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No. 129 (1994)

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H.A. Trethowen, P. Eng.,
Member ASHRAE

Reprinted from: ASHRAE Transactions 1994, Part 1, pp. 1427-1438 ("Symposium on Recommended Practices for Controlling Moisture in Crawl Spaces")

ISSN: 0111-7459

NO-94-22-3

THREE SURVEYS OF SUBFLOOR MOISTURE IN NEW ZEALAND

H.A. Trethowen, P.Eng.
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ABSTRACT

This paper outlines three surveys relating to moisture in house crawl spaces in a cool temperate climate and conclusions drawn from them. The surveys were:

- *A two-year survey of 10 houses, monitoring moisture conditions in crawl spaces and roof spaces where the two were coupled by air leakage paths. Three different remedial treatments were tested, including covering the ground with polyethylene film. This ground cover was assessed later as at least 70% and possibly up to 95% effective.*
- *A pilot study on measurement of subfloor ground evaporation using lysimeters, leading to a one-year survey on ground evaporation under 60 houses in three towns. Average evaporation was approximately 400 g/m^2·day (1.3 oz/ft^2·day).*
- *A small survey on subfloor natural ventilation rates and the interchanges between the subfloor and other parts of the building. This survey showed that a NIST model correlated well with observed air exchange.*

INTRODUCTION

The work outlined in this paper arose partly from a planned program aimed at better understanding the moisture behavior of buildings, quantitatively wherever possible. The program was partly in response to what seemed to be an epidemic of roof space condensation problems in New Zealand following increased thermal insulation through the 1970s and later. The climates in which the work was carried out were cool and temperate, with similarities to parts of the west coastal strip of North America. Rain and/or wind is likely at any time of the year. There are moderate daily and seasonal temperature swings (5°C to 9°C [10°F to 16°F] daily range, mean daily temperature over the year ranging from about 5°C to 15°C [40°F to 50°F] in the south to 13°C to 20°C [50°F to 65°F] in the north). Buildings were mostly traditional timber-framed, single-floor, detached construction, usually with uninsulated suspended timber floors of strip timber or sheet particleboard and framed pitched roofs. Wall claddings were commonly timber plank, with a sizable minority of masonry veneer over timber framing. Previous ventilation studies (e.g., Bassett 1988) have consistently shown a strong dependence of infiltration on wind and only a weak dependence on temperature differences. This reversal of Northern Hemisphere behavior is attributed mainly to climatic differences.

Survey 1 was designed as a demonstration to find a practical solution for these roof space condensation problems. That project also confirmed a widely held view that the subfloor spaces were not adequately ventilated. The regulations at the time (and still) offered only a recipe for installing subfloor ventilation and no engineering guidance on how to control moisture. Surveys 2 and 3 were intended to begin to redress this lack of guidance. Survey 2 set out to find a method of measuring ground evaporation and to establish typical values of the moisture emission rates to the subfloor. Survey 3 was to determine typical ventilation rates in the crawl spaces and the interchange with other zones.

This paper summarizes these three surveys, their outcomes, and implications.

SURVEY 1—REMEDIAL TREATMENT METHODS

This survey is described in Trethowen (1988a). It followed a protracted stage of accumulating case histories of roof space condensation problems, with the presence of masonry veneer cladding being identified as the characteristic common factor. Figure 1 shows an example of wet framing from underlay condensation, and the association with construction features is shown in Table 1. The central cause of the problems in this group of houses was then identified as one of airborne subfloor moisture being carried to the roof by combined thermal convection and wind-induced convection. There it met roof claddings that may be cooled by night sky radiation to 5°C to 7°C (9°F to 12°F) below the outdoor air temperature, resulting in heavy condensation on the cladding or underlay.

To demonstrate whether this hypothesis was valid and to simultaneously evaluate possible solutions, a small survey was conducted. Ten houses were selected more or less arbitrarily from the current group of problem houses, hundreds of which are reported to the local town council

Harold A. Trethowen is a senior research engineer at the Building Research Association of New Zealand, Porirua.

TABLE 1
Moisture Damage vs. Presence of Open Veneer Cavity (Survey 1)

		No. of cases with Masonry Veneer Cladding Present			
		Yes	No	Don't know	Total
Roof Condensation Observed¹	Yes	34	2	2	38
	No	2	26	21	49
	Total	36	28	23	87

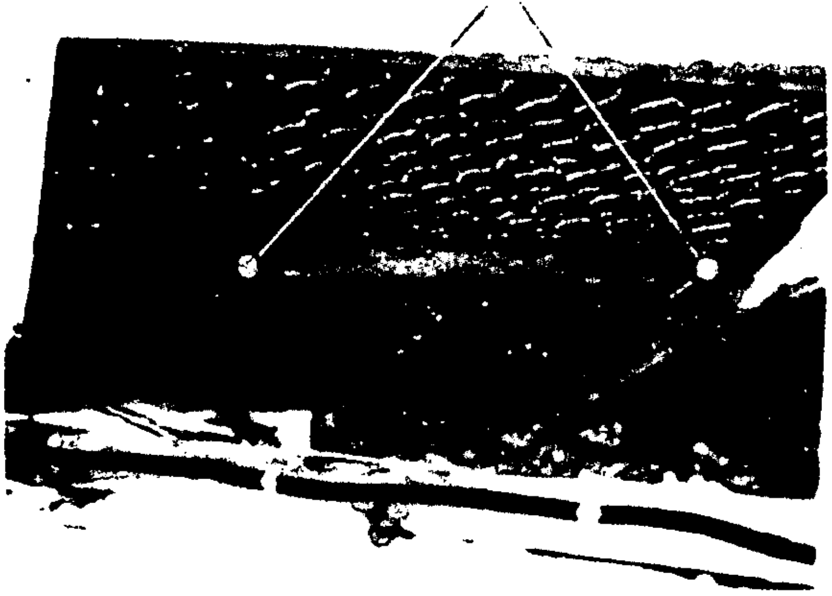


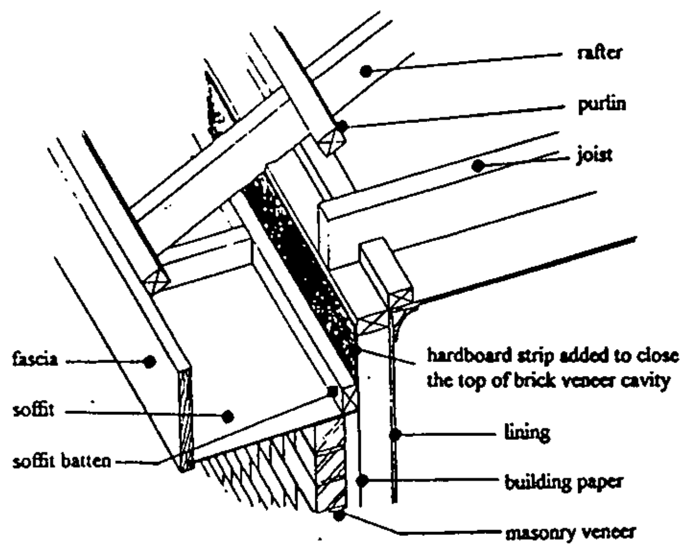
Figure 1 *Roof space condensation (survey 1).*

The houses in the survey were 10 to 30 years old and had uninsulated, suspended strip timber floors over naturally ventilated crawl spaces, uninsulated brick veneer walls with masonry spaced off timber frames, and timber-framed pitched roofs with various levels of insulation. None was air conditioned or fitted with central heating.

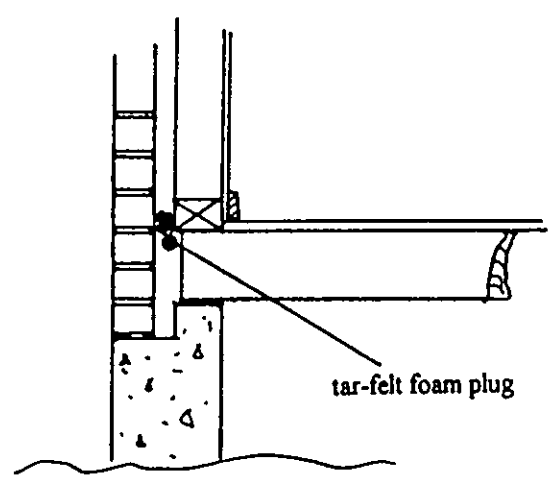
The cost per house averaged less than $NZ400 for applying ground cover, compared to $NZ300 for closing the office each year. These were split into four groups receiving different remedial treatments and monitored over one full year or more. The three treatments were

A. to cover the ground below the floor with polyethylene film (see Figure 3) (houses 1, 2, 3, and 4),
B. to block the veneer cavity at floor level (houses 5 and 6),
C. to block the veneer cavity at eave level (see Figure 2) (houses 7 and 8), and
D. no initial treatment (houses 9 and 10).

The methods of carrying out these modifications were selected with a view to their eventual suitability as retrofit measures. Cavity blocking at the eaves was done by lifting part of the roof cladding and nailing hardboard strips over the top of the frame, as in Figure 2a. Gables were more difficult to treat, but hardboard closers were used here also, applied from within the roof space. Cavity blocking at floor level was carried out with polyurethane foam spray or with bitumen-impregnated foam strips, as indicated in Figure 2b. Covering the ground with polyethylene film, shown in Figure 3, was preceded by some smoothing and raking. The sheets were lapped and taped to each other and to the foundations and piles. These measures were necessary to achieve a tidy finish.



(a). at eaves



(b). at floor level

Figure 2 *Method of blocking veneer cavities (a) at eaves, (b) at floor level.*

Figure 3 Polyethylene ground cover (survey 1).

veneer cavity at the bottom and $NZ800 for closing at the top ($NZ2 ~ $US1—these costs reflect the ease of access rather than the area treated).

Monitoring Program

The 10 houses in the main sample were selected and inspected in March/April (late summer). Remedial work was carried out on eight houses as below, and the formal monitoring program began in May.

Visual inspections and measurements (see below) were made each month through the winter and every two months over the summer. The following summer (January), the two untreated houses (9 and 10) and houses 7 and 8, where the first treatment failed, were treated by covering the ground beneath the houses with polyethylene film. In these last four, inspections continued monthly in the second year from March through to the peak of winter in July.

For each inspection, the timber moisture contents of four roof and four floor structural members were taken in a number of positions (five or more) using a standard commercial meter of the electrical resistance type to obtain the highest, lowest, and most common readings. Roof space temperatures were read from in situ liquid-in-glass thermometers that remained in position for the entire program. Relative humidities in the roof spaces were obtained from uncalibrated portable hygrometers, and their readings must accordingly be given less credence. From time to time, 30-day temperature/humidity pen recorders were placed into either the roof or the subfloor spaces.

One person was contracted to carry out all inspections to achieve a more consistent standard of assessment. A standard inspection report form was used to record these values, and photographs were taken by the inspecting contractor as he saw fit.

Results

The recorded timber moisture contents for the four groups of houses are illustrated in Figure 4.

At the time of selection in late summer, although few moisture contents (m.c.) were recorded, all roof space timbers were regarded as "dry" by experienced observers. The mean m.c. was thought to be in the vicinity of 15%, a typical value in this climate.

Houses 1 through 4 These four houses responded in almost the same way after receiving treatment A (covering the subfloor ground) in May of year one. At that time many of the roof spaces and all the subfloor spaces were noticeably wetter, with a high timber moisture content (20% to 30%) in many locations. In all four houses, drying began immediately in both roof spaces and floor spaces and continued throughout the winter and spring months. The moisture contents remained low through the next summer, when monitoring ceased.

Houses 5 and 6 These two houses, one with a gabled roof and one with a hipped roof, were given treatment B (closing the veneer cavity near floor level) in May of year one. The responses differed quite markedly, with the roof space of house 5 remaining at a relatively high moisture content throughout the winter and that of house 6 drying out as rapidly and as positively as in houses 1 through 4. Both roof spaces became dry during the following summer, and monitoring continued through to the early winter of year two, when it was decided that no further change was likely to be seen.

The timber in both floor spaces remained at a high moisture content through the entire program, summer as well as winter. Moisture content scarcely dropped below 20% at any time and in a number of places remained more than 25% almost continuously.

The cause of the discrepancy between these two houses was not explored. Installation access was difficult, and workmanship may have been erratic. However, the prime suspicion for the failure of house 5 to respond is that it (alone) had an attached garage. The normal construction details of that area commonly left the garage open to both the subfloor space and the roof space, and this has been separately identified as an alternative pathway to carry moist subfloor air into the roof.

Houses 7 and 8 These two houses were given treatment C (blocking the veneer cavity at eave level) in May of year one. Neither appeared to gain any value from the treatment. Roof space moisture behavior through the winter was typical of other untreated problem houses in the district.

In both houses, roof space timber moisture contents rose to very high levels in winter and remained at high levels for most of the winter. The wettest timbers were those closest to the roof cladding, purlins, rafters, and joists—in that order. There were common sightings of extensive visibly wet areas within the roof, with the inspector estimating that 50% of all purlin surfaces and 20% of rafter surfaces were wet or dripping. Roof underlay to most of the roof was reported visibly wet or dripping on several successive monthly visits. Both roof spaces dried out to the same state as the other eight trial houses during

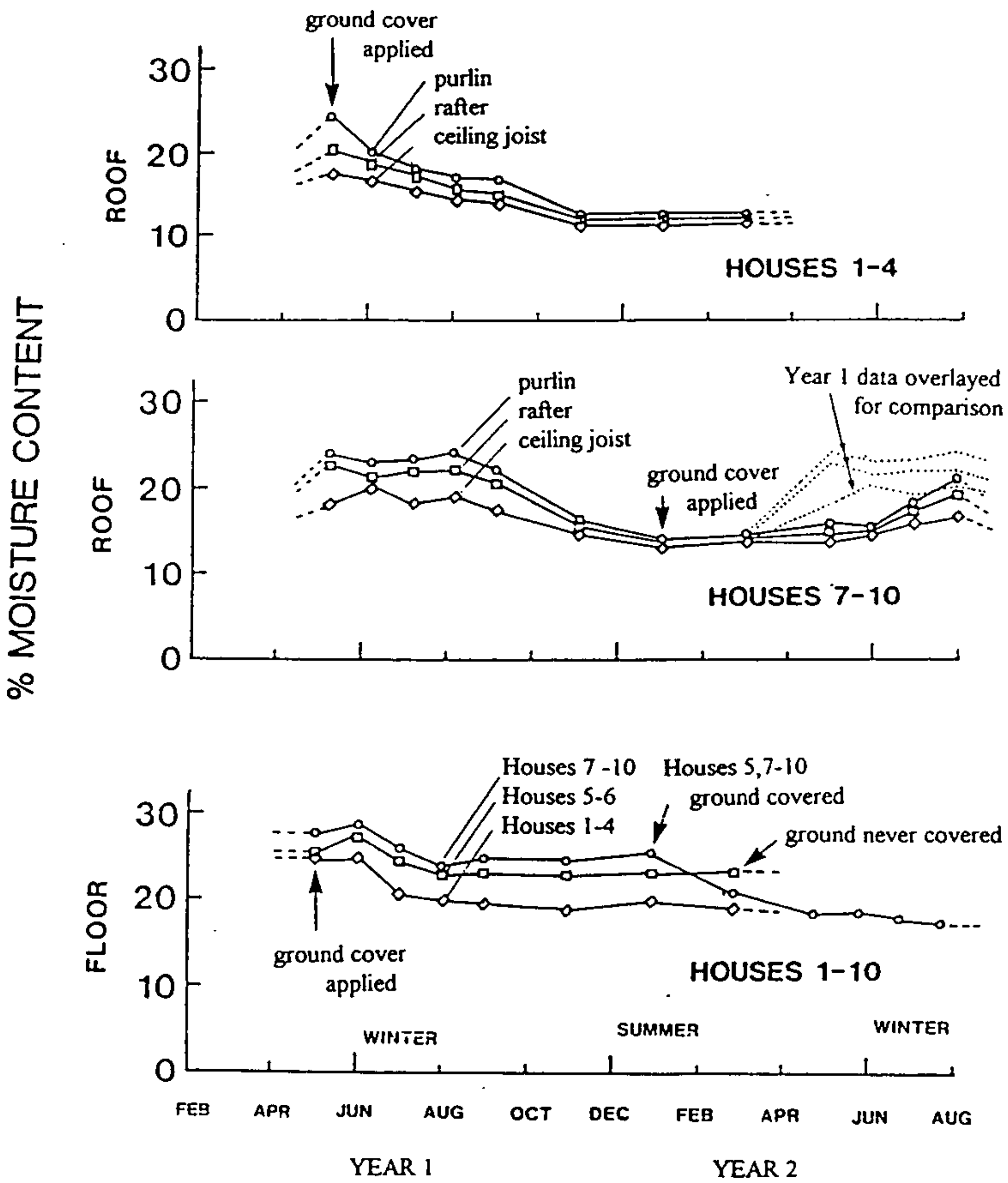


Figure 4 *Average roof and floor timber moisture content (survey 1).*

summer. In both subfloor spaces, the timber remained at a very high moisture content—at or close to 30% at all locations, summer and winter.

During the following summer at the beginning of year two, treatment A was applied. This resulted in a prompt and permanent change. All subfloor timber m.c. immediately began to fall, by some 2% to 3% m.c. per month, to at least 10% m.c. below the previous levels, where it remained. During the winter of year two, the roof space moisture content rose to 15% to 20%, substantially less than the 20% to 25% of the previous winter, and reached the peak for only one month instead of three. Visibly wet patches were seen only once, in one house. Otherwise, roof timber, ceiling insulation, and roof underlay were all reported as "warm and dry to touch" through the winter.

Houses 9 and 10 These two houses received no treatment for the first winter observation. Both subfloor and roof moisture behavior was similar to that in houses 7 and 8. Again, the subfloor timber moisture content was persistently very high, with no change between summer and winter.

Application of treatment A (installation of subfloor ground cover during the summer period) had the same effect as in houses 7 and 8—that of reducing floor timber moisture contents from more than 25% all year to approximately 15% even in winter.

Occupant Response

No occupant response to this work was sought but was commonly offered voluntarily. In all cases, up to the application of ground cover, these comments were negative, e.g., ". . . house still cold and damp . . .," ". . . there's been no improvement. . . ." In every case when subfloor ground was covered, there was an almost immediate positive response from occupants about how "warm and dry" the house now was, "first time in 12 years I can knit in winter." In no case was such a response encountered after any other remedial treatment.

Efficiency of the Ground Cover

It is of interest to try to determine how effective the applied polyethylene ground cover film is in restricting ground evaporation into the crawl space. There was no provision for such a possibility in the original data gathering, and we have to proceed indirectly. The ground cover was applied by contract labor, without supervision, and the results should be taken as typical of commercial installation and not of material capability.

The crawl space is viewed basically as a space warmed mainly by the floor deck over it, with some assistance from ground thermal storage. It receives a supply of water evaporated from the ground, which is mostly removed by natural ventilation, perhaps slightly assisted by storage into the floor and subfloor materials. The relative significance of each of these factors was not known at the time.

Although wind infiltration into the crawl space and the evaporation rate will vary continuously, the long-term average value of infiltration is not expected to change after covering the ground, as the infiltration rate is wind-dominated and the wind is not strongly seasonal. Thus, to find the quasi-equilibrium change in the mean crawl space condition:

$$\text{Water flow in} = \text{Water flow out}$$

$$V \cdot p_o \cdot C + W = V \cdot p_s \cdot C \quad (1)$$

$$\therefore (p_s - p_o) = \frac{W}{V \cdot C} \quad (2)$$

or,

$$W_1 / W_2 = (p_{s1} - p_o)/(p_{s2} - p_o) \quad (2a)$$

where

T_o = outside temperature (°C);
p_o = outside vapor pressure (mbar);
T_s = subfloor temperature (°C);
p_s = subfloor vapor pressure (mbar), subscripts 1 and 2 refer to covered and bare ground, respectively;
V = ventilation rate (m^3/h);
W = mean ground evaporation rate (kg/h), subscripts 1 and 2 refer to covered and bare ground, respectively; and
C = constant relating vapor pressure to moisture content of air (vapor pressure [mbar] = 1600*m.c. [g/g]).

If the long-term mean value of V remains the same after covering the ground and C is a constant, Equation 2a can be used to establish the approximate relative ground moisture emission rates (W) with and without ground cover from estimates of the vapor pressures in the two cases.

Using typical sorption data for timbers (e.g., Cunningham 1984), from the mean crawl space timber moisture contents, the relative humidity (RH) would have been approximately 100% initially (all timber ≃ fiber saturation at most times) and was approximately 85% after the ground cover was placed (timber m.c. remained approximately 20% by weight). Temperature measurements from the survey were limited to spot values of outdoor and subfloor temperatures at each (daylight) visit. The average difference between subfloor and outdoor temperatures from 96 such values was +0.7°C (1.3°F), with more than half these values within the range ±2°C (3.6°F). These measurements do not show if there were diurnal fluctuations.

Data from survey 2 also indicate crawl space temperature differences in this range. These data come from one house in which twice-daily measurements of soil, water, and air temperatures and evaporation were recorded over virtually a full year. This showed subfloor temperatures that, after smoothing, remained consistently about 2°C (1.8°F) warmer than the outdoor temperature through all seasons. So for the calculation in Table 2, three trial crawl space temperatures—1°C, 2°C, and 3°C (1.8°F, 3.6°F, and 5.4°F) above the outdoor temperature—have been used.

In Table 2, the estimated relative ground moisture emission when the soil was covered depends strongly on how much the crawl spaces were in fact warmed during the observation period. That information is not decisively known for this data set, but the best estimate is that ground evaporation was reduced by the polyethylene cover to 5% to 30% of that from the bare ground, according to whether the crawl space was warmed by 1°C or 2°C (1.8°F or 3.6°F). These values are considered to be the lowest and highest mean winter values that can be supported from this data set.

SURVEY 2—EVAPORATION FROM SUBFLOOR SOIL

Measurement Methods

This survey is described in Trethowen (1988b) and Abbott (1983).

The first task was to find a method for measuring the emission of water from the subfloor ground. Of several methods considered (including the moisture content gradient above ground surface and the use of hygrometric change in a small controlled airflow over the ground surface), the only methods finally tested were two variations of a method called *lysimetry* (Curtis and Trudgill 1974), namely, soil lysimetry and free-water lysimetry. A lysimeter is essential-

TABLE 2
Estimation of Reduction in Ground Evaporation with Polyethylene Film Cover (Survey 1)

(ΔT = crawlspace temperature - outside temperature)

Month	Average Outdoor Mean Temp (°C)	Average Outdoor Mean Vapour Press (mbar)	With No Ground Cover: Crawl Space RH ~ 100%, ΔT 1°	ΔT 2°	ΔT 3°	With Ground Cover: Crawl Space RH ~ 85%, ΔT 1°	ΔT 2°	ΔT 3°	∴ Relative Ground Moisture Emission, ΔT 1°	ΔT 2°	ΔT 3°
			P_S mbar			P_S mbar			W_1/W_2 from Eqn (2a)		
Jan	13.9	14.3	16.9	18.1	19.2	14.4	15.4	16.3	.04	.28	.42
Feb	14.4	14.8	17.5	18.6	19.9	14.9	15.8	16.9	.04	.28	.41
Mar	12.2	12.8	15.2	16.2	17.3	12.9	13.8	14.7	.046	.28	.42
Apr	10.0	11.0	13.1	14.0	15.0	11.2	11.9	12.7	.053	.29	.43
May	8.3	9.8	11.7	12.5	13.4	10.0	10.6	11.4	.054	.30	.43
Jun	5.6	8.2	9.7	10.4	11.2	8.3	8.9	9.5	.063	.31	.44
Jul	5.0	7.8	9.3	10.0	10.7	7.9	8.5	9.1	.063	.30	.44
Aug	6.1	8.5	10.1	10.7	11.5	8.6	9.2	9.8	.041	.30	.44
Sep	8.3	9.8	11.7	12.5	13.4	10.0	10.6	11.4	.054	.29	.43
Oct	10.0	11.0	13.1	14.0	15.0	11.2	11.9	12.7	.053	.29	.43
Nov	11.1	11.9	14.1	15.1	16.0	12.2	12.8	13.7	.050	.29	.42
Dec	12.2	12.9	15.6	16.2	17.3	12.9	13.8	14.7	.046	.28	.42
								Mean =	.05	.29	.43

ly a bucket. The principle is that a sample of soil is placed in the bucket, which is, in turn, placed on the soil where the sample was taken. The bucket is periodically weighed, and the weight changes indicate the change of moisture that has occurred. In practice, the method is not easy. Great care must be taken that the soil sample is not internally disturbed, that the physical environment over the lysimeter is not unduly disturbed by the lysimeter, and that the lysimeter exterior is totally cleaned and dried for each weighing. Because each lysimeter progressively loses water that is not replaced from the surrounding soil, it has a limited life. A program of setting up new lysimeters of overlapping age would be needed for reliable data to continue to be taken.

A fairly extensive technology of soil lysimetry and soil surface moisture balance exists (see Curtis and Trudgill 1974), and lysimeters from as small as a drinking glass up to many cubic meters' volume have been reported. This knowledge, however, has been developed for horticultural or agricultural purposes and applies only to soils exposed directly to the natural weather. Conditions for subfloor soils are different because there is no rain, no sunshine, little or no wind, no normal dew or frost-forming influences, and no vegetation.

The standard soil lysimeter is regarded as reliable (Curtis and Trudgill 1974) but is difficult and expensive to operate. Abbott (1983) set out to test the possibility of using free-water lysimeters in lieu of soil lysimeters for measuring soil evaporation rate. The vapor pressure over any given soil increases as the soil moisture content increases. For each soil type, there is a soil m.c. above which the vapor pressure reaches that of a free-water surface. This level is referred to here as the "critical m.c." The outcome of Abbott's work, indicated in Figure 5 for four local soil types, shows a critical m.c. of approximately 5% for two sands, approximately 25% for a clay, up to about 30% for some loams, possibly volcanic. The results in Figure 5, where evaporation from the soil lysimeter exceeds that from a free-water lysimeter, were attributed by Abbott to increased surface area of soil due to the presence of lumps. Thus Abbott has confirmed that for soils near or over the critical m.c., the evaporation from the soil is the same as that for a free surface.

Free-water lysimetry is a fairly inexpensive method. Its success depends on the soil being wet enough most of the time. (The lysimeter evaporation rate may alternatively be regarded as a limiting value that would not be exceeded even with wet soil.) This method was selected because its deficiencies were thought to be totally outweighed by its simplicity. In this survey, the soil moisture contents were also routinely measured, and for all those cases where the m.c. was less than the expected critical m.c., the evaporation rate values were rejected.

Subfloor Evaporation in Houses in Three Cities

The survey was carried out using free-water lysimeters in 60 houses without ground cover selected from a range of sites in Auckland, Wellington, and Christchurch. The

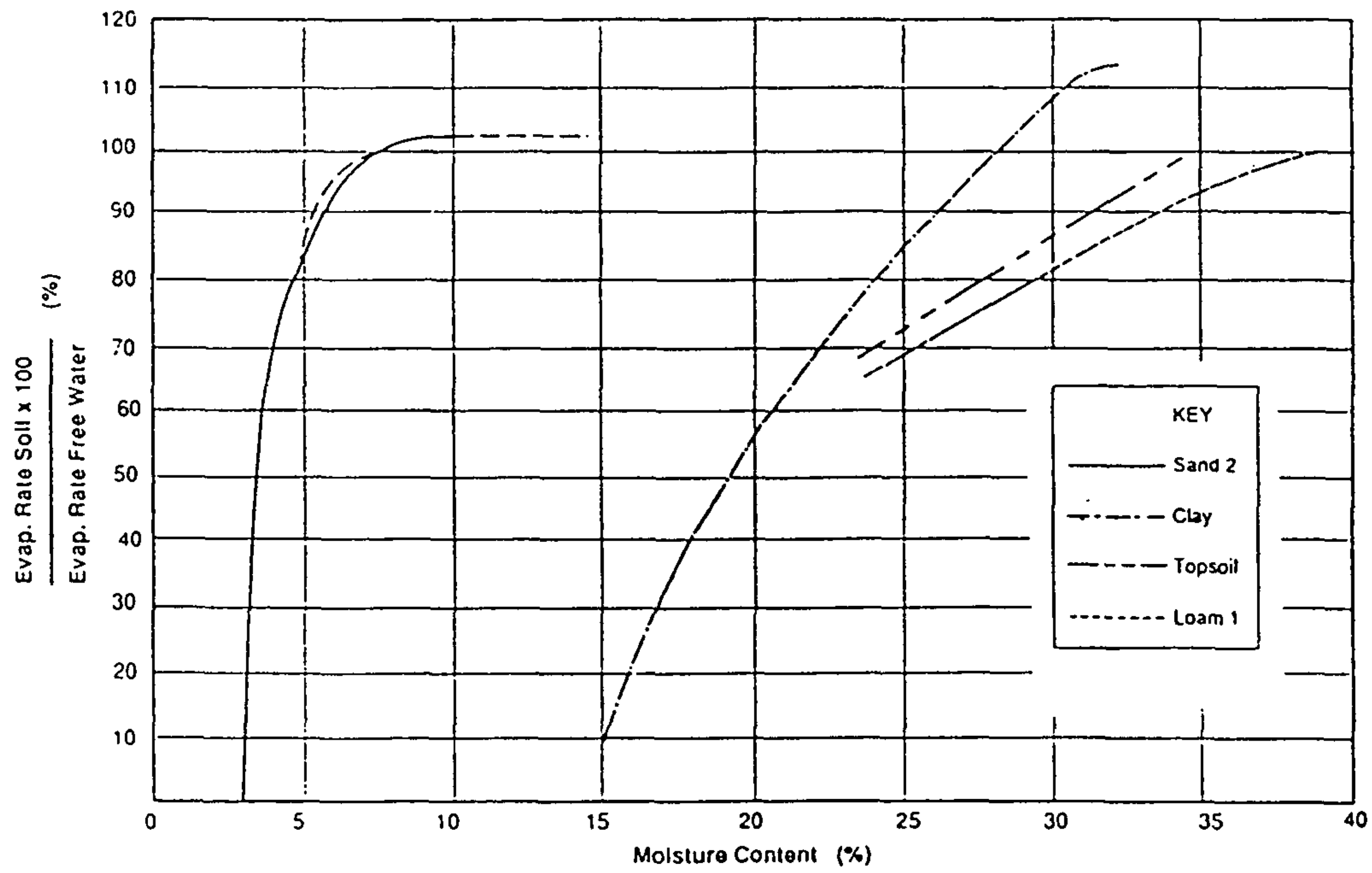


Figure 5 *Relative evaporation rates over moist soils (survey 2).*

subfloor soil moisture content was also reported, and those results where the soil m.c. did not meet the critical m.c. for its soil type were rejected.

Equipment

The lysimeter equipment used is shown in Figure 6. The three main elements are the evaporation tank (which is partially immersed in the soil), a feed reservoir tube with a height scale, and air and water pipes that together provide control of the water level in the evaporation tank to within approximately 1 mm (1/16 in.). The evaporation tank is buried so that it is as close as possible to the temperature of the top layer of soil. The edge height is a compromise between the conflicting needs to have zero obstruction to air cross-currents and to keep soil from falling into the tank. Because the water level is controlled to precisely the height of the "air pipe" outlet, any evaporation (or condensation) from the evaporation tank is accompanied by a change in stored volume in the reservoir and may be directly read from the height scale. The reservoir rested on two support rings and could be directly lifted off for easy recharging with water.

Procedure

Twenty houses in each of the three cities were selected. The sites were distributed over different suburbs of the three cities. A free-water lysimeter of the type in Figure 6 was installed in the subfloor space of each house. The initial installation took place in late winter (August).

At each visit, the reservoir was charged to an arbitrary level near the top of its measuring scale and the value was recorded after allowing the water levels time to equilibrate. This usually took a few minutes.

Further readings of the lysimeter reservoir levels were taken on five occasions at two- to three-month intervals over one year. When required, the lysimeter reservoirs were refilled, with "before" and "after" water levels recorded. Even if the reservoir was found to be empty, the observers were able to establish the "water debt," and the true evaporate quantity could still be determined. This is possible because after exhaustion of the reservoir, further evaporation takes place from the evaporation tank with only a very small drop in water level and no change in exposed surface area.

Where the soil m.c. exceeded the critical m.c. for the soil type, the evaporation rate result was rejected. The proportion of rejected/total results was 20% for Auckland, 35% for Wellington, and 21% for Christchurch.

The results of this survey, excluding the rejected values, are shown in Figure 7, separately for each city. The mean soil evaporation rate over all sites was found to be approximately 400 $g/m^2 \cdot day$ (1.3 $oz/ft^2 \cdot day$), with very large individual variations; there are clearly some regional and seasonal differences as well.

A comparison of lysimeter evaporation rates with subfloor vent provisions found in each house is summarized in Figure 8. The data indicate that there is no particular correlation between the two. However, it must be noted that the subfloor vent provision is subject to a bias. While some important vent openings can be identified and measured,

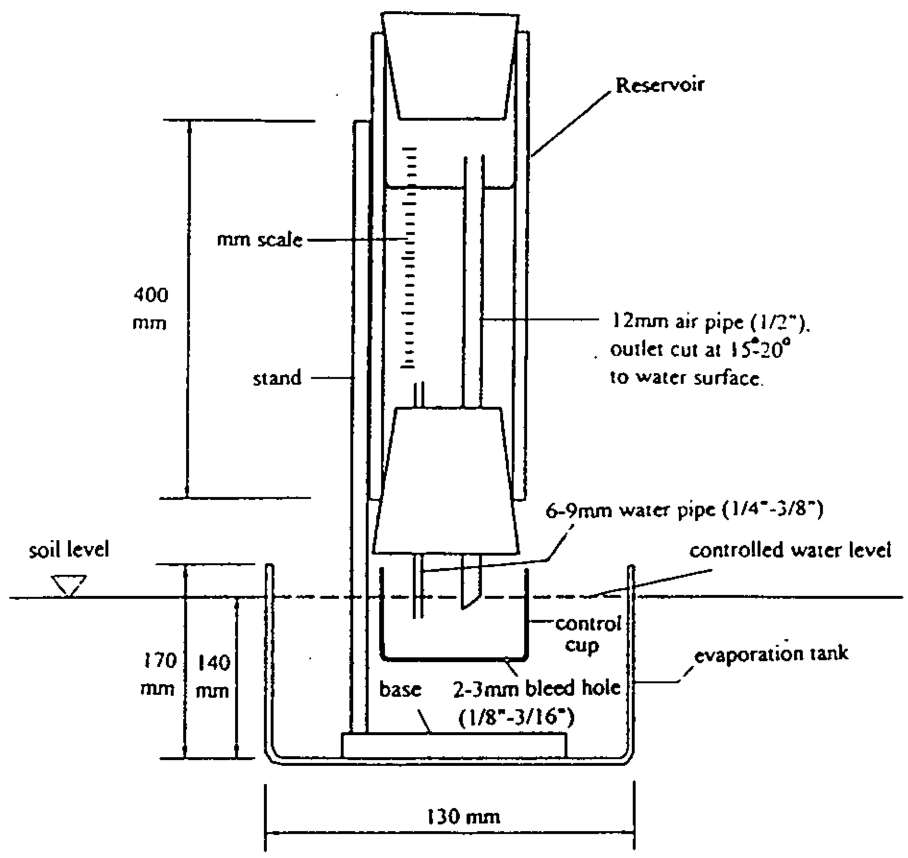


Figure 6   Details of "bird-bath" free-water lysimeter (survey 2).

others cannot be measured, and still others are completely concealed. So the actual vent area will be equal to or larger than the estimate but not less. Some 50% of the houses had identifiable vent openings meeting or exceeding the NZS 3604 (SANZ 1984) requirement of 3,500 mm^2/m^2 (0.5 $in.^2/ft^2$) of floor area. Figure 8 indicates that actual vent provisions have little similarity to the regulations and that the moisture emitted from the ground is uncorrelated to the vent area (r^2 = 0 to 3%).

SURVEY 3—NATURAL SUBFLOOR VENTILATION RATES

The third survey was part of a field study on the natural interchange of airflows in five houses, A-E, between subfloor, roof space, and occupied spaces in houses (see Bassett 1988, 1990). All five houses had about the same number and type of ventilators in the subfloor perimeter wall, contributing 1,000 to 3,000 mm^2/m^2 of floor area (0.15 to 0.45 $in.^2/ft^2$ of floor area) to the leakage area. However, the effective measured leakage area was 3,500 to 6,500 mm^2/m^2 of floor area (0.5 to 0.93 $in.^2/ft^2$ of floor area), indicating that much of the leakage area actually available was fortuitous.

This study began by measuring the overall airtightness of the roof, subfloor, and living zones, with some of the air leakage paths being determined by elimination. This was followed by a multitracer study using R-12 and SF_6 as tracers, with automated control and data gathering with an electron capture gas chromatograph. The infiltration and interchange rates were monitored over four to six days for the three zones and were shown to be strongly and linearly related to the wind speed and almost unrelated to temperature differences. These responses to wind and temperature influences are typical of the temperate windy climate of New Zealand. The rates were found to correlate well with the model of Walton (1981), with some additional zonal interflow resistance coefficients.

The principal results of this survey are summarized in Table 3 and Figures 9 and 10. Figure 9 shows how these results compared with the Walton model and also indicates that the subfloor ventilation rates during the observation period were 2 to 8 air changes per hour. By comparison of the mean wind speeds during the survey period and over an average year, it is considered that the annual average ventilation would be a little larger than that during the survey period. Figure 10 indicates the air interchange rates between subfloor, roof space, and occupied space for two types of timber-frame construction—timber plank cladding and masonry veneer cladding. These differ in the detail of ventilation coupling as well as in the cladding material. In the case of masonry veneer construction, about one-third of the roof-space ventilation was found to come from the subfloor region, as inferred in survey 1. Other air interchanges were relatively small, especially for downward directions.

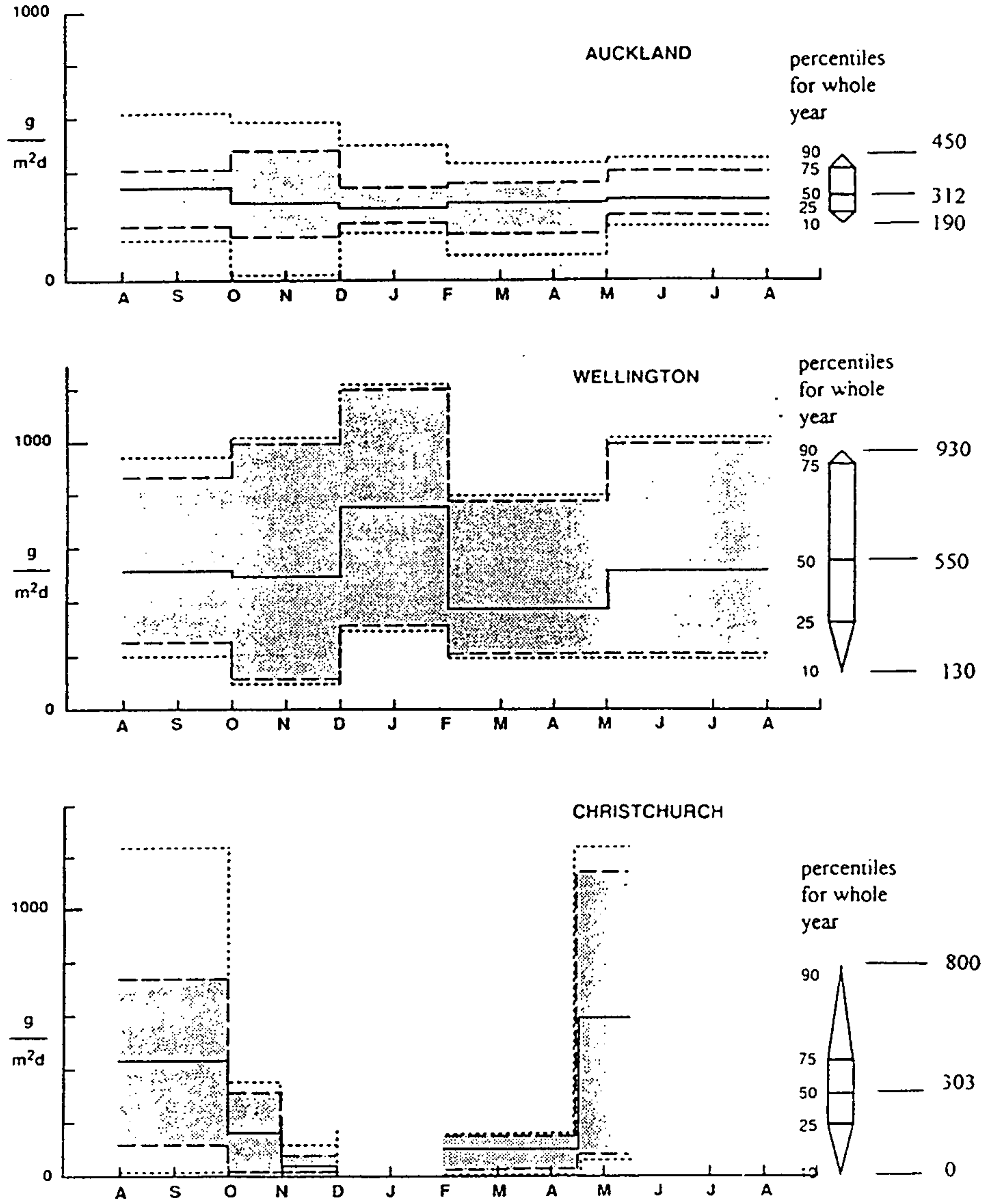


Figure 7 *Summary of free-water lysimeter evaporation over one year (survey 2). (The 90, 75, 50, 25, and 10 percentiles are indicated both for each period and for the year total.)*

DISCUSSION

A considerable amount of information has now been collected about crawl space moisture and the factors affecting it. Mostly these data are consistent, but two issues need further attention.

The first issue concerns the ground heat balance. Any evaporation that takes place will extract a corresponding quantity of latent heat. Simple comparisons of the magnitudes of heat supply to the ground indicate that the principal source of heat is from the floor deck itself and that it is a little difficult to find sufficient heat sources to fully account for the heat needed to evaporate the 400 $g/m^2 \cdot day$ (1.3 $oz/ft^2 \cdot day$) ground evaporation observed in survey 2. A corollary not tested in these surveys would be that insulated floor decks should be expected to have lower ground evaporation.

The second issue concerns the rate of airflow, where, again, simple comparisons suggest that more than 10 air changes per hour would be needed to remove the mean indicated evaporation rates from survey 2 without exceeding 100% RH. However, survey 3 indicates that the likely actual subfloor ventilation rates are lower than 10 air changes per hour.

These discrepancies are not particularly large, and no conclusive analysis has been made. The simplest interpretation would be that the evaporation rates from survey 2 may be a little high, but these two factors should be addressed in future studies.

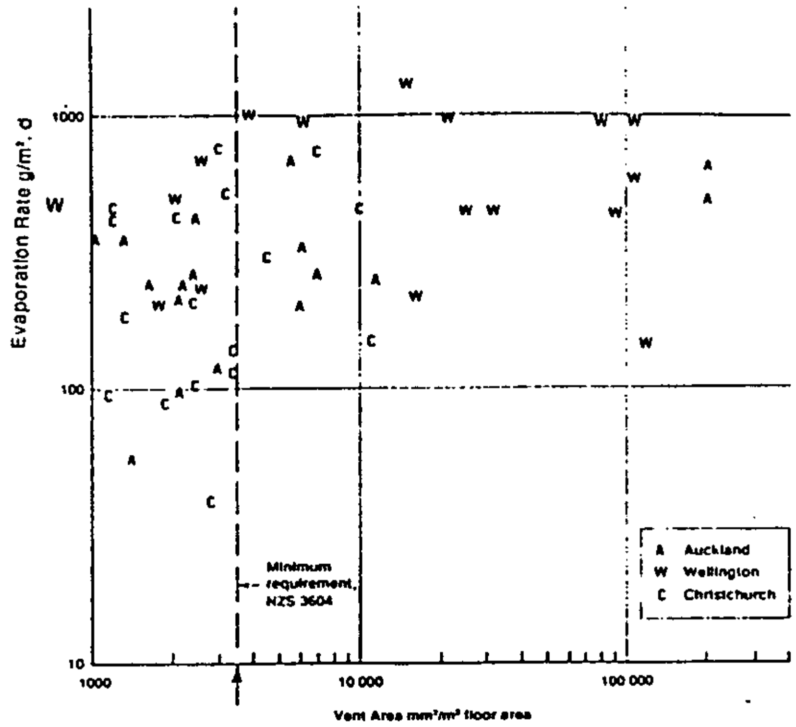


Figure 8 *Ground evaporation vs. vent area (survey 2).*

TABLE 3
Natural Ventilation and Interchange Rates in Five Houses (Survey 3)

	Timber Plank Cladding				Masonry Veneer Cladding		
Zone Infiltration, air change/h	House ID B	C	D	mean	House ID A	E	mean
Roof Space	7.0	1.0	1.5	3.2	4.0	9.0	6.5
Living Space	0.7	0.35	0.2	0.42	0.55	0.45	0.5
Subfloor Space	5.5	1.3	2.0	2.9	4.5	7.0	6.8
Zone Interchanges m^3/h							
Subfloor to Living	20	10	4	11	20	14	17
Living to Subfloor	10	2	10	7	-	5	5
Subfloor to Roof	30	6	10	15	190	135	163
Roof to Subfloor	0	2	1	1	0	0	0
Living to Roof	35	30	25	30	90	50	70
Roof to Living	0	10	1	4	30	8	19

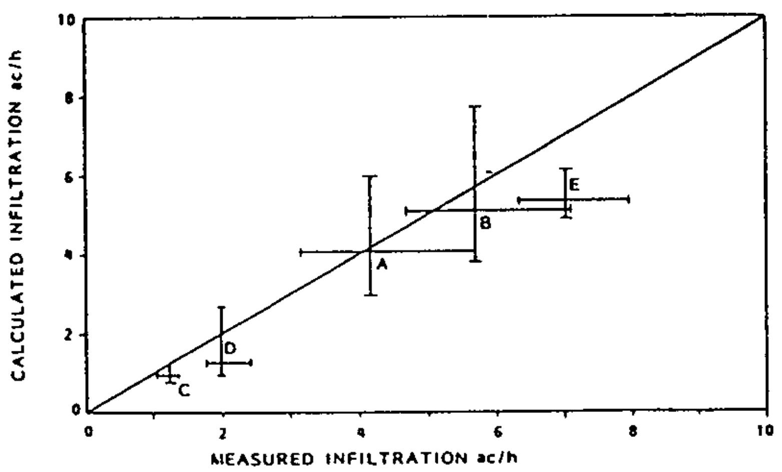


Figure 9 *Mean measured and calculated infiltration in subfloors of five houses, A-E, survey 3 (from Bassett 1990).*

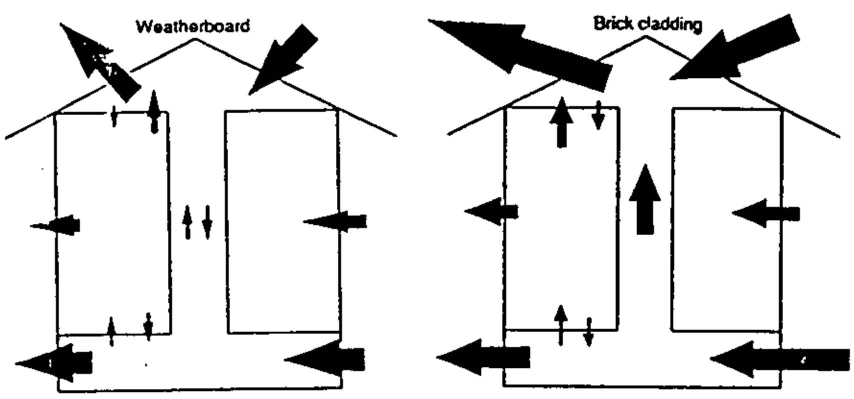


Figure 10 *Approximate interzonal airflows in five houses, A-E, survey 3. The shaft through the center of the house represents the leakage paths that bypass the living space. The magnitude of the airflow is indicated by the arrow size (from Bassett 1988). See also Table 3.*

SUMMARY

An outline of the three surveys relating to crawl space conditions in New Zealand has been given and indicates the following:

- Crawl space timber moisture levels were in many cases very high, with floor framing often exceeding fiber saturation for long periods when no ground cover was present.
- Covering subfloor ground with polyethylene film almost immediately produced a significant drop in the mean moisture content in floor framing timber.
- The average subfloor evaporation rate was about 400 $g/m^2 \cdot day$ (1.3 $oz/ft^2 \cdot day$), with a large individual range from near zero to more than 1,000 mm^2/m^2 (3.3 $in.^2/ft^2$) of floor area.
- Polyethylene films applied commercially, unsupervised (as in Figure 3), reduced the ground moisture evaporation by at least 70% and possibly as much as 95%.
- Unsolicited occupant responses to the installation of ground cover were in every case strongly positive regarding how "dry and warm" the houses had become, although it is almost certain the houses were not any warmer.
- If the ground moisture content is nearly or fully saturated, free-water lysimetry can be used to conveniently and inexpensively monitor ground moisture emission.
- Observed natural subfloor ventilation rates for houses as built typically averaged 2 to 8 air changes per hour for wind speeds of 2 to 7 m/s (6 to 22 fps), increasing linearly with wind speed, but they were not affected by temperature.

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DISCUSSION

Paul Tseng, Chief, Engineering Services, Montgomery County Government, Rockville, MD: Given the "updraft" from crawl space ventilation into attic space for the brick veneer model, would the practice of blocking or sealing the crawl space vents be recommended for winter or drier seasons to improve energy efficiency? Would blocking of vent openings, on a seasonal basis, be a design consideration (i.e., using damper-operated vent louvers)?

H.A. Trethowen: The framing cavity should be fully closed and that is where any insulation would be. The veneer cavity is traditionally left-vented as a discouragement to effluorescent growth on the exterior of the masonry.

Steve Braun, Director of Technical Services, North American Insulation Manufacturers Association (NAIMA), Alexandria, VA: By adding a polyethylene vapor retarder over the surface of the crawl space floor/ground surface, the moisture content is dramatically reduced. Also, the moisture content of the soil affects the evaporation rate, therefore, the greater the moisture content in the soil, the greater the humidity in the crawl space. Could the moisture content of the soil within the crawl space be sufficiently reduced to a level where the humidity is at an acceptable level if crushed stone and drainage tile/pipe around the outside periphery of the foundation wall were used at the time of construction?

Trethowen: External drainage has been found to be effective in ameliorating extreme wetness under floors. It is not clear whether soil moisture could be reduced to low levels by this means, especially in a wet climate.

Lynn Stiles, Professor of Physics, Richard Stockton College of New Jersey, Pomona: Is there any evidence that crawl space moisture content is related to the use of the distribution system (i.e., whether ducts are in the crawl space)?

Trethowen: It has been observed that a source of heat in the crawl space can cause substantial moisture problems if the sources of moisture are not cut off.

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