ET VENTILATION DU GRENIER

ATTIC VENTILATION
AND
MOISTURE

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ABSTRACT

Ventilation with outdoor air has been the accepted method for controlling moisture and overheating in residential attics. This is recognized in the Building Code which requires that the total vent area must be 1/300th of the attic floor area. However, how much ventilation is provided and how this ventilation affects moisture accumulation in an attic are not well understood. The present study attempts to provide some answers to these questions.

The study consists of two parts. First, detailed measurements were carried out in two separate attics located at a field test site. The full-sized attics were instrumented to measure ventilation rates, indoor-attic exchange rates, temperatures, and moisture contents with these measurements extending over a two year period. Second, a model was developed to predict the moisture performance of an attic for a given leakage configuration and weather conditions. The model consisted of three interactive sub-models: a ventilation model that predicts attic ventilation rates (and interior house ventilation rates) for the above inputs, a thermal model that predicts the temperature distribution, and a moisture model that predicts moisture distribution within an attic. The model was verified with the field data and showed reasonably good agreement with measurements.

The model was used in a number of simulations. First, several parametric simulations were carried out where both attic configuration and climatic parameters were varied systematically; these included attic leakage, use of mechanical ventilation, outdoor temperature and relative humidity, wind speed, and cloud cover. These results helped to identify which parameters where important in influencing moisture levels in attics. A second set of season-long simulations were carried out using actual weather data for a number of Canadian cities in different climatic zones.

This report highlights some of the measurements and model calculations that were performed. An appendix to this report provides a more extensive compilation of these results and is available from the Canada Mortgage and Housing Corporation.

1. OBJECTIVES AND BACKGROUND

Attic ventilation is the accepted method for moisture control and is achieved by providing some open vent areas on the attic envelope. Specifications for the appropriate vent area are given in the Building Code as the "1:300" rule for attics. Unfortunately, there are few measurements of typical attic ventilation rates, let alone the interaction of ventilation air with moisture in an attic exposed to varying climatic conditions. The present study was initiated to develop and verify a comprehensive model that would predict the attic ventilation rate, temperature and moisture distribution for given attic leakage configuration and climatic conditions. Such a model could then be used to carry out realistic simulations of attics and explore various ventilation strategies for controlling moisture.

Several studies have been directed at modelling the moisture dynamics in ventilated attics. All of these models concentrated on developing a detailed representation of the interaction between the wood components (roof sheathing and trusses) and attic air. These details included modelling the wood by a thin surface layer which interacts rapidly with the attic air and provides a mechanism by which moisture can be stored and released over a short period. In all models, the single largest moisture transport mechanism was that associated with the bulk convective flow of air from outdoors (ventilation flow) and air leaking into the attic from indoors. Unfortunately, the magnitudes of the ventilation and indoor-attic exchange flows are not known nor is it known how these flows vary with attic leakage configuration and ambient conditions. This lack of information has limited these moisture models to parametric studies where the ventilation and exchange rates must first be specified.

The key to the present study on moisture in attics has been the integration of a ventilation model with a slight variation of the moisture models that have been previously developed. The ventilation and combined models have been verified with data collected at The Alberta Home Heating Research Facility over a two year test period. During this period, ventilation rates, indoor-attic exchange rates, temperatures, relative humidities, and wood moisture contents were measured in two separate attics that had different leakage configurations. The combined model was used to simulate the performance of attics over complete heating seasons in a given climate in order to study the effect of various attic configurations on the seasonal moisture accumulation. In addition, other ventilation strategies using mechanical ventilation were simulated in order to determine an optimum level of ventilation for effective moisture control.

This report summarizes the model development, field measurements, and simulations that were carried out. A more extensive appendix to this report which provides greater detail on this work is available from the Canada Mortgage and Housing Corporation.

2. FIELD TESTING PROGRAM

2.1 Attic Measurements Over the past two years, from 1990 to 1992, measurements of ventilation rates, indoor-attic exchange rates, temperatures, and moisture contents were carried out in two separately configured attics at The Alberta Home Heating Test Facility, located near Edmonton, Alberta. The facility consists of six, single-storey houses with gable-end attics, oriented in an east-west row. Each house has dimensions of 6.7 m by 7.3 m and an isometric view of one of the houses used in the test program is shown in Fig.1. The attic volume was estimated to be 61 m^3. One attic was configured as a "tight" attic with no intentional vent openings while the other attic had soffits along the north and south sides and two roof vents with total vent area specified according to the code requirement of 1:300. The background leakage of each attic was measured by blocking the roof vents and conducting fan pressurization tests on the attic. A dual blower system was used with one blower pressurizing the attic and the other blower holding the interior and attic at the same pressure.

The ventilation rates in both the interior and attic zones were measured using a dual tracer gas technique. Ventilation rates in each zone were measured by measuring the amount of tracer gas that was required to maintain a constant concentration of 5 ppm. In addition, the inter-zonal leakage flow was obtained by measuring the concentration of a particular tracer gas in the zone where it was not injected. Thermocouples were used to measure temperatures while relative humidity sensors measured the moisture content of the attic air and electrical resistance pins were placed in the wood to measure wood moisture contents. These data were collected along with the ambient weather conditions measured directly at the test site. As with any field tests, the key to producing useful data was to collect enough measurements so that all ambient conditions were adequately encompassed. With ventilation measurements, these conditions include wind speed, wind direction, and outdoor temperature. Based on previous experience at the test site, a minimum of one full year is generally required; the attic ventilation rates reported in this study come from a database of well over 4000 hourly-averaged data points which was sufficient to identify definite trends in the data. A sample of these data is presented below and a more extensive presentation is given in the Appendix to this report.

3. MODEL DEVELOPMENT

3.1 Ventilation Model The ventilation model is a two zone model consisting of the interior and attic zones of a house which are weakly coupled by inter-zonal leakage. The ventilation model performs an air mass balance on the two zones to calculate ventilation flows. First, all leakage sites on the exterior envelope of the zone are divided into three different categories. The background leakage of the envelope associated with tiny cracks and holes is assumed to be uniformly distributed over the entire zone envelope and is characterized by the flow coefficient, C and flow exponent, n in the equation

$$\dot{m} = \rho C \Delta P^{n}$$

where $\dot{m}$ is mass flow rate of air and ρ is air density; the flow coefficient, C, and exponent, n, are obtained from fan pressurization tests on the zone of interest. The passive vents are site-specific leakage areas, such as roof vents, flues, open windows, etc. Each of these leakage areas is characterized by their own unique values of C and n; in many cases, these large leakage areas behave as orifices where C is related to the net free area of the vent and n is close or equal to

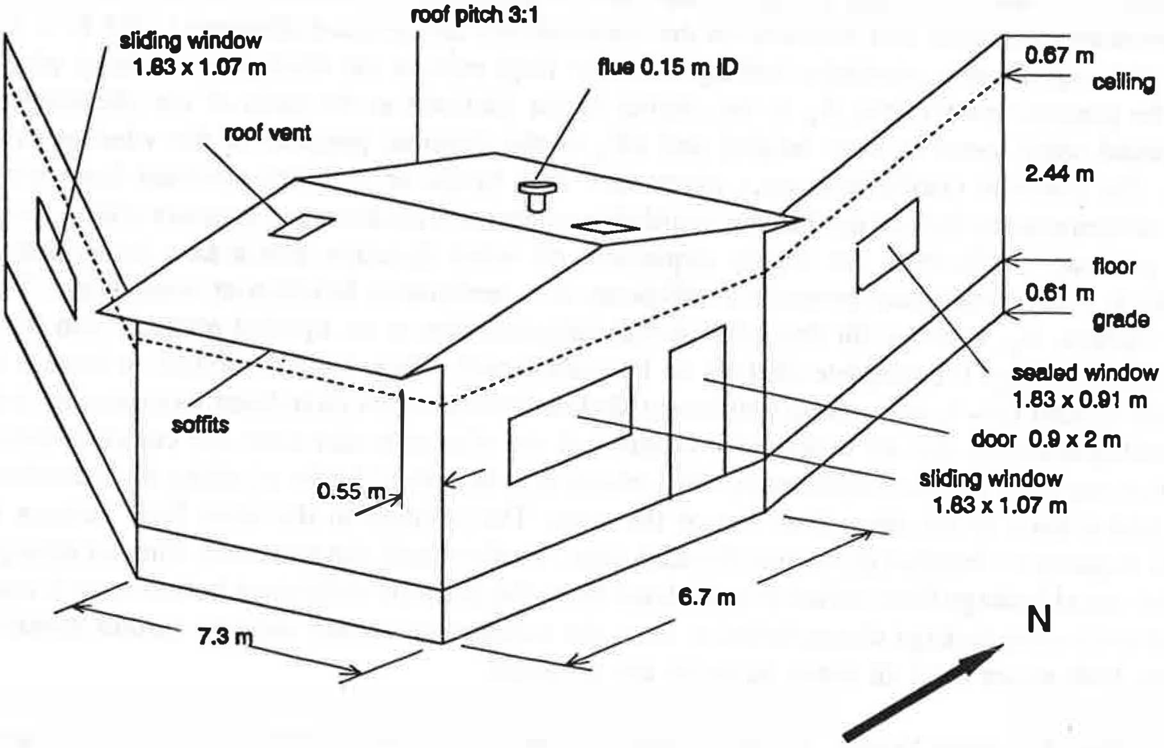

Figure 1. Isometric view of a typical house at The Alberta Home Heating Research Facility showing pertinent details and dimensions.

½ . Finally, active vents are designated to be the leakage sites of fans mounted on the envelope; the ventilation model incorporates the pressure-flow characteristic of the fan so that the mass flow through the fan can vary with ambient conditions.

Once the leakage areas are specified, the mass flow rate through each type of leakage area is expressed in terms of the local pressure difference as

$$\Delta P = \Delta P_{ref} - \Delta P_T H + \Delta P_w C_p S_w^2$$

where ΔP is the outdoor-zone pressure difference, ΔP_{ref} is the outdoor-zone pressure difference at the reference height (in this model, grade level is used as the reference height), ΔP_T is the stack pressure difference and depends on the zone outdoor temperature difference, and H is the height above grade of a particular leakage site; the final term is the wind pressure term where C_P is the pressure coefficient, S_w is the shelter factor (defined as the ratio of the sheltered to undisturbed wind speed at eave height) and ΔP_w is the dynamic pressure of the wind at eave height. The pressure coefficients on a given face of a house or attic are obtained from wind tunnel measurements and are used in the ventilation model as wall-averaged pressure coefficients. These pressure coefficients are highly dependent on wind direction and a new interpolation function is used to calculate pressure coefficients as a continuous function of wind angle. The shelter factors, S_w, account for the wind speed reduction due to an upwind obstacle and have values ranging from 0 (complete shelter) to 1 (unsheltered). Thus, isolated houses or houses in a closely-spaced row have markedly different shelter factors which have been incorporated into the ventilation model. For all leakage flows into and out of a particular zone, the common factor is the outdoor-zone pressure difference, ΔP_{ref} which is to be solved for by equating the mass flow of air into a zone to the mass flow out of the zone. The solution to the mass flow balance in general requires an iterative procedure for each zone. Furthermore, the two zones interact through the inter-zonal leakage flow which is calculated from the pressure difference between each zone and the inter-zone leakage characteristics; thus, the solution procedure requires further iteration between both zones until all mass balances are achieved.

3.2 Attic Thermal Model In calculating attic ventilation rates in the above model, the attic air temperature is required to obtain the correct "stack" effect and air density for the mass flow rates. In this work, the attic was assumed to be a gable-end attic (identical to the shape of the attics used in the field tests) and a lumped capacity approach was adopted. The attic was divided into ten nodes where the sloped roof surfaces were separated into the north and south-facing slopes. Each of the three exterior surfaces of the attic envelope (the two gable ends are lumped together) were separated into an exterior and interior node; the ceiling was separated into an interior and attic-side node; the other two nodes were the attic air (assumed to be well-mixed and at a uniform temperature) and the remaining wood in the attic (joists and trusses). At each node, the sum of the heat fluxes to the node was equated to the change in thermal energy of the node; this transient analysis was required to capture the diurnal temperature variations that occur in an attic. For the attic air, the additional flow of heat associated with the ventilation air and indoor-attic leakage flow was included in the energy balance.

In solving for the temperature distribution, the transient term at each node was approximated by a finite difference using a time interval of one hour. This was done to match the measurements that were made in the test attics and stored as hourly-averaged values. The above set of equations that are linear in temperature were solved simultaneously. When the temperatures were calculated, the attic air temperature was returned to the attic ventilation model so that a new attic ventilation rate could be calculated. This new ventilation rate was then used in the thermal model at the attic air node to calculate temperatures. This iterative process was continued until the attic air temperature changed by less than 0.1°C. Because the attic ventilation rates are relatively insensitive to the attic air temperature usually fewer than five iterations between thermal and ventilation models were required.

3.3 Attic Moisture Model The attic moisture model uses the same lumped capacity approach used in the thermal model, except that the attic was modelled with only seven nodes. The critical elements of the attic are the wood components which were divided into the north and south-facing roof sheathing, and the joists and trusses. These components were divided into two nodes; a thin surface layer (3 mm thick) and the underlying wood. The seventh node was the attic air which was assumed to be well-mixed and at uniform conditions. The diffusive and convective fluxes at each node (using vapour pressure as the driving force) were equated to the time rate of change of moisture at the node. For the attic air, the additional flow of moisture associated with ventilation air (which transports outdoor moisture into the attic) and indoor-attic leakage flow (which transports interior moisture into the attic) was included in the moisture balance. An important feature of the moisture model is the moisture content/vapour pressure/temperature relationship for wood. A previously derived empirical equation for this relationship was incorporated based on equilibrium wood moisture content measurements above 0°C. This equation was used in this model and extrapolated to temperatures below 0°C where the equation predicts that cooling of wood that is initially below its fibre-saturation moisture content will drive moisture out of the wood cell wall where it appears as "unbound" water (this physical behaviour of wood needs to be substantiated by detailed measurements). At temperatures below 0°C, the effect that this produces in the model is the appearance of free moisture in wood even though wood moisture contents may be well below fibre saturation.

The node moisture balances were first linearized by approximating the time derivative as a finite difference using a time step of one hour. The vapour pressure at each node was obtained by iteratively solving the set of linear equations using the results of the ventilation and thermal models as input. At each iteration, the vapour pressure of each node was compared with the saturation vapour pressure to check for the possibility of condensation. Any node that reached saturation had its vapour pressure held at that value and the amount of condensed mass accumulating at that node was calculated from the net mass flux. Thus, the model was able to track moisture condensing or evaporating at any of the seven nodes. The coldest surfaces of the attic experienced moisture accumulation, making the roof sheathing the component most susceptible to moisture damage.

The combined model for predicting moisture within an attic is a simulation tool that only requires the following inputs:

- attic configuration and leakage distribution including background leakage, the size and location of attic vents, and any fans

- leakage distribution of the interior zone of the house including the ceiling leakage
- indoor temperature and relative humidity
- location of the house (latitude for solar gain calculations) and location of nearby obstacles (for calculating wind shelter)
- ambient weather conditions including outdoor temperature, relative humidity, wind speed, wind direction, cloud cover, and solar gains on a horizontal or vertical surface.

4. RESULTS AND DISCUSSION

4.1 Comparison of Measurements and Predictions Initial comparisons of measurements and predictions were made for attic ventilation rates since the ventilation model is crucial to the moisture model. Figure 2a shows the measured ventilation rates in attic 5 (the "tight" attic) as a function of wind speed including all wind directions, and Fig.2b compares the measured, binned data with the ventilation model predictions for the mean ventilation rate; mean predictions were made by predicting the ventilation rate at each hour and then averaging. A similar comparison is presented in Figs.3a and 3b for attic 6 which has the code-required vent area. The ventilation rates in attic 6 are seen to be much higher than in attic 5 due to the added vents in attic 6. The large scatter in the data is characteristic of all field measurements of ventilation rates and is due primarily to the sheltering provided by near-by obstacles (in this case the neighbouring houses in the east-west row). By separating the various wind directions, the sheltering effect can be observed; this is shown in Fig.4a for attic 6 where 0° corresponds to winds from the north. The north and south directions have the largest ventilation rates because the attics are unsheltered for these winds while east and west winds produce the lowest ventilation rates because the attics are highly sheltered by the row of houses for these wind directions. For this binned data, the ventilation model predictions are shown in Fig.4b and it can be seen that the ventilation model is able to predict the wind angle dependence very well. It should be noted that the measured ventilation rates for attics 5 and 6 shown in Figs.2 and 3, respectively, include all attic-outdoor temperature differences and therefore, include ventilation rates driven by wind and stack effects. Results presented in the Appendix to this report, show that for attics, the stack effect alone only contributes a maximum of approximately 0.5 and 2 air changes per hour (ac/h) for attics 5 and 6, respectively. Over all wind speeds and temperature differences, the mean error in the ventilation model was +3% for attic 6 and -9% for attic 5.

The indoor-attic exchange rates are an important input to the moisture model and these measured rates were compared with model predictions in Figs.5 and 6 for attics 5 and 6, respectively. From the measurements, it was observed that indoor-attic exchange rates are mainly dependent on the indoor-attic temperature difference which suggests that the main driving force for this flow is the indoor-attic "stack" effect; there was little or no correlation of this flow with wind speed as is shown in the main report. The model predictions are seen too agree quite well with the measured data with mean errors of +4.5% for attic 5 and +14.3% for attic 6.

Over a portion of the final year of tests, a small 163 l/s (345 cfm) fan was installed in attic

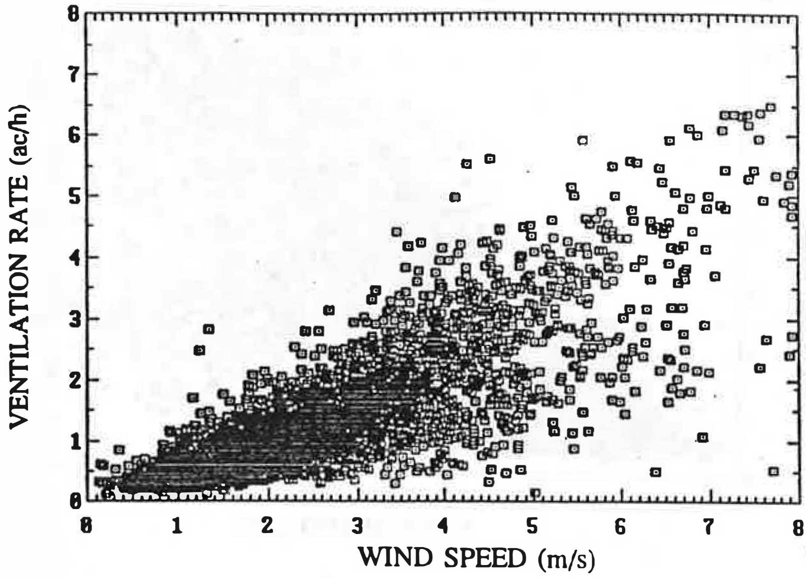

Figure 2a. Measured ventilation rates in attic 5 for all wind speeds and temperature differences (3758 data points).

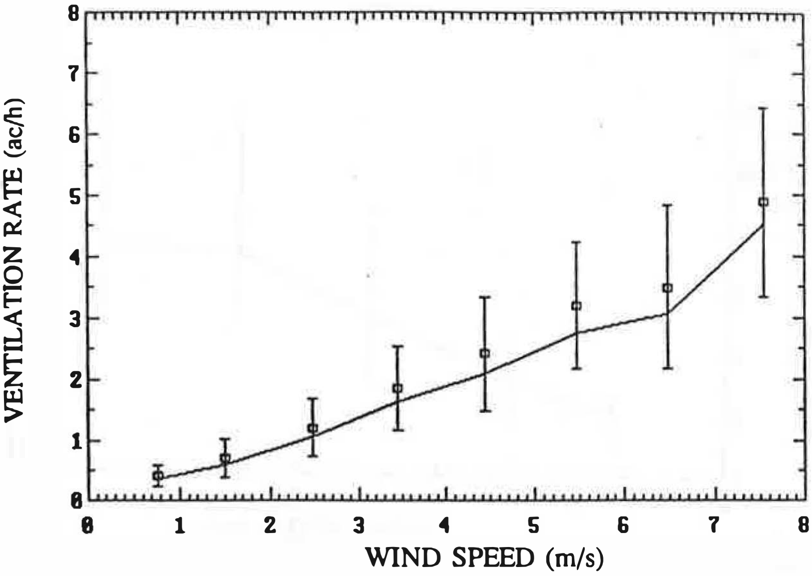

Figure 2b. Measured binned attic 5 ventilation data (3758 hours) with predicted line for all wind directions and temperatures.

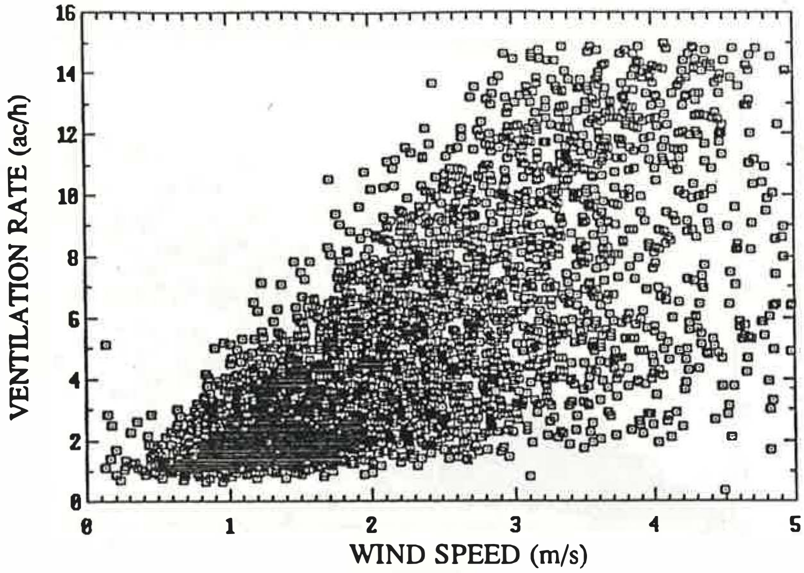

Figure 3a. Measured ventilation rates in attic 6 for wind speeds up to 5 m/s and all temperature differences (3522 data points).

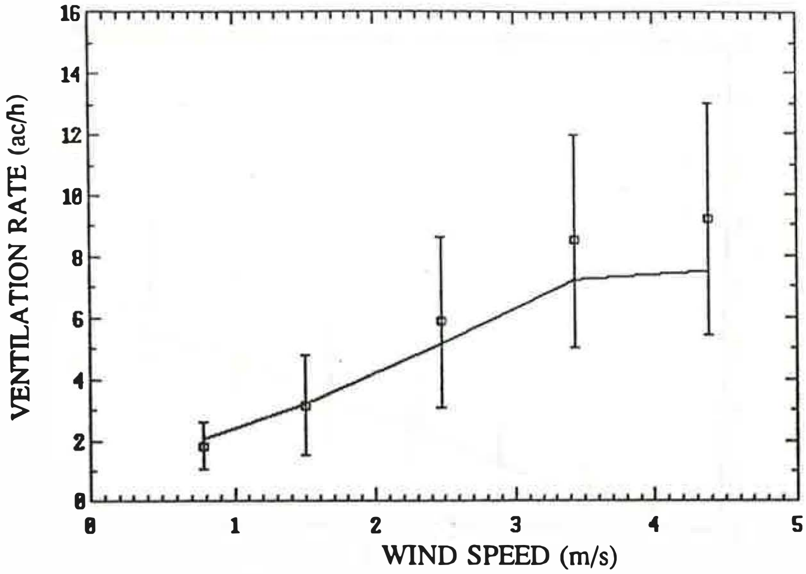

Figure 3b. Measured binned attic 6 ventilation data (3522 hours) with predicted line for all wind directions and temperatures.

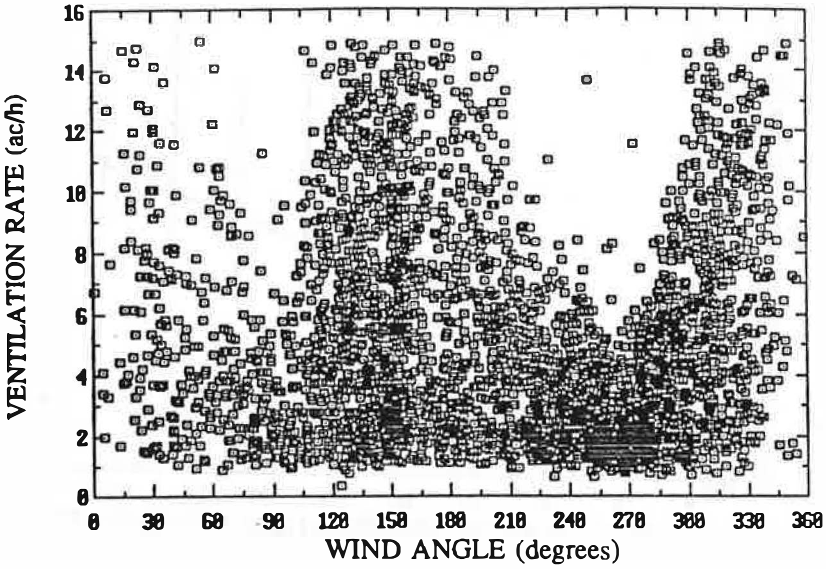

Figure 4a. Variation of measured ventilation rates for attic 6 with wind direction (3522 hours).

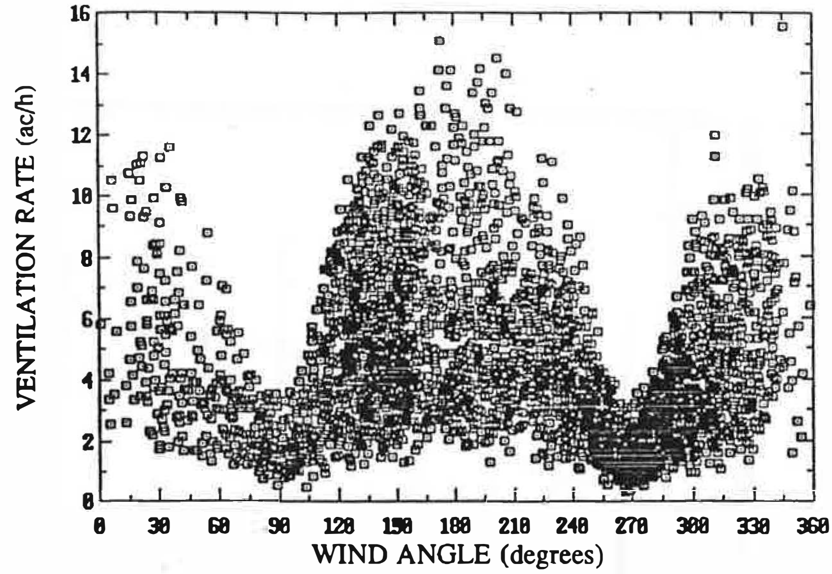

Figure 4b. Variation of predicted ventilation rates for attic 6 with wind direction (3522 hours).

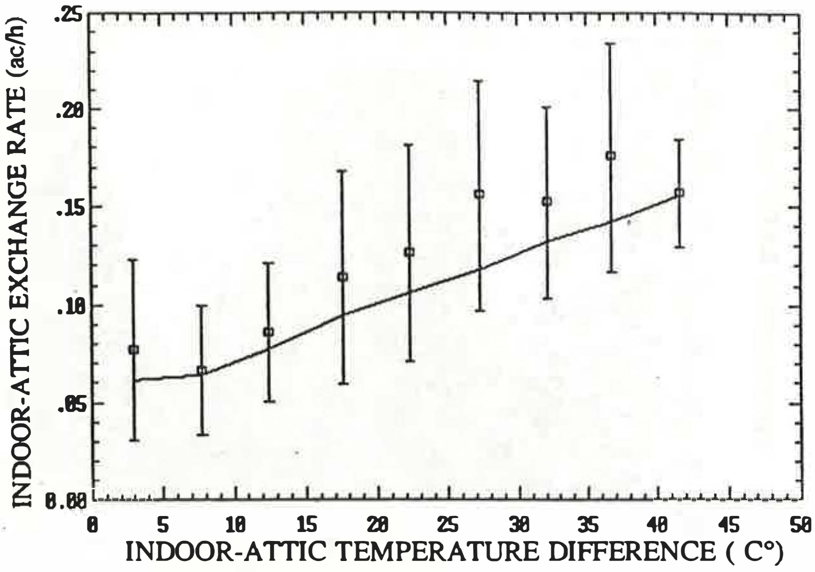

Figure 5 Comparison of measured (binned) and predicted (line) indoor-attic exchange rates for attic 5 for wind speeds < 2 m/s (990 hours) showing mean and standard deviation of binned measured data and a line connecting the mean predicted values for each bin.

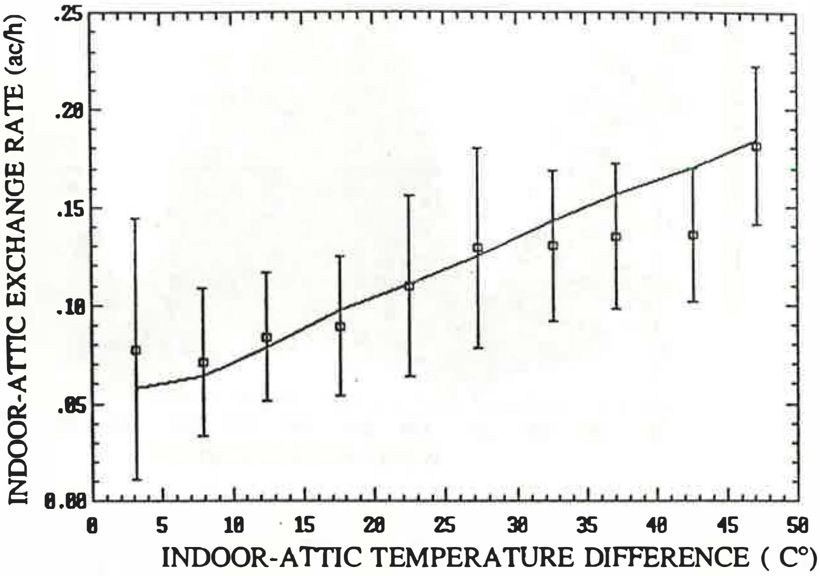

Figure 6 Comparison of measured (binned) and predicted (line) indoor-attic exchange rates for attic 6 for wind speeds < 2 m/s (722 hours) showing mean and standard deviation of binned measured data and a line connecting the mean predicted values for each bin.

6 and tested in two flow configurations: exhaust mode which depressurized the attic (normal mode of operation) and supply mode which pressurized the attic. Based on the rated flow, the fan provides 9.6 AC/H of ventilation flow. In each mode, the fan was operated on a timer which turned the fan on at 10:00 am and off at 4:00 pm. The influence of the fan on attic ventilation rates is seen in Figs.7a and 7b for exhaust and supply modes over selected four day periods. At low wind speeds, the fan provides close to the rated ventilation flow; however, on windy days, the fan flow augments the background ventilation flow. The ventilation model predictions are shown in each figure and it can be seen from the comparisons that the model is able to correctly "add" the fan flow together with the background ventilation flow. The mean prediction error with the fan on was -6.1% for the exhaust mode and -4.3% for the supply mode.

The combined model was then used to predict the moisture contents in the attic and compare with measured values. The most active nodes were the attic air and the inner surface wood nodes. Attic air temperature and relative humidity was measured but it was not possible to measure the surface wood moisture content. Comparisons of measured and predicted attic air vapour pressures are presented in Figs.8a and 8b for attic 6 covering two periods between August 13 and 18, 1991 and May 15 and 20, 1991. These figures show the strong diurnal variation in vapour pressure that occurs in attic 6 which the combined model is able to track reasonably well. The skill of the model is demonstrated by comparing the attic vapour pressures and the outdoor ambient values; the attic does not simply track the outdoor conditions and a model is required to predict the attic conditions.

4.2 Attic Simulations The combined model was used in a number of simulations to investigate the moisture dynamics within an attic. The first set of simulations was a parametric study where various leakage configurations and climatic variables were systematically altered. The second set of simulations was a season-long simulation of various attics in a number of different climatic zones in Canada.

Parametric simulations were carried out to investigate what climatic factors and leakage configurations were important in determining moisture accumulation in attics. A small sample of these results is presented in Table 1 for a winter period in a maritime climate. The maritime climate was assumed to have the following constant properties: outdoor temperature at -1°C, outdoor relative humidity at 100%, complete cloud cover with peak solar gains of 120 W/m^2, and a mean wind speed of 6 m/s from the north. The standard attic configuration used in these simulations was: a gable-end attic with the roof peak oriented in an east-west direction, attic volume of 38 m^3, and a total 4 Pa leakage area of 1900 cm^2 with 50% in soffits on the north and south faces, 45% in two roof vents, and 5% in the background leaks. This standard attic was compared with a sealed attic that had no vents or soffits and a 4 Pa leakage area of only 134 cm^2. The interior of the house was assumed to be constant at 20°C and 50% RH and have a 4 Pa leakage area of 100 cm^2 with 20% in the ceiling, 20% at floor level, and 60% spread uniformly over all the walls. A number of fan configurations were also tested including exhaust fan producing a nominal ventilation rate of 14 ac/h and balanced fans, each producing a nominal rate of 7 ac/h. The four cases that are presented in Table 1 are the standard attic, the sealed attic, the sealed attic with exhaust fan on a timer, and the sealed attic with balanced fans; all

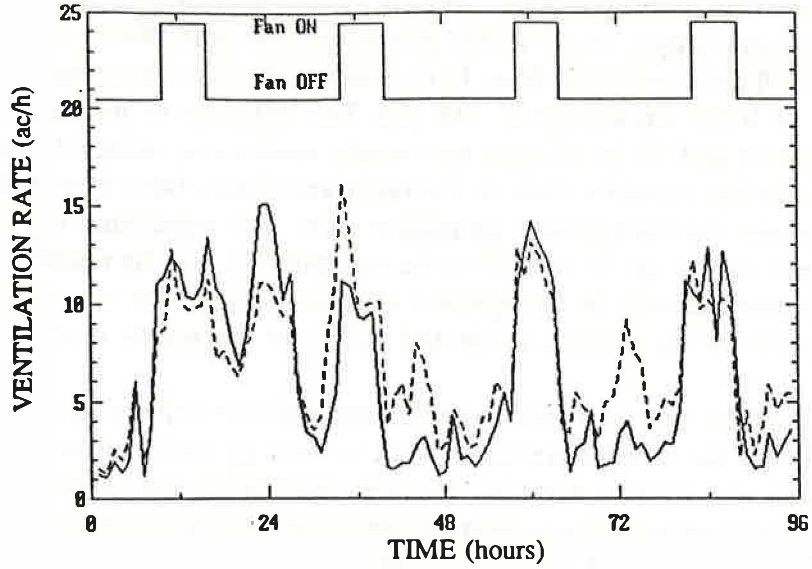

Figure 7a. Measured (solid line) and predicted (dashed line) attic 6 ventilation rates with an exhaust fan providing 9.6 ac/h from 10:00 am to 4 pm each day. January 17 through 20, 1992.

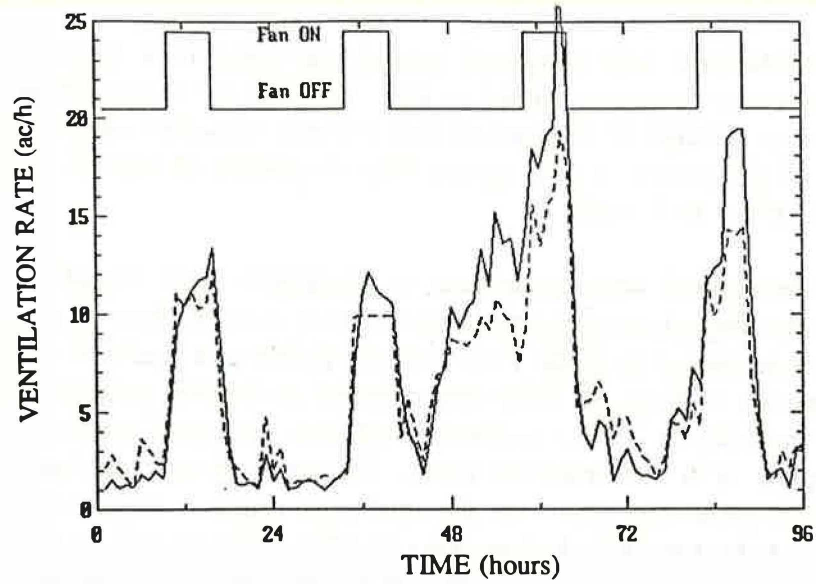

Figure 7b. Measured (solid line) and predicted (dashed line) attic 6 ventilation rates with a supply fan providing 9.6 ac/h from 10:00 am to 4 pm each day. March 13 through 16, 1992.

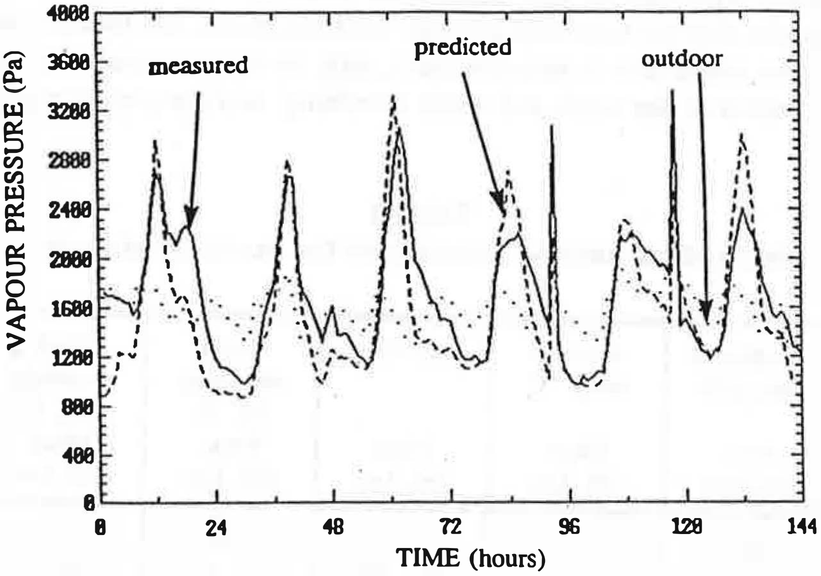

Figure 8a. Measured (solid line) and predicted (dashed line) vapour pressure for attic 6 and outdoor vapour pressure (dotted line) over 6 day period from August 13 through 18, 1991.

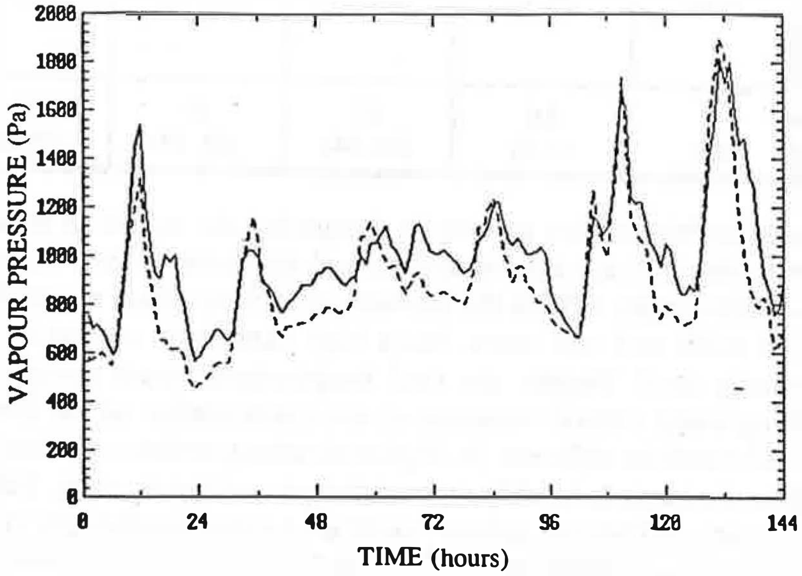

Figure 8b. Measured (solid line) and predicted (dashed line) vapour pressure for attic 6 over 6 day period from May 15 through 20, 1991.

parametric simulations were run for one week with initial roof sheathing moisture contents set at 15% MC. The results that are tabulated are attic ventilation rate and indoor-attic exchange rate (defined to be positive when flow is into the attic), attic air temperature, attic relative humidity, surface moisture contents of the north and south sheathing, and the presence of excess moisture or condensation.

Table 1
Selected parametric simulations for maritime climate

Attic configuration	Ventilation rate, ac/h Attic (ceiling)	Attic air temp. °C Mean (Hi, Lo)	Attic RH % Mean (Hi, Lo)	South sheathing MC % Mean (Hi, Lo)	North sheathing MC % Mean (Hi, Lo)	Condensation
Standard	24 (-0.1)	-0.1 (1, -1)	91 (93, 90)	26 (27, 25)	26 (27,25)	none
Sealed	0.7 (0.7)	1.5 (3, 1)	97 (97, 97)	32 (32, 32)	32 (32,32)	1 kg/day accumulates north and south
Sealed with exhaust fan on 9 am to 4 pm	5.4 (1.3)	1.3 (3, 1)	97 (99, 96)	32 (33, 32)	32 (33, 32)	0.4 kg/day accumulates north and south
Sealed with balanced fans	9 (0.8)	0.6 (2, 0)	95 (96, 94)	29 (29, 29)	29 (29, 29)	none

Several interesting features are evident in comparing the results of these four attics. In all cases, conditions in the attic are near saturation and stay more or less constant throughout the simulation period; this simply reflects the ambient conditions which are relatively constant. The standard attic with soffit and roof vents, has a high ventilation rate which keeps the attic air temperature relatively cool. Despite the cool temperatures, these conditions do not lead to excessive sheathing wood moisture contents or any condensation on the sheathing. It should be noted that this result could be different (ie. higher sheathing moisture contents and condensation) if ambient conditions changed, notably more radiative cooling at night. Sealing the attic (as is common in many parts of Canada) reduces ventilation rates dramatically resulting in relatively high attic air temperatures. Unfortunately, all of this ventilation flow comes from the interior of the house which imposes a large moisture load on the attic. The result is a net daily accumulation of moisture on the sheathing which ultimately would lead to problems. The addition of an exhaust fan on the sealed attic provided no real benefit despite the increased ventilation that the fan delivered. This increase in ventilation was offset by a doubling of the indoor-attic exchange rate which convected moisture into the attic. The net effect of the exhaust fan was a slight reduction in the daily moisture accumulation rate; however, this attic would still exhibit moisture problems. Finally, the sealed attic was ventilated with a balanced fan system that operated continuously. This was a definite improvement over the sealed attic alone or with an exhaust fan, in that this system was able to prevent moisture from accumulating on the sheathing; however, the performance was no better than the standard attic and in fact, was marginally worse with slightly higher sheathing moisture contents. These results are a few of the many different parametric simulations that were carried out which are detailed in the Appendix to this report.

A number of season-long simulations were carried out using actual weather data. Typical of these results is the simulation of the standard gable-end attic with the code-required vent area distributed between soffits and roof vents, in the climate of Whitehorse, Yukon. The results for attic air relative humidity, surface wood moisture contents for the north and south sheathing, and the condensed mass accumulation on the north sheathing are shown in Figs.9a through 9c over the time period from October 10 to March 25. For much of the heating period, attic relative humidity was close to saturation, while the corresponding seasonally-averaged surface wood moisture content was only around 15%. For this cold climate, wood moisture contents cannot reach very high moisture content levels before they become saturated, as was noted in the discussion on the moisture model. This directly reflects the wood moisture content/vapour pressure/temperature relationship that was assumed in the moisture model. Thus, at low moisture contents, condensed mass accumulates at the wood surface nodes as shown in Fig.9c for the north sheathing.

5. CONCLUSIONS

From the attic ventilation measurements that were carried out over a two year period, a number of observations were made:

- attic ventilation rates were dominated by the action of wind and correlations showed a definite trend of increasing ventilation rate with increasing wind speed
- the total attic vent area required by the Building Code produced unsheltered attic ventilation rates of approximately 3 ac/h (air changes per hour) per m/s of wind speed
- attic ventilation rates were sensitive to wind direction, particularly when there was an upwind obstacle that provided shelter; close-row shelter from neighbouring houses reduced ventilation rates by a factor of 3 to 4
- stack-driven attic ventilation rates were much less than wind-driven rates; for the vented attic, peak stack-driven rates were approximately 2 ac/h
- the stack effect produced by indoor-attic temperature differences was the main driving force for indoor-attic exchange rates; there was little correlation of this flow with wind speed.

The complex relationship between the moisture dynamics in an attic and the ambient weather conditions has been modelled by a combined ventilation, thermal, and moisture model and has been shown to agree quite well with field measurements. The key component of this combined model is the two zone ventilation model which was shown to be able to predict correctly shelter effects and the combination of mechanical and natural ventilation. The combined

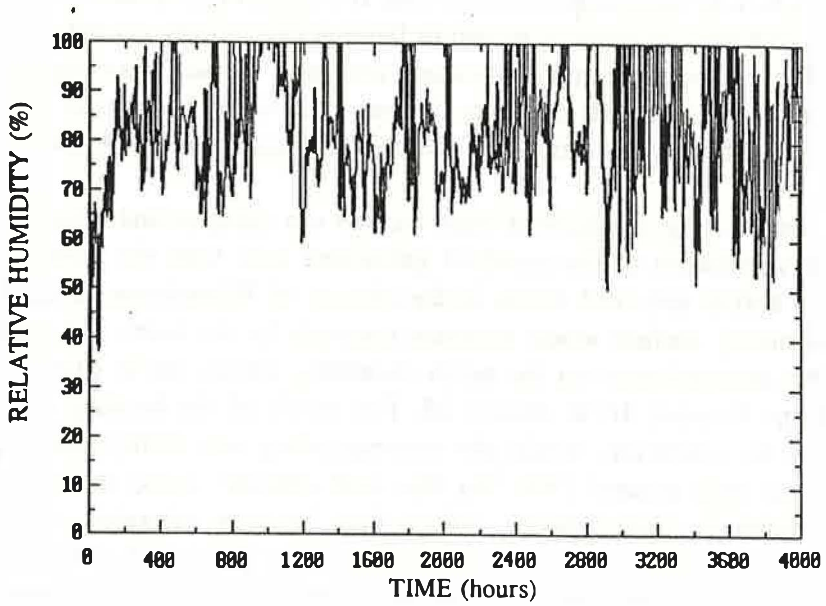

Figure 9a. Relative humidity of attic air for simulation of the standard attic in Whitehorse, Yukon from Oct. 10 to Mar.25.

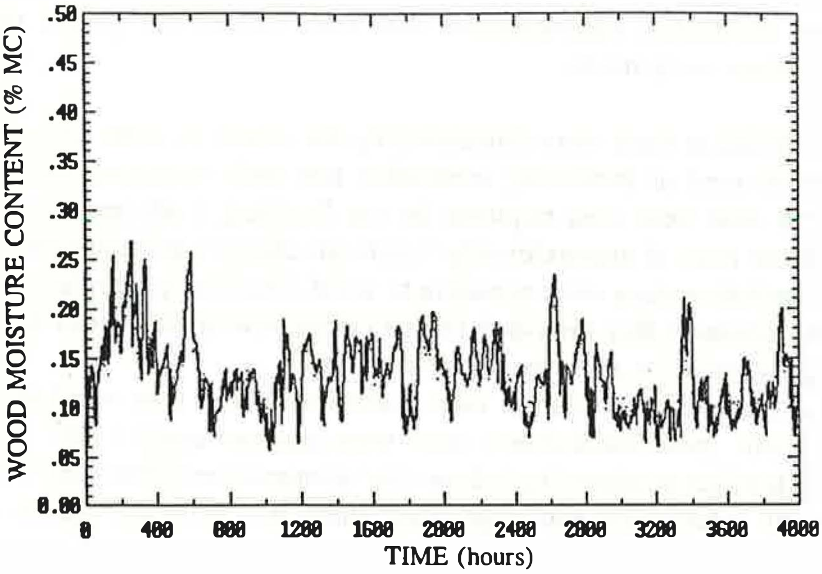

Figure 9b. Surface wood moisture contents for north and south sheathing and trusses for simulation of the standard attic in Whitehorse, Yukon from Oct. 10 to Mar.25.

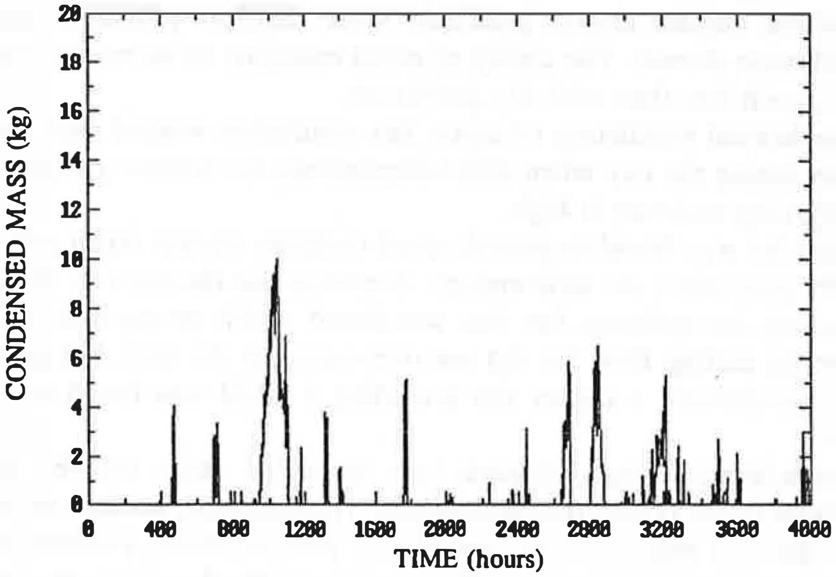

Figure 9c. Condensed mass on the north sheathing for simulation of the standard attic in Whitehorse, Yukon from Oct. 10 to Mar.25.

model was used in a number of simulations and some preliminary conclusions have been reached based on this work:

- The two important sources of moisture for an attic are moisture convected from the interior to the attic by ceiling flow and moisture convected from outdoors by ventilation flow. Moisture due to ceiling flow is dominant when the attic is well sealed and ventilation rates are low. Moisture due to ventilation flow is dominant when ventilation rates are high and poses a problem when the sheathing is cooled at night.
- High ventilation rates did not reduce attic air relative humidity, wood moisture content or condensation, and the worst case results always occurred at high wind speeds. In this case, the moisture source is the humidity of the outdoor air.
- Sealed attics had low ventilation rates and consequently, were warmer than ventilated attics but this was offset by indoor-attic air flow that convected large amounts of moisture from the interior of the house into the attic. This results in high wood moisture contents and condensation problems in all climatic zones.
- A maritime climate always produced worse moisture problems than the dryer and colder prairie climate. The ability of moist maritime air to remove moisture from the attic is much less than with dry prairie air.
- For mechanical ventilation of attics, fan ventilation worked best when the fan was only on during the day when attic temperatures are relatively high and the potential for removing moisture is high.
- A single fan was found to provide good moisture control when installed as a supply fan that pressurizes the attic enough to reverse the direction of the air flow through the ceiling. An optimum fan size was found which pressurized the attic enough to reverse the ceiling flow but did not over-ventilate the attic. For the attic considered in the simulations, a supply fan providing 5 ACH was found to produce the best results.
- The simulations using balanced fans in sealed attics showed that the ambient conditions are an important consideration in fan installation. In a prairie climate it was found that the balanced fans resulted in reduced wood moisture contents but the damper maritime air resulted in increased wood moisture contents compared with the standard attic.

Further work needs to be done on verifying some of the inputs to the complete model, in particular, the moisture content/vapour pressure/temperature relationship for wood, and carrying out more simulations to explore the complete envelope of attic performance before definitive recommendations can be made. The model developed in this study will enable such recommendations to be refined.