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Airborne Moisture Transfer: New Zealand Workshop Proceedings and Bibliographic Review

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Air Infiltration and Ventilation Centre
Old Bracknell Lane West, Bracknell,
Berkshire RG12 4AH, Great Britain.

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Annex V Air Infiltration and Ventilation Centre

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The Air Infiltration and Ventilation Centre,
Old Bracknell Lane West,
Bracknell, Berkshire
RG12 4AH, Great Britain.

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CONTENTS (i)

Preface (iii)

Introduction — Opening address
The Hon. Margaret Shields (v)

Section 1 — Proceedings

Papers:

1 Air, earth, water .... the sources of moisture
H.A. Trethowen 1.1

2 Seasonal storage of moisture in roof sheathing
M. Sherman 2.1

3 Air flow resistances in timber frame walls
M. Bassett 3.1

4 The use of equivalent electrical circuits to describe the moisture behaviour of structures
M.J. Cunningham 4.1

5 Moisture research in Sweden
J. Kronvall 5.1

6 Short presentation of the airborne moisture problems and research activities within this field in Norway
J. Brunsell 6.1

7 The control of condensation within buildings in the United Kingdom
A. Wilson 7.1

8 Field experiences of building moisture
A.R. Bongard 8.1

9 Air leakage tests on polyethylene membrane installed in a wood frame wall
C-Y. Shaw 9.1

10 Ventilation to reduce indoor condensation
R.C. Bishop 10.1

Discussion 11.1

Section 2 — Review and Bibliography
M.W. Liddament, J. Blacknell, Y. Parfitt 12.1

PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme, the IEA encourages research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is encouraging various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods, as well as air quality and inhabitant behaviour studies.

The Executive Committee

Overall control of the R&D programme "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and, based on a knowledge of work already done, to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

INTRODUCTION

Opening address by the Hon. Margaret Shields
Associate Minister of Housing, New Zealand

I am pleased to be here today to open New Zealand's first Air Infiltration and Ventilation Centre Conference which I think deals with an important, but generally little understood, subject. Before I begin, however, I would like to say a word of thanks to Mark Bassett who has had the time-consuming task of organising this conference and ensuring that everything runs smoothly.

When I say "important but little understood subject", I am referring of course to condensation, the silent destroyer of the frabic of many of our New Zealand homes. You are gathered here for this conference to discuss how to overcome this insidious destroyer.

There are few statistics of the extent of the problem, but BRANZ alone expects to receive up to 1,000 calls a year and rates it as one of the most frequent inquiries it receives. Research for this speech indicated availability of a considerable amount of technical knowledge which Government has assisted you in obtaining through helping pay for membership of the Centre. The Housing Corporation, as the country's largest landlord, is, through a long-term record of problems, very aware of the ramifications.

Yet, for all your technical knowledge, it is perhaps public awareness of the problem which is more important. You could almost call condensation a "social" disease, for it is the way we live in our houses which contributes most to the problem. Security of our homes is important but, while locking them up tightly to keep out thieves and vandals, it can help also to promote dampness and decay. With more of the family out in the workforce, homes now tend to be left locked up all day and subjected to considerable temperature fluctuations without the compensating balance of air flows through normal traffic in and out of a dwelling. What this tells us is not so much that we have a technical problem, but an educational one. Building research studies have shown that ventilation determined by building occupancy will have more control over condensation than air infiltration. Yet people are not aware that their houses need to breath, just as they do. Designers apparently are not taking into account the growing need for a combination of ventilation and security. Ask a person to leave a house with a window open for ventilation and take the option of condensation or a burglary and I need not tell you the answer. Yet they can suffer monetary loss as severe as the burglar's gain as condensation quietly damages the fabric of the house.

Dogs locked inside, large window expanses on the cold sides of buildings and poorly ventilated bathrooms have all been causes of the Corporation having condensation damage problems. Yet there still appears to be little direct information as the economic impact of similar cases which, I suspect and you might be able to confirm, are quite considerable. Replacement of wall linings, redecorating and more frequent maintenance are tangible individual householder costs, but the overall cost is something of a mystery.

Local authorities' attention should be drawn to their responsibility to ensure that, during the building process, wall linings go in only after timbers are at the correct moisture content. As a routine measure with its buildings, the Corporation insists on overlapping of polythene within foundations, adequate sub-floor ventilation, and condensation traps and collectors on aluminium joinery.

We had a case in a new Christchurch flat where a baby's cot was beside an aluminium window, just above a power point. During the winter it was discovered that condensation was running off the window, down the wall to the power point. Fortunately nothing happened on that occasion, but it does stress the hidden dangers of unchecked, rampant household moisture.

Our builders, too, need education. A simple, inexpensive expedient such as the use of polythene sheets on the ground can, surprisingly enough, be an effective answer to combatting likely moisture in roof spaces. Education is also needed to ensure timber used is properly dried and insulation is up to specification (or even better) if necessary. New Zealand, due to its maritime climate, has a special problem with condensation and I would think there are many houses in the newer construction era affected by this factor. The building industry and consumers will be interested to hear your news, that suggested changes to building practices to control moisture levels by controlling air currents, are not expected to affect building costs.

As Associate Minister of Housing, I am well aware that housing is one of our most valuable resources. Government's goal is to work to ensure that every New Zealand family has decent and affordable housing. That does not solely depend on regularly adding to our 60,000 state rentals, or making finance available in a variety of ways to help modest income earners into their first homes. It is also important that we preserve our existing housing resource. Government is doing this through home improvement loans and urban renewal schemes, but it is important that every avenue be explored.

Government has made calls for the provision of affordable housing through innovative design and construction, better site utilisation and provision of flexible housing finance packages for modest income earners. When we talk about affordability through innovation, we do not mean savings by building smaller houses on smaller sections. We want cost-saving housing innovation that provides a good quality of life and fits in with the environment both in appearance and function.

It is the latter which concerns you and I am pleased to see that your Workshop is dealing specifically with home airborne dampness. It is apparent that, as international members of the Air Infiltration and Ventilation Centre, you have access to vital information. But I again wonder if the spread of the message is wide enough and whether there is enough pre-emptive public education available.

Do home builders know enough to ask their builders or architects questions about ventilation which can cope with their lifestyle and even if they do, do they get adequate answers ? If they do not, they can be faced not only with damage and economic factors already mentioned, but also with drains on expensive energy, and, what is more important, health hazards.

Education is one way to overcome this, and the other broad approach which must be looked at is the designing of the building envelope and fittings to minimise the problems. The Housing Corporation, as it is doing in a number of fields, has taken an initiative here. It is endeavouring to cope with moisture entrapment and build-up by using passive solar design principles to build warmer, tighter houses with higher insulation levels. For instance, double tongue wedge fasteners cater for both ventilation and security needs. The Corporation will be monitoring its solar houses in the contrasting climates of Christchurch and Tauranga, and should gain valuable information which I am sure it would be only too happy to make available to your organisation.

Just before I end, I would like to give you some idea of the overall impact of the Government's input into New Zealand housing through the Housing Corporation. Last year, the Corporation helped finance 4,800 building and home improvement projects worth 136 million dollars. So far this year the figures are 3,300 projects worth 93 million dollars. On top of that, in two years 600 million dollars has been provided for purchase of 17,600 existing homes and 2,750 state rental units have been acquired. We are helping young couples through special equity schemes designed to get them into homes they otherwise would not have acquired. We have "granny flats" in which the elderly can live on relatives' or friends' properties, and a home swap system where they can exchange large homes for more appropriate units, freeing up their houses for family use. Also, in what has been a most significant development, we have overcome the problem of building on multiply-owned Maori land.

I thank you for your attention and hope your important deliberations, which are so important to all home owners and residents in New Zealand, have the results you are seeking. I have pleasure in declaring your Conference officially opened.

Section 1:

Proceedings

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 1

AIR, EARTH, WATER ......
THE SOURCES OF MOISTURE

H.A. TRETHOWEN

Building Research Association of New Zealand
Private Bag
Porirua
New Zealand

AIR, EARTH, WATER .....
THE SOURCES OF MOISTURE

H.A. Trethowen

Synopsis

For 50 years moisture control technology in buildings has been presented as primarily a matter of vapour diffusion and vapour barriers. The evidence on which the technology is based is briefly reviewed, and shows that for 25 years there has been evidence that air movements are more important. In evaluating the amounts and behaviour of typical moisture flows in timber framed houses this paper draws particular distinction between "forced" and "floating" indoor vapour pressure regimes, and argues that in the normal "floating" case certain features of the traditional vapour diffusion model are inconsistent with observations.

The paper concludes that moisture control is predominantly related to air movements, often in miniscule amounts, and that deliberate effort to encourage application literature to reflect this is needed.

1. Introduction

The intention of this paper is to review three issues concerning moisture in buildings:

- the methods and basis for moisture design
- the sources and transfer of moisture
- attitudes to moisture control

There are two major classes of building moisture problem, excluding those related to leaks. The first is "surface condensation" or "mildew growth", on indoor surfaces visible to the occupants. The second is interstitial "structural" or "cavity" condensation, within the structure and usually not visible to the occupants. The two classes have little to do with each other.

An important but little-discussed classification point is whether the building indoor moisture state is "floating", or "forced". The floating condition is taken to mean that whilst the building may be heated and there may be miscellaneous moisture sources, these occur in a way equivalent to "natural ventilation", without any particular end result being forced. The forced condition is taken to mean that a particular level of indoor moisture is persistently imposed, eg., by humidification or dehumidification equipment. The point of interest is whether indoor moisture level is floating or fixed, rather than what that level is, and is discussed later.

The usual sources of building moisture, in typical order of importance in New Zealand, are:

- construction moisture
- subfloor ground moisture (by direct contact or by evaporation into subfloor air)
- indoor air-borne moisture (including improperly vented dryers)

- rain and pipe leaks
- indoor vapour diffusion

No discussion of building moisture is complete enough to be valid, without simultaneous consideration of the effects of sunshine, material hygroscopy, moisture storage capacity, thermal and moisture response times.

2. The foundations of building moisture science

The science of moisture control would be taken to originate with Fick (10) in his classic work showing that water vapour moved through materials under the influence of the local vapour pressure gradient. However it now seems that Dalton and others who established the science of psychrometry should be bracketed with Fick.

Although much work was done since those origins, the next developments having major influence on building technology were the studies in U.S.A. by Rowley (20, 21, 22) and Teesdale (24). These were notable for the experimental work they included on typical building structure elements. Sample structures or test huts were exposed to specific environmental conditions for a period, then opened and examined.

Although Rowley concentrated his attention on what was presumably the current difficulty of showing that occupant-generated moisture was capable of accumulating in the structure under the influence of vapour diffusion, he was also careful to consider the influence of material hygroscopy, and showed that moisture accumulation was more severe under constant conditions than under cyclic conditions of the same mean values. He did not consider air leakage or construction moisture in any depth, and dismissed the influence of sunshine on the grounds that it would not apply to polar-facing walls. Rowley described what was later called the "dew-point profile" method for moisture design, and laid principal stress on the use of vapour barriers.

The next well-known milestone came in the late 1950's when Glaser (11) popularised the method since named after him. This method differed from the dew-point profile method only in that the mathematics used were better defined, and that the local vapour pressure was forced to be not higher than the dew point at every point in the walls. The latter was taken at the time to be an important conceptual step by technologists, although it appears in all Canadian literature through the early 1950's and indeed was a specific part of Rowley's 1939 method.

A major change was signalled in 1962, when Platts (19) reported Canadian observations that "... vapour diffusion plays only a small part ..." and "... air flow, rather than vapour diffusion, is nearly always the cause of severe condensation ..." in structures. This observation has been repeated in many Canadian research papers since, e.g., Wilson and Garden (33), Latta (16), Handegord (13), to mention only a few. Dutt (9) reported the same conclusion from work at Princeton. Most contributions to the "Moisture Problems in residential construction" conference Seattle, 1985, (eg. Lstiburek (17)) demonstrated or implied that air-borne moisture, construction moisture and leaks, rather than vapour diffusion, was the cause of most significant moisture failures.

In the 1970's and 1980's several field surveys were reported - Tsongas (28), (29), Weidt (32) - which show in more detail the real influence of moisture in buildings, with the influence of vapour barriers being found to be not significant in the avoidance of moisture problems. Most problems were ascribed to leaks, and to airborne moisture.

3. Applied Technology

Consider now the information available to designers, builders, inspectors in regard to moisture control.

In 1952 Billington (4) in U.K. must have concluded that Rowley's 1938 work was the last word on the subject, as his chapter on structural moisture control was a verbatim copy from Rowley. Other British engineering handbooks did not mention moisture control until the (then) Institution of Heating and Ventilation Engineers, London, published the 1970 edition (15) of their Guide Books. The I.H.V.E/C.I.B.S. Guides are widely used, and in Britain and New Zealand at least are quite influential. The 1970 edition presents information on how to calculate "the dew point" and considers diffusion only. Around 1960 the London College of Heating and Ventilating was teaching its students the same thing, with barely even mention of the Glaser corrections. Other influential British documents include the M.P.B.W. 'Condensation in dwellings', (18) and B.R.E. Digest 110 (5). Books from the 1960's by Diamant (8), Van Straaten (31), Gratwick (12), and others, follow much the same tenor. Collectively these publications have spawned a wide variety of building recommendations, and institutional and commercial publications which endorse a collective attitude that vapour diffusion and vapour barriers are the only issue.

In U.S.A, the influential ASHRAE Guide to Fundamentals (2) was until 1969 also giving detailed information on how to calculate dew point profiles, and although giving a brief discussion on air-borne moisture, stated that this would commonly not be of interest. However by 1972 the emphasis on air-borne moisture movement was strengthened, and further strengthening has continued with each subsequent issue. By 1981, the "practice" section of the guide to Fundamentals carried the message "....It has become recognised that air movement which carries the water vapour with it, is a far more powerful mechanism for transporting water vapour to the point of condensation." and "..Rarely has vapour diffusion been identified as a major factor". These are strong words, they are in direct contradiction to the conventional wisdom of the time, and their sources are highly respected.

However in many circles these changes appear to have gone unnoticed, with the principal interest of designers, manufacturers, inspectors and publications still frequently being directed at vapour diffusion. Most leading designers at any time will have received their training many years previously, and the present group will have been taught to believe that vapour diffusion is the key. Only the leading designers see much of the research papers and conference proceedings and the bulk of routine designers only receive what their seniors or market contacts provide. Although the ASHRAE handbooks now offer a reasonably balanced review of moisture control, they still include - as the only <u>quantitative</u> item - the calculation of dew point profiles, and this item retains prominence. Under today's economic pressure the designer can be expected to take a quick glance at the new Handbook chapter, note that the familiar bits are still there, and ignore additional text.

Engineers are trained to calculate, and what they can't calculate they don't trust. There seems to be a tendency to regard things which can be calculated as more relevant than those which haven't been calculated. The expected result is apparent in N.Z. designers: few think of moisture: many of those who do ask only "where do I put the vapour barrier?"

4. Moisture Sources

Much of non-leak building moisture comes from occupant activity. It has been repeatedly noted that unoccupied buildings don't suffer from surface condensation. A notable exception occurs in the case of construction moisture, where unoccupied new houses are sometimes found to suffer rapid and extreme damage from surface condensation or mildew.

More needs to be known about indoor conditions in real buildings. Fig 1. shows the observed long-term trend of indoor humidity in a set of eight houses studied intensively in 1974 (Trethowen 25). This data is derived from pen records with monthly charts. When replotted onto a psychrometric chart, as in Fig 2, it is immediately evident that these records imply that the (smoothed) indoor vapour pressure was virtually independent of indoor temperature, but was dependent on outdoor conditions. In the short-term daily fluctuation, however, this pattern was not maintained, and the indoor conditions followed a trend intermediate between constant vapour pressure and constant humidity. Only one cycle is drawn, but it is very characteristic of this set of observations for 8 houses over 2 years.

Various estimates of occupant moisture release range from 3-4 kg/day to 10-12 kg/day, with peak days perhaps doubling these estimates. Hansen (14) gives a typical summary. Many of these estimates apply to worst-case rather than to normal cases. The "worst" buildings may have two to four times the moisture generation as in the normal case, and in addition the average day emission for any particular house is usually much lower than the peak-day emission. Whilst peak-day emission is important in respect of surface condensation, it is the average-day emission which matters for structural condensation.

It has been amply demonstrated that this indoor moisture is removed principally by ventilation, with only a small portion passing into the structure, even without vapour barriers (e.g., Trethowen (25), Hansen (14) 1985). The indoor moisture release of 5-10 kg/day, with a mean ventilation rate of 0.5 air change per hour, therefore indicates a mean indoor vapour pressure 2-4 mbar higher than outdoors. Trethowen (25) suggested a "design value" of 3 mbar and an extreme value of 5 mbar, based on separate considerations of moisture balance, energy balance, and field observation. If 10% of the 5-10 kg/day passed into some 250 m^2 of structure, this would represent a moisture flux of only 2-4 g/m^2 day. Peak vapour flow rates for low permeability linings (1 MNs/g) have been calculated in the range $\pm$ 5 to $\pm$ 20 g/m^2 day.

Other sources of moisture include subfloor ground surface evaporation under suspended floors. A BRANZ survey (yet to be published) showed that such evaporation typically averages 300-600 g/m^2 day in New Zealand, amounting to some 40 kg/day for a 100 m^2 house, over a wide range of conditions year-round. Short-term variations from - 200 g/m^2 day to + 3000 g/m^2 day were noted. Hansen (14) reported a very similar mean figure. Elementary calculation again shows that this moisture must be removed principally by subfloor ventilation, which must exceed 10 air changes/h to be successful. Structural details such as open cavity walls or vented linen cupboards which allow subfloor air to pass into exterior wall or roof spaces, lead to rapid and severe roof space condensation of air-borne subfloor moisture. The condensation rate has been estimated (by calculating likely airflow from buoyancy and flow path size, and comparing observed roofspace and subfloor conditions) as up to 200-400 g/m^2 nightly, with some daytime evaporation. This estimate is consistent with actual moisture accumulation. The process has been observed extensively by BRANZ, particularly with masonry veneer construction. Additional roof ventilation has been found to be of no assistance, and the reason for this becomes clear when it is noted that the condensation occurs predominantly on clear nights. The roof cladding is then perhaps 5°C below outdoor air temperature because of radiation cooling, and so introducing more near-saturated outdoor air at 5°C above the cladding temperature will aggravate rather than help.

These various moisture flows are indicated in summary form in Fig.3, which shows that rather large moisture flows are common, and that long term flow rates are not well represented by short-term flow rates.

5. Movement of moisture in the structure.

What of the 2-20 g/m^2d water vapour that enters the structure? Here several classical physics issues arise which might well turn the traditional arguments on vapour movements on their head.

The first issue is hygroscopy of materials. If a structure includes a substantial amount of timber, then that timber will always emit or absorb water in an attempt to maintain its surroundings at a humidity corresponding to the current moisture content of the timber. This humidity depends on the moisture content of the wood, and also on the current temperatures of wood and surroundings. The moisture transfer rates can be very large, and can be maintained for sizable periods because the moisture storage capacity is large. In short term, and usually medium term also, the moisture flow patterns in timber-based construction depend on the current moisture content and temperatures in the timber, not on the externally imposed vapour pressure gradient. For example, part of the initial drying of a new construction will be inwards to occupied space whence it is vented to outdoors, in spite of a persisting adverse vapour pressure gradient. In very ordinary structures examined by computer simulation by Trethowen (26), the drying was principally inwards.

The second issue is dynamics. Note firstly that the "dew-point profile" calculation method is a steady-state calculation. It is invalid where steady-state has not been reached. But in contrast to the corresponding thermal case where equilibrium is typically reached in hours or days, moisture equilibrium is approached only in weeks or months. Thus the calculation is invalid where applied to any form of peak conditions. Furthermore, computer simulations involving cyclic variations of boundary temperatures show that drying through the warm part of the cycle tends to outweigh wetting during the cold part (e.g. Trethowen (26)). Rowley (21) demonstrated this effect experimentally, by showing that moisture accumulation was much less in cyclic than in steady conditions of what he described as equal mean value.

Thirdly there is solar radiation. Moisture workers have traditionally dismissed solar radiation on the grounds that it can't be assured, especially on the polar faces of a building. This seems too severe, as it is now well known that appreciable diffuse radiation reaches all exterior surfaces, that the proportion of diffuse radiation approaches 100% of total radiation on cloudy days, and that days where less than 10% of maximum radiation is received are rare. The effects of sunshine were reported by Sherwood & Peters (23) who showed that winter moisture contents on equatorial facing walls in Wisconsin were some 5% lower than polar walls, with E/W walls intermediate. Since Wisconsin has a quite cloudy winter (mean radiation received is some 40-45% of extraterrestrial), it can be expected that even the polar walls in this case were benefiting from diffused sunshine.

Fourthly there is cavity ventilation. This subject has been discussed in general terms for decades but it has not apparently been made plain just how small are the rates of ventilation needed to achieve moisture control. Trethowen (27) showed by use of the Keiper method that cavity ventilation rates of 0.1-0.5 cavity air change/h (too small to have any thermal influence) would be sufficient in a case of moderate condensation to totally prevent all accumulation of moisture. Similar results were obtained from computer simulation. These represent trace quantities of ventilation of the cavities. Consider these rates in terms of building infiltration. Typical in-service infiltration rates for New Zeland houses are 0.3 - 0.5 room airchanges/h. Bassett (3) reports that in typical timber houses with "unvented" wall cavities, about 1 $l/s.m^2$ (or 0.15 room airchange/h) passes out through indeterminate widely distributed leakage paths in the structure. This equates to some 3 cavity air changes/h in the cavities, about one order of magnitude more than needed to totally control the cavity moisture condition. Bassett also reports that in typical houses with unvented wall cavities, the outward (cladding) air flow resistance was less than 10% of inward (lining) airflow resistance.

There seems to be grounds to expect that outdoor-cavity-outdoor air flows may be larger than the indoor-cavity-outdoor air flows.

Perhaps the above four points will answer much of the now well-reported discrepancy mentioned by Lieff and Treschel in their introduction to ASTM STP 779 (1) that:- "(a) laboratory work continues to forecast increasing moisture problems (b) field evidence persistently shows that it does not happen". Evidence for the latter comment is found in the Tsongas field studies in Western Oregan (28) (93 houses) and in Spokane (29) (103 houses), and the Weidt study (32) in Minnesota (39 houses), all of which show that structural condensation is not a general problem, whether winter is mild or severe, vapour barriers are present or not, insulation is present or not.

BRANZ experience on this point, based on routine advisory work, is that insulation per se has not been found to be a cause of building moisture problems, although it can influence the degree. The cause has always been traced to some specific building defect. Wall and ceiling vapour barriers are rarely used in N.Z.

As if this were not enough evidence for a change in traditional concepts concerning moisture movement, consider also the field observations reported by Trethowen (25) (8 houses). Here the distinction between "floating" and "forced" moisture conditions becomes crucial. In the event of a sudden spell of cold weather, the traditional concept is that cladding temperature will fall, moisture flow towards the cladding will increase, condensation there will probably commence, and moisture flow into the structure from indoors will increase under the now-greater vapour pressure difference. This sequence is followed in most of the experimental work reported, from Rowley onwards. But it applies to "forced" indoor moisture conditions, where indoor vapour pressure is forced to remain at some set value.

In reality in most of the houses of the world, certainly in N.Z. the indoor moisture condition is floating, not forced. When a cold snap occurs, the cladding temperatures will still fall. But very quickly the indoor moisture concentration also falls, by virtue of infiltration, and in fact is inhibited from falling as far as it might, by a corresponding flow of moisture from the structure to the now-drier building interior. Some evidence for this can be seen in the processed field records of Fig 4. On each occasion when there is a drop in outdoor dewpoint there is a corresponding (smaller) drop in indoor dewpoint. The condition now indicated is that a cold spell would result in a burst of inwards drying or at least reduced wetting of the structure along with some internal moisture redistribution, and not to a burst of increased wetting. Sherwood and Peters (23) found that in a set of three rooms in Madison which were set up to be as nearly comparable as possible, those with floating moisture conditions had drier framing and cladding than in a room forced to 35% relative humidity.

The above factors point to a total inappropriateness of the traditional view of moisture as an outward flow process, and that concept should be abandoned. A more appropriate concept would appear to be that used by Cunningham (6,7) of viewing the structure as a set of moisture sinks, each of which may pass moisture to or from its neighbours according to the conditions of the moment. The most important short and medium term conditions are the local temperatures, and the availability of any moving air streams to carry water vapour.

Finally, I want to advocate that the research community begins to put real pressure on technology, as purveyed in handbooks, design procedures, building codes, to accept and apply the messages which began emerging with Platts (19) and put behind the near-exclusive preoccupation with vapour diffusion and vapour barriers, except where moisture conditions really are forced (as in cold stores, swimming pool halls, cotton mills). There is a tendency even in publications which set out overtly to avoid the "vapour barrier syndrome" - as for instance the 1983 US Department of Energy publication "Moisture and house energy conservation" (30) - to include a rather traditional statement on vapour barriers with only token exceptions. This is not enough - it must be made clear to entrenched thinkers that the rules have been found to be different.

Conclusions

- Key historical events have been noted which underpin the science and practice of moisture control.

- A concept of classifying the moisture risk of buildings according to whether indoor moisture conditions are "forced" or "floating" is introduced.

- The dominant role of airborne rather than diffusion driven moisture as the key issue has been highlighted.

- The powerful influences of material, hygroscopy, non-steady conditions, diffuse solar radiation, and air infiltration have been outlined.

- The concept of moisture movement as an outward flow process should be abandoned, and replaced by one of viewing a structure as a set of moisture sinks responding to surrounding conditions, especially temperatures and air movements.

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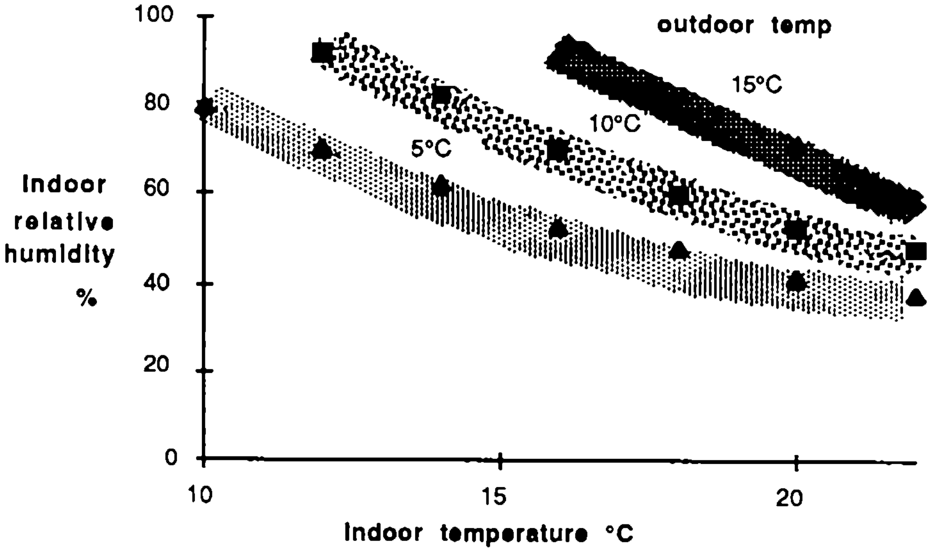


Fig. 1: Observed indoor humidity v temperature
(visual mean of 8 houses, Wainuiomata)

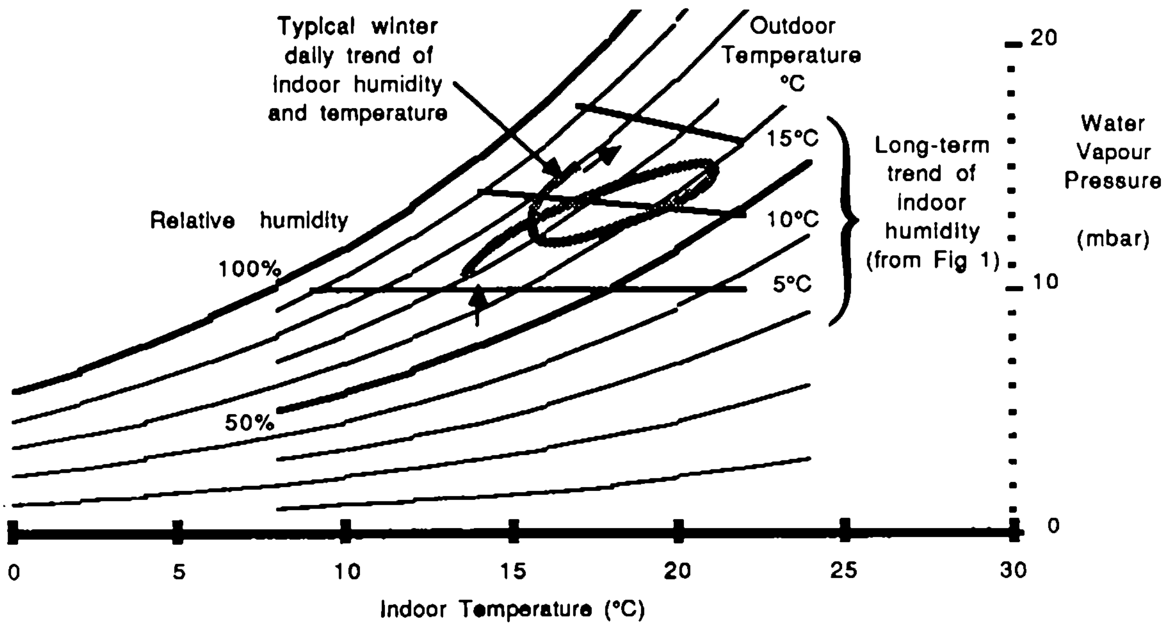
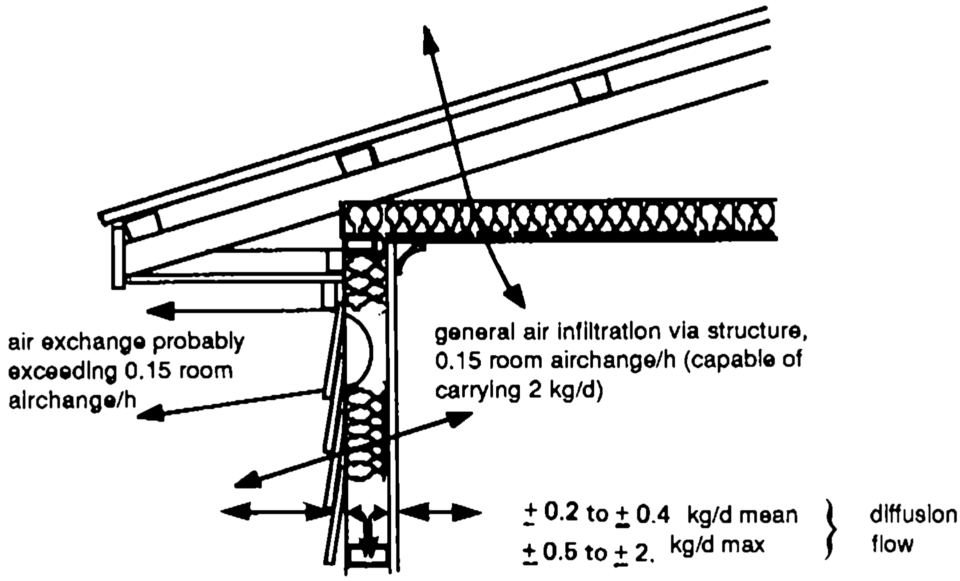
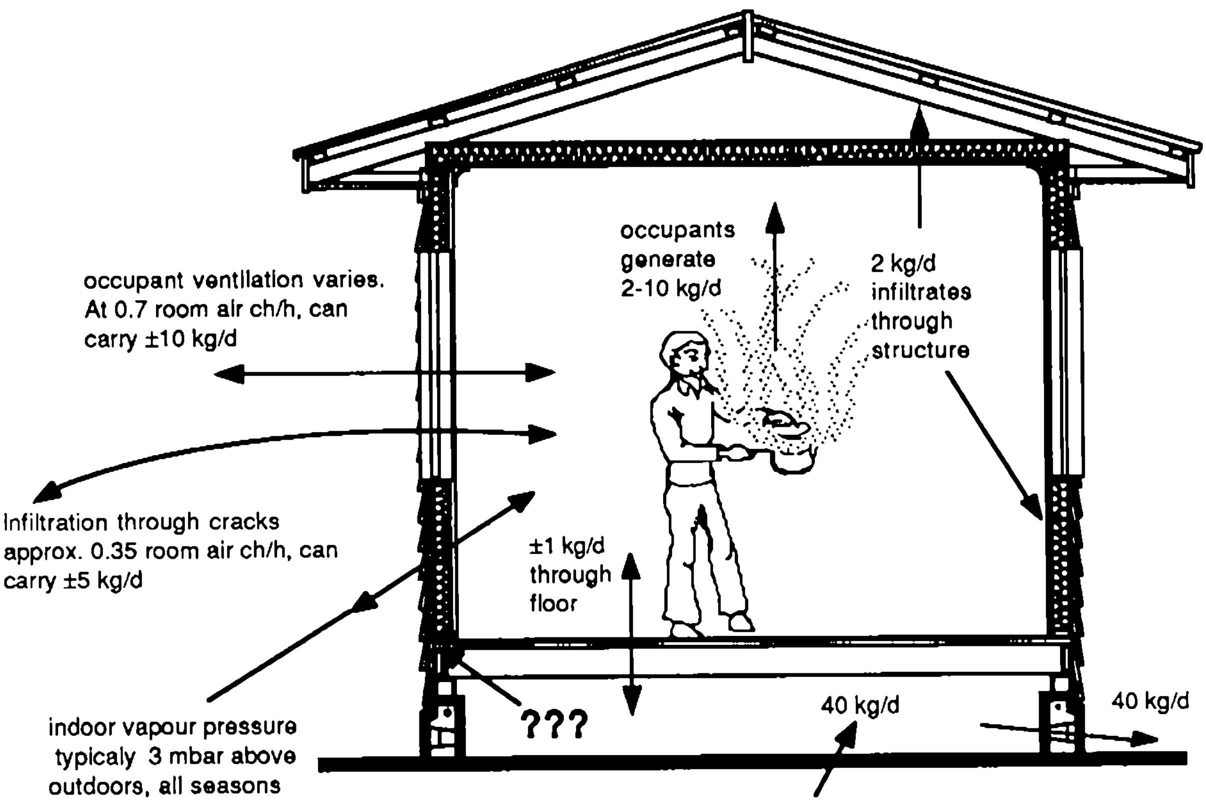


Fig.2: Typical daily and long-term indoor conditions
(visual mean of 8 houses, Wainuiomata)



(b) Within structure



(a) whole house

Figure 3: Size of moisture flows, typical NZ timber house.

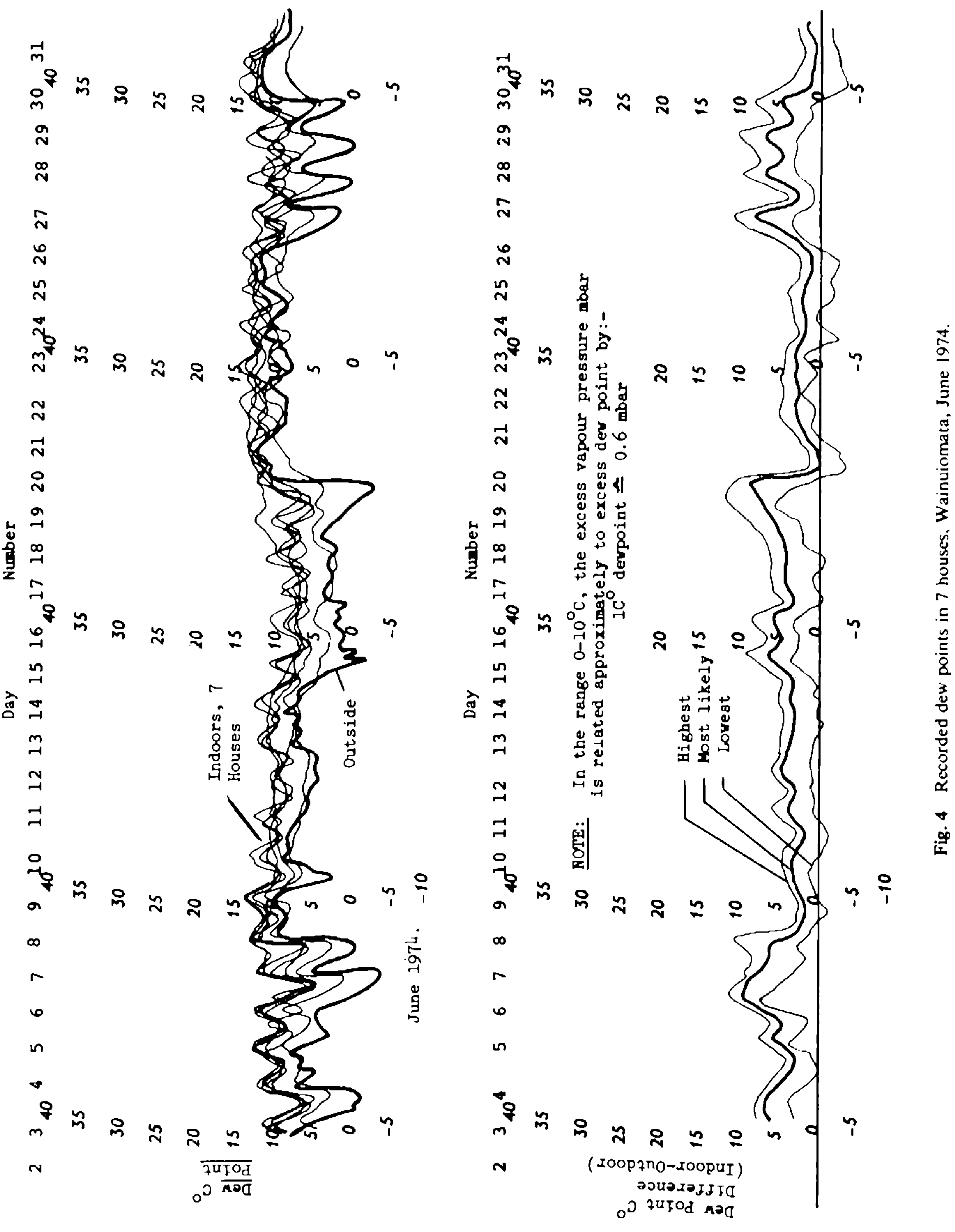


Figure 4: Recorded dew points in 7 houses (from ref 25)

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

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PAPER 2

SEASONAL STORAGE OF MOISTURE IN ROOF SHEATHING

P. CLEARY AND M. SHERMAN

Applied Science Division
Lawrence Berkeley Laboratory
Berkeley
California 94720
USA

ABSTRACT

Classic research into attic moisture problems tended to concentrate on the static prediction of instantaneous temperatures at the underside of the roof sheathing, which was regarded as an inert medium. However, recent work has demonstrated the existence of daily and seasonal cycles in attic moisture parameters. Over the course of a day, the attic air humidity may vary by a factor of three, and during the course of a winter there is storage of perhaps 45 kg (100 lb) of water in the roof sheathing and roofing trusses. On a daily basis the moisture flow is quite significant, of the order of 2 kg per hour (5 lb per hour); this is far greater than the moisture generation rate in a house, which is typically 0.45 kg per hour (1 l per hour). The daily cycles suggest that as the roof sheathing is warmed by incident solar radiation, water is driven off and removed by the ventilation air. A simple method to predict the seasonal variation of wood moisture content has been developed by considering the hour-by-hour transport of water into and out of the wood surfaces of the attic. To validate the model, hour-by-hour measurements of wood resistance, attic and outside dew-point and meteorological variables were made over a four-month period on an unoccupied house in Oroville, CA. The roof sheathing moisture content was found to vary from approximately 14% in December to 7% in early April. Measurements are compared with predictions.

INTRODUCTION

In the era of low energy prices, the attic of a residential building was regarded as a buffer zone and a storage place. Attics were commonly uninsulated, and heat transport from the living space below kept the attic air at a temperature higher than the outside air. Nowadays, attics are often heavily insulated, and it is not uncommon to find that night sky radiation results in attic air temperatures several degrees below outside air temperatures. Since lower attic temperatures could increase the likelihood of condensation, it was decided to review the applicability of current ventilation guidelines to well-insulated attics.

Because attics are unconditioned, the temperature and relative humidity are controlled by the ceiling insulation level, the living-space-to-attic permeability and the attic vent area. Insulation levels are now determined by energy cost considerations. Thus attic ventilation and the installation of air barriers between the living space and the attic are the prime means of controlling attic humidity.

Classic Picture

The attic is a naturally ventilated unconditioned space, protecting the ceiling of the house below from the full force of the weather. The purpose of ventilation is two-fold: in the winter it must prevent structural damage by carrying away moisture that enters the attic from the living space below, and in the summer it should remove solar gain to reduce the cooling load on the building.

This paper is concerned with winter ventilation, i.e. with moisture control. In the classic picture, the roof is an inert structure. Outside air enters the attic, mixes with any moist air that rises from the living space, and comes into contact with the underside of the roof sheathing. According to this view, if the temperature of the surface is below the dew point of the air, condensation occurs: the water soaks "into the structure, causing wood to decay. ...The remedy for condensation of moisture in the attic in winter is moving a sufficient volume of air through the attic space to carry off the moisture before it condenses."(1) That is the classic picture of the roof sheathing as an inert surface.

Moisture Storage

Recent studies have cast doubt on this picture. The conditions in a well-insulated attic vary considerably from winter to summer. During wet overcast winter days the attic temperature is low and the relative humidity high. During clear dry summer days the temperature is high and the relative humidity low. Even during humid cloudy periods, the attic air temperature is often higher than the outside air temperature because of diffuse solar radiation. These conditions could be expected to lead to seasonal variations in wood moisture content. Research in England in the 1940's indicated a seasonal cycle in the moisture content of wood samples stored indoors(2), where conditions are less variable. More recent work in the United States(3-5) has shown a strong daily cycle in attic air humidity ratio and a year-long cycle in the moisture content of attic wood. It appears that the wood members of a typical, well-ventilated attic might have a moisture content of 7% (expressed as a percentage of the dry weight of the wood) in the summer, and a moisture content of 14% at mid-winter. The total amount of water stored can amount to 45 kg (100 lb) or more.

The conditions to be prevented in an attic are the presence of liquid water and the occurance of conditions conducive to wood decay. Both these depend on the wood moisture content. Liquid water will be found if the wood is saturated or if water is delivered to the surface faster than it can be adsorbed by the wood. Wood decay occurs at temperatures between 10 and 32 ^{o}C (50 and 90 ^{o}F) at moisture contents above 20% (6).

The driving force behind the seasonal variations in wood moisture is the hour-by-hour variation of wood temperature and attic air humidity ratio. To investigate these parameters, and to develop a model to predict required ventilation rates, the attic of an unoccupied single-family house in Oroville, California, was monitored over a winter. Details of the house and the instrumentation are given in the Appendix.

RESULTS

The wood in the attic forms a large reservoir from which moisture can be released when temperatures rise. Wood moisture content varies quite slowly; over any 24-hour period, the wood moisture content remains almost constant. Even if 10 kg (22 lb) of moisture is released from the 1100 kg (2400 lb) of wood in the attic, the average wood moisture content varies only by (10/1100) x 100 = 0.91 %. However, this is sufficient to vary the attic air humidity ratio by several hundred percent. Figure 1 shows the hourly variation in attic and outside humidity ratio for the Oroville attic for a sunny period in February. The amount of water emitted by the wood can be calculated by a mass balance for water entering and leaving the attic. Assuming that the wood is the sole source of moisture and that the attic air is perfectly mixed, the mass balance gives:

$$m = M(W_{attic} - W_{outside}) \qquad (1)$$

where:

- m = rate of water flow from the wood, kg/s (lb/hour)
- M = dry mass flow rate of ventilation air kg/s (lb/hour)
- W_{attic} = attic air humidity ratio, unitless
- $W_{outside}$ = outside air humidity ratio, unitless

In an occupied house, a third term would have to be added for moisture transport into and out of the living space.

The calculated water flow rate for February 16 to 18 is shown in Figure 2. It can be seen that the flow peaks just after noon each day, and that during the night the attic wood actually absorbs water from the ventilation air. The peak flow of water is a little under 2 kg/hour (4.4 lb per hour), on 16 February. Figure 3 shows the mass of moisture adsorbed during this period. (It should be noted that all this water is released in the form of water vapour; no liquid water was observed during the course of this study.) The dynamic flow is in sharp contrast to the classic picture of an attic, in which the wood is regarded as an inert surface on which water will condense when the dew point is reached.

A simple model has been developed to predict the flow of water from the wood. (For a more complete analysis of moisture and heat flow, see Kohonen and Maatta (7)). Following a standard model of mass flow (see for example Kays and Crawford (8)) the flow of water from the wood is given by:

$$m = k\,A\,(W_{surface} - W_{attic}) \qquad (2)$$

where:

- m = flow of water kg/s (lb/hour)
- k = transfer coeffficient, kg/m^2.s (lb/ft^2.hour)
- A = transfer surface area, m^2 (ft^2)
- W_s = humidity ratio of the air surface film, unitless
- W_{attic} = humidity ratio of attic air, unitless

The transfer coefficient, assuming a Lewis relationship of 1.0 (see, for example ASHRAE Fundamentals (9)), is:

$$k = h_c/C_p \qquad (3)$$

where:

- h_c = convective heat transfer coefficient W/m^2.°C (Btu/h.ft^2.°F)
- C_p = specific heat of moist air J/kg.°C (Btu/lb.°F)

This transfer coefficient for the roof is, within the limits of overall experimental error, 0.08 kg/m^2.s (1.0 lb/hour.ft^2). (Burch and co-workers (4) used a value of 1.1 lb/hour.ft^2). The surface film humidity ratio may be found from data on wood properties, e.g Table 3-4 of the Wood Handbook[10] gives the moisture content of wood at various temperatures and relative humidities. (It is said to apply to any species of wood.) If it is assumed that the wood moisture distribution is uniform and that the surface film humidity ratio is a function solely of temperature and wood moisture content, this data can be used to find the surface film humidity ratio. The data set was transformed into humidity ratio for various combinations of temperature and wood moisture content, and a curve fit made to the data. A good fit was found of the form:

$$W_{surface} = e^{T/a}\,\{b + cu + du^2 + eu^3\} \qquad (4)$$

where

- T = wood temperature, °C
- u = weight of water in wood divided by dry-weight of wood, unitless
- a = 15.8 °C
- b = −0.0015
- c = 0.053
- d = −0.184
- e = 0.233

The term for water flow may be eliminated from Equations 1 and 2, giving an equation for the attic air humidity ratio:

$$W_{attic} = \frac{\dfrac{A\,k\,W_{surface}}{M} + W_{outside}}{1 + \dfrac{A\,k}{M}} \qquad (5)$$

This equation predicts attic humidity ratio as a function of wood area, ventilation rate, outside humidity ratio, and wood surface film humidity ratio. This last variable is a function of wood moisture content and temperature; wood moisture content is found from the electrical resistance of the wood, and is assumed constant over each 24-hour period. The unitless quantity Ak/M determines whether the attic humidity ratio is surface dominated (i.e. $Ak/M \gg 1$) or ventilation dominated ($Ak/M \ll 1$), and thus may be used to determine if ventilation is adequate.

A comparison of the predicted and measured attic air humidity ratio is shown in Figure 4. Reasonable agreement is seen. During the night hours the prediction is systematically low; this suggests that there is another source of moisture that is not included in the model.

A possible cause of the overprediction on the third day is drying out of the wood surface. The average wood moisture content is measured by electrical resistance probes. If the wood surface has a lower moisture content than this value, the model will overestimate the rate of moisture release.

Cumulative Moisture Adsorbed

The variation in the sheathing moisture content for the whole period is shown in Figure 5. It can be seen that overall the roof was drying out. Preliminary measurements made in August, 1983 indicated a wood moisture content of approximately 6%. The roof sheathing therefore must have absorbed moisture from the ventilation air during the cool wet months of October and November. A peak wood moisture content of 13.5% corresponds to additional storage of almost 35 kg (76 lb) of water in the sheathing. The trusses showed a lesser variation, with a peak of only 10%, corresponding to additional storage of 25 kg (55 lb).

Given initial values for wood moisture content, and continuous data for sheathing and truss temperature, attic and outside humidity ratio, and attic ventilation rate, Equation 2 could be used to model the seasonal variation of wood moisture content. It was hoped that the Oroville data could be used for this, but equipment failures resulted in numerous breaks in the data.

Since the wood can release moisture rapidly during a short hot spell, even a gap of a few days can lead to large uncertainties in the simulation. There are complete data sets for up to 7 days, but during such a short period errors in the wood moisture content measurements can be overwhelming. The electrical resistance method gives a result which is weighted in favour of the most moist part of the wood. During a rapid drying period, this tends to underestimate moisture changes since the center of the wood takes longer to dry than the surface. For example, between February 16 and 18, resistance measurements indicated 4.6kg (10 lb) desorbed, while the attic air humidity ratio measurements indicated 20 kg (44 lb). For February 11 to 15, a period of almost continuous rain, the resistance measurements indicated 14.3 kg (32 lb) adsorbed, while dew point measurements gave 11.6 kg (26 lb).

Since the Oroville data could not be used, other sources were investigated. Hans (11) collected hygrothermograph and wood moisture data for a Madison attic for a complete winter, except for a short break in February-March. This data is almost complete, and has been used to give a rough test of the seasonal prediction.

The data are attic dry bulb and relative humidity. Values were taken from the traces at four-hour intervals, and converted into humidity ratio by means of standard algorithms. In the calculation, it was assumed that the wood was at the same temperature as the attic air. This introduces a systematic error: the roof is probably colder than the air on a winter night, and warmer than the air on a sunny spring day. This effect could not be corrected for, and gives a systematic error in the results. A sensitivity run showed that a 1.1 $^{\circ}C$ (2 $^{\circ}F$) increase in temperature led to approximately a 2% decrease in predicted wood moisture content.

The method used is as follows. The initial wood moisture content is unknown. A value of 10% was chosen. Equation 4 was used to calculate $W_{surface}$ for this moisture content and the temperature for the first time period. From Equation 2 the moisture flow from or to the wood is found. As water flows from the wood, it reduces the wood moisture content according to the relationship:

$$\text{delta u} = \frac{-\,m\,t}{A\,r\,d} \qquad (6)$$

where:

delta u = change in wood moisture content, unitless

m = rate of water flow from the wood, kg/s (lb/hour)

t = time interval, s (hour)

A = wood surface area, m^2 (ft^2)

r = density of the dry wood, kg/m^3 (lb/ft^3)

d = thickness of the wood, m (ft)

Ard = mass of the wood, kg (lb)

This gives a new value for the wood moisture content, which is used for the next time step. The value chosen for the initial moisture content affects only the first few days of the prediction, as can be seen from the way the prediction responds after the missing data in March. A comparison of measured and predicted wood moisture content is shown in Figure 6. Reasonable agreement is seen.

The agreement is better than expected, since a small error in the hour-by-hour predictions, as shown in Figure 4, should accumulate to a significant error over the six months of the test period. However, if the wood gradually reached equilibrium with quasi-steady winter conditions, and then rapidly dried out to equilibrate with quasi-steady summer conditions, the kind of agreement seen might be expected.

CONCLUSION

The classic picture of roof sheathing is that it is an inert surface on which moisture can condense. Recent research has shown that, on the contrary, the wood in an attic gradually adsorbs a large quantity of moisture over the course of a winter and desorbs it in the spring. A model has been developed which calculates these seasonal changes as the cumulative result of hour-by-hour flows of moisture into and out of the wood.

The model can form a part of a methodology to test ventilation strategies to ensure that well insulated attics do not have moisture problems. Further research is needed to predict attic ventilation rates and the flow of air from the living space to the attic.

It should be noted that this model may not apply to more harsh climates, e.g. Alasksa, where winter temperatures are low and moisture transport rates within the wood are extremely low. The model may also not apply to moist cooling climates, e.g. Mississippi, where the attic is not dried out in the summer. To date, it has only been tested for moderate heating climates, viz. Oroville, California, and Madison, Wisconsin.

Acknowledgments

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APPENDIX

Experimental Method

The attic of a single-family unoccupied house in Oroville, California, was monitored over the four-month period January 1984 - April 1984. Oroville is located in the northeast Sacramento valley, approximately 120 km (75 miles) northwest of Sacramento itself. The winter is mild. Chico, about 30 miles away in the same climate-zone, has the following 30-year averages (12): January minimum temperatures 2.2 °C (36.0 °F), 1599 base 18.3 °C centigrade annual heating degree-days (2878 base 65 °F Fahrenheit degree-days), and an annual rainfall of 66 cm (26 inches).

The house is part of Winston Gardens, a housing project for the elderly in the County of Butte. It has a single-storey, 7.9m by 7.9m (26 ft by 26 ft), with a gable roof of 8 in 12 pitch (i.e. a slope of 33.7 degrees with the horizontal). The area of each of the sloping sides of the roof is 38 m^2 (406 ft^2). The dry weight of the roof sheathing, assuming a density of 480 kg/m^3 (30 lb/ft^3) and a thickness of 12.7mm (0.5 inch), is 463 kg (1015 lb). The roof is framed with fourteen equally-spaced two by four wood trusses. (A two by four is 1.5 by 3.5 inches (3.8 by 8.9 cm)). Each truss contains 27.4 linear m (90 linear ft) of wood. The total weight of wood in the trusses is estimated as 636 kg (1400 lb). The house was built to the US Department of Housing and Urban Development's Minimum Property Standards, and has RSI 3.3 (R-19) fiberglass batt insulation in the attic. The attic is vented by approximately 1000 cm^2 (156 sq inches) of soffit vents along one side of the house, approximately 1850 cm^2 (288 sq inches) of vent area above a porch on the opposite side of the house. There is a 30 cm (12 inch) diameter flap-damper, opened by a bimetallic strip, in a cupola on the ridge. It was not seen open during the course of this study. The house shares part of one wall with an adjacent house; there is no connection for air flow between the attics.

Parameters measured continuously at the site included outside dry bulb temperature and dew point, wind speed and direction, total horizontal solar radiation, attic sheathing temperature at four points, wood electrical resistance at three points, attic air dew point, indoor temperature, and indoor relative humidity. Readings were taken every ten-seconds, and half-hour averages were stored on magnetic floppy disk (13). Periodic measurements of attic ventilation rate were made by sulfur hexafluoride injection and decay. The data set is less than two-thirds complete for the six-month period. Problems occurred with many parts of the data collection system, mainly the computer hardware and the chilled-mirror dew-point sensors.

There were no sources of moisture in the house except for that caused by the periodic visits of researchers (e.g. showers, washing), approximately once every two weeks. Air flow between the house and the attic was judged to be small on the basis of smokestick tests. On one occasion it was measured by injecting SF_6 at a constant rate into the attic and measuring the resultant concentration in the house. (The rates of outside air flow into the house and into the attic were found by immediately subsequent SF_6 decays.) It was found that the attic ventilation rate was 124 m^3/h (73 cfm), the house ventilation rate was 16 m^3/h (9.4 cfm), and there was a flow of 4 m^3/h (2.4 cfm) from the attic to the house. The ventilation rate was not measured continously, but a number of measurements were made at different windspeeds and a correlation developed as a function of windspeed. Temperature differences between the house, the attic and outside were not found to have a significant effect on the ventilation rate. The correlation was used to calculate hour-by-hour ventilation rates from the measured windspeed.

The house heating system is a forced-air heat pump, which was thermostated at 17 °C (63 °F) for the early winter and later at 23 °C (73 °F). The house relative humidity stayed almost constant at between 45% and 55%, as measured by a hygrothermograph. (The hygrothermograph was given a one-point calibration every two weeks.)

The concentration of moisture in the attic and outside air was measured by means of aspirated chilled-mirror hygrometers (DEW-10, General Eastern). The outdoor unit was shielded in a 15.2 cm (6 inch) diameter plastic cylinder, 45.7 cm (18 inches) high. Natural dew formation or electronic instability periodically caused the units to overchill their mirrors. (A contributory cause may have been the aspiration rate, which was far lower than the design value.) They then remained out of action until a site visit was made to remove the ice block. This was a particular problem with the outdoor unit (the units were not designed for outdoor use) until a small (0.4 watt) heater was installed in the mirror cavity. A timer was later used to turn off the power to both the units for half an hour each day to permit ice melting. Then the units performed very well. Humidity ratio (kg of water per kg of dry air) was determined from dew-point by means of standard psychrometric routines.

Roof sheathing temperature was measured inside the attic with AD590 (Analog Devices) solid-state sensors. These are two-terminal integrated circuits which produce a current of 1 micro-ampere per degree Kelvin. Prior to installation, the sensors were given one-point calibrations. The sensors were epoxied to copper discs, and the copper disks nailed to the undersurface of the sheathing at four points equidistant from adjacent rafters, close to the resistance electrodes. The sheathing is half-inch (1.27 cm) thick exterior grade plywood.

Long term changes in the moisture content of the wood were found from the variation in electrical resistance between two pairs of electrodes inserted in the plywood sheathing and one pair of electrodes inserted in a roofing truss. The electrodes were silver plated copper nails, 2.3mm (0.09 inches) in diameter, inserted 10mm (0.39 inches) into the wood, 26mm (1.02 inches) apart. The electrical resistance was measured for ten seconds every three minutes with an inexpensive solid-state ohm-meter developed at Lawrence Berkeley Laboratory. The ohm-meter is based on the ICL8048 monolithic logarithmic amplifier (Intersil). The amplifier specifications give a dynamic input range of 1 nA to 1 mA. For the voltage used (15 V), this corresponds to a resistance range of 1.5 10^{10} to 1.5 10^4 ohms. The resistance was found to range from a low of 10^7 ohms to a high of 10^{12} ohms. Above 10^{11} ohms readings were somewhat variable. This simple instrument has proven to be very rugged and reliable.

Wood resistance varies with both moisture content and temperature. It varies with temperature according to the equation (14):

$$R = R_o e^{T_o/T} \qquad (7)$$

where:

R	=	measured wood resistance, ohms
R_o	=	a constant, ohms
T	=	wood temperature, K (R)
T_o	=	a constant, K (R)

The measured value of R must be reduced to standad conditions. The values of the constants R_o and T_o vary with wood moisture content. If that wood moisture content remains constant over each 24-hour period, or if these constants vary only slowy with wood moisture content, a plot of the logarithm of wood resistance against the reciprocal of the wood temperature for this period will be a straight line. Figure 1 shows the data for two selected days. There is some unexplained hysteresis. A least-squares linear fit was made to each day's data, and an extropolation (or interpolation) made to a temperature of 25 °C (77 °F). The corresponding wood moisture content was found from table 1 in Electric Moisture Meters for Wood (15). The table entry for coastal Douglas Fir was taken.

In deriving the wood moisture content, it is assumed that the moisture is uniformly distributed through the wood. Large inaccuracies can result from this assumption. For example, when wood is drying, the core of the sample can have a resistivity an order of magnitude less than that of the surface. Since all the layers of the wood are in parallel across the electrodes, this lower resistance will dominate the result and indicate a high value for moisture content. Results from a wood sample that is not in equilibrium with the ambient air must thus be interpreted with caution. It is expected that while short-term fluctuations in wood moisture content are unreliable, long-term trends should be accurate.

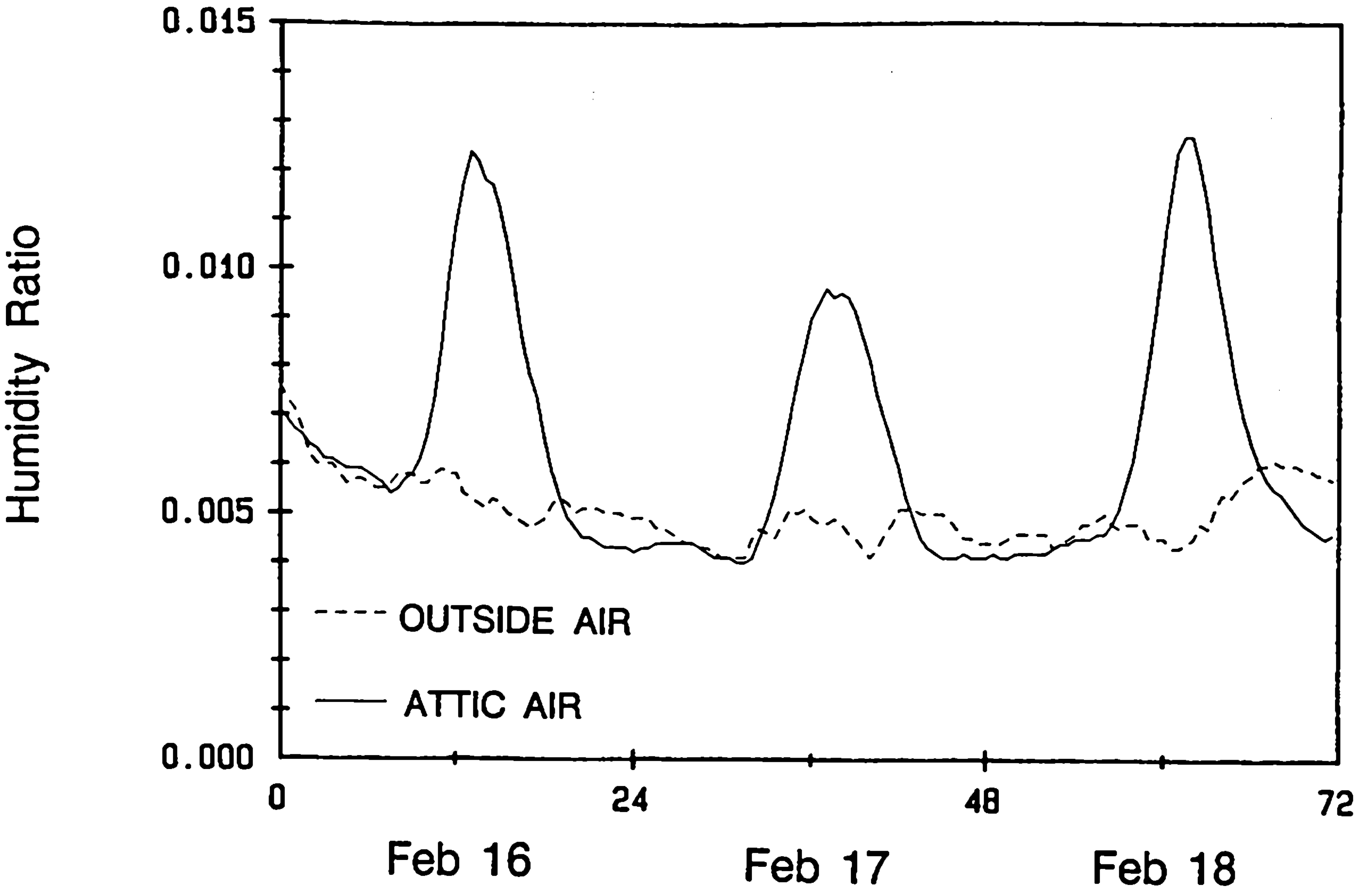

Figure 1. Humidity Ratios At Test House

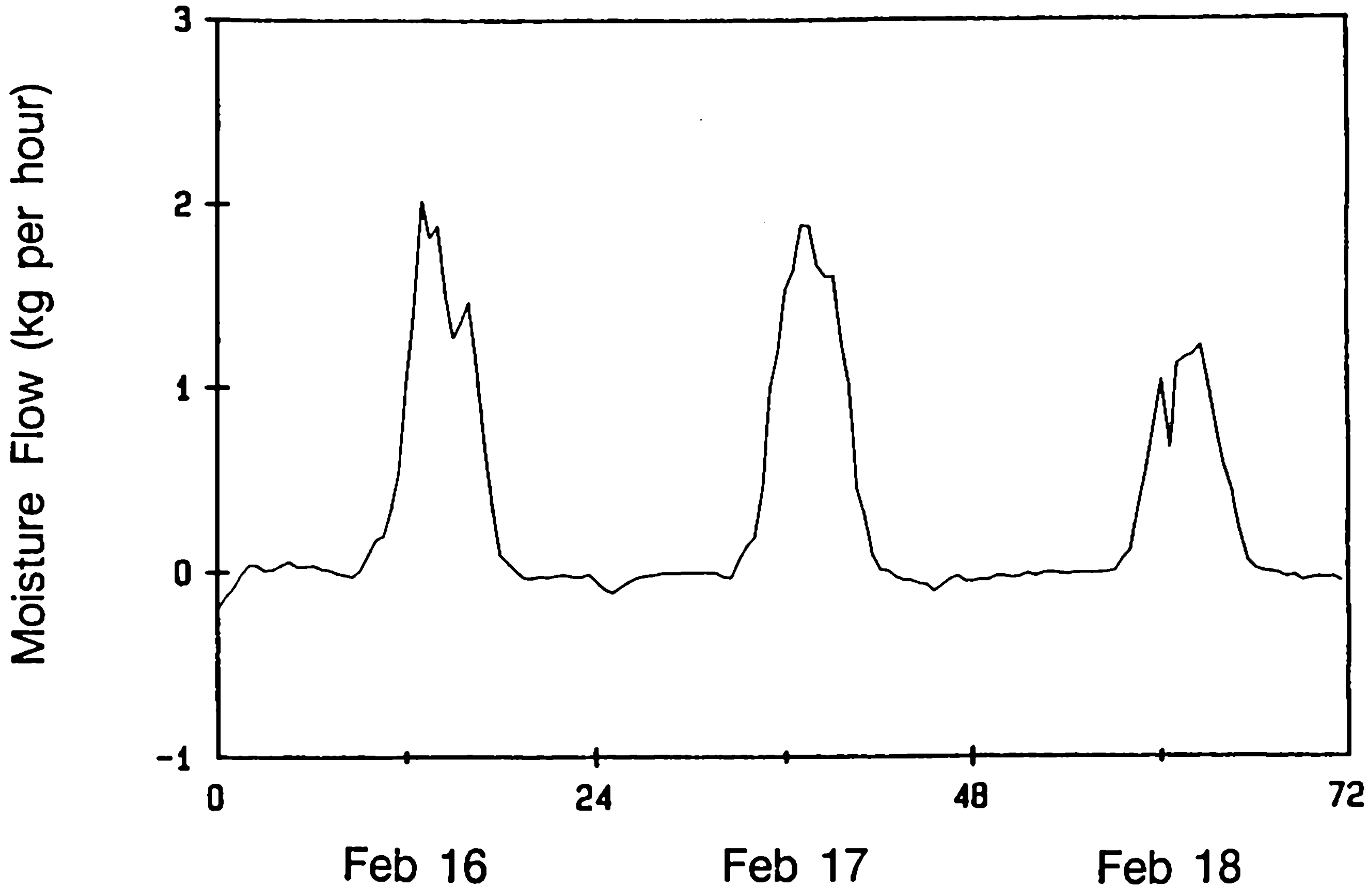

Figure 2. Moisture Flow In Test Attic

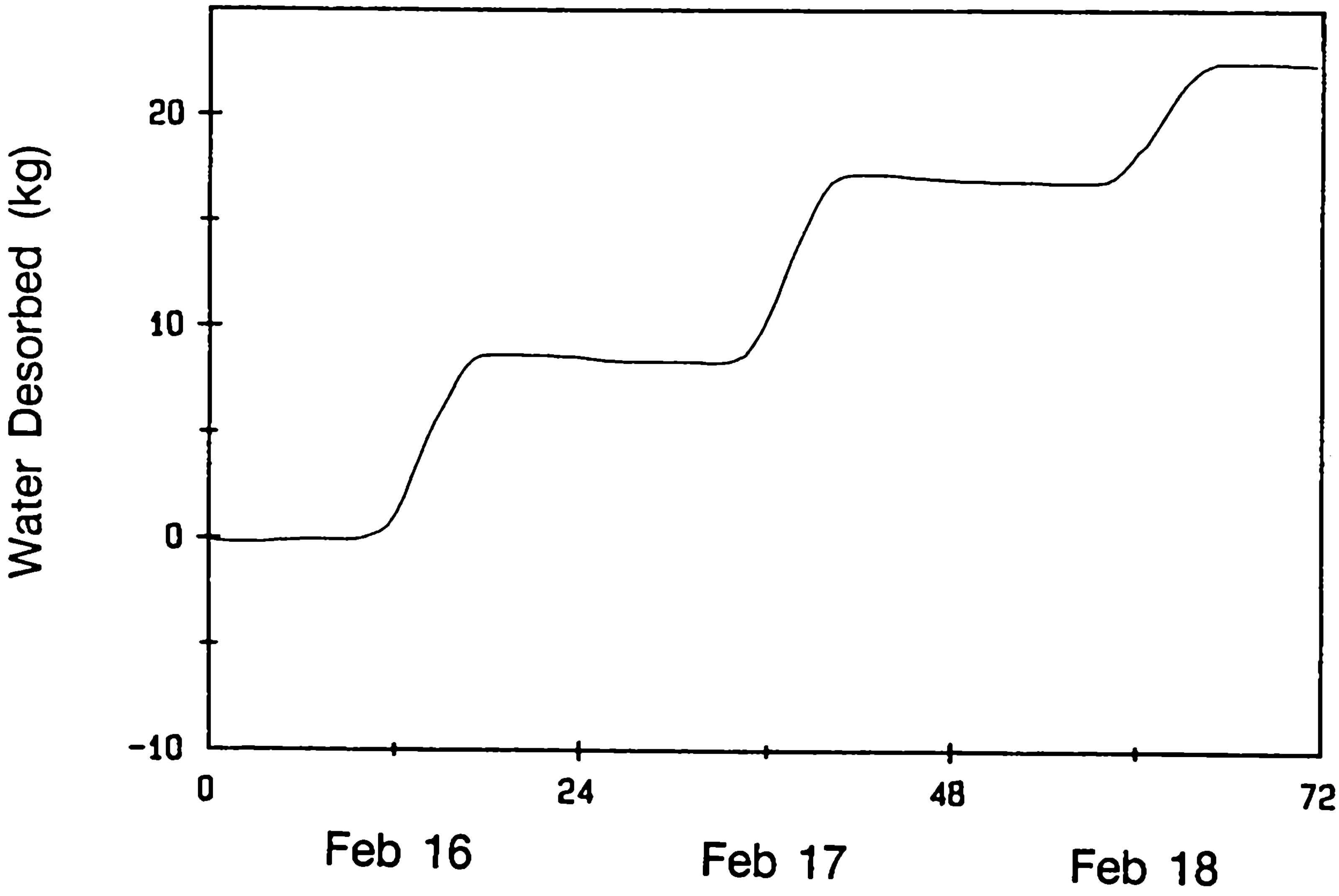

Figure 3. Water Desorbed From The Attic

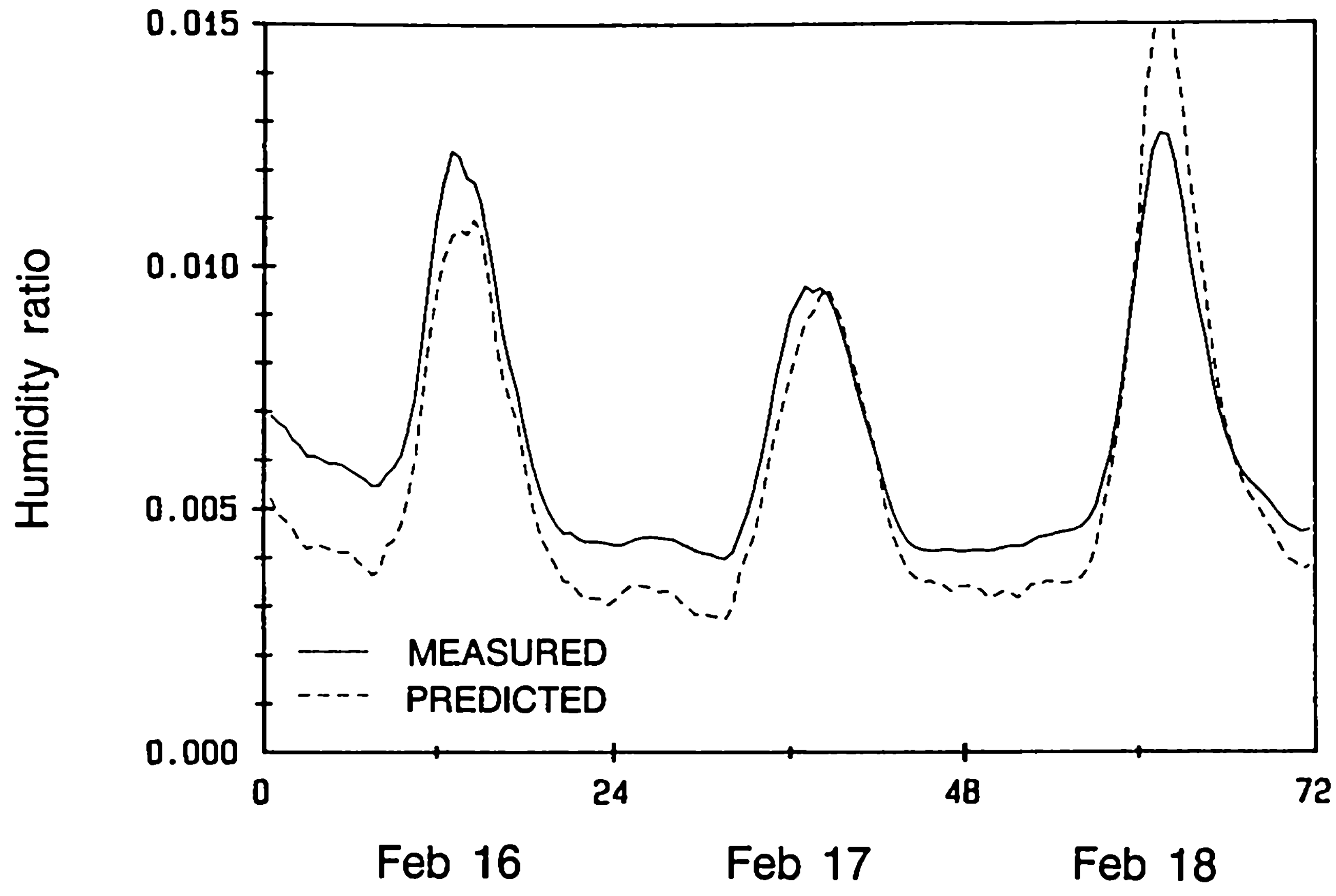

Figure 4. Attic Air Humidity Ratio

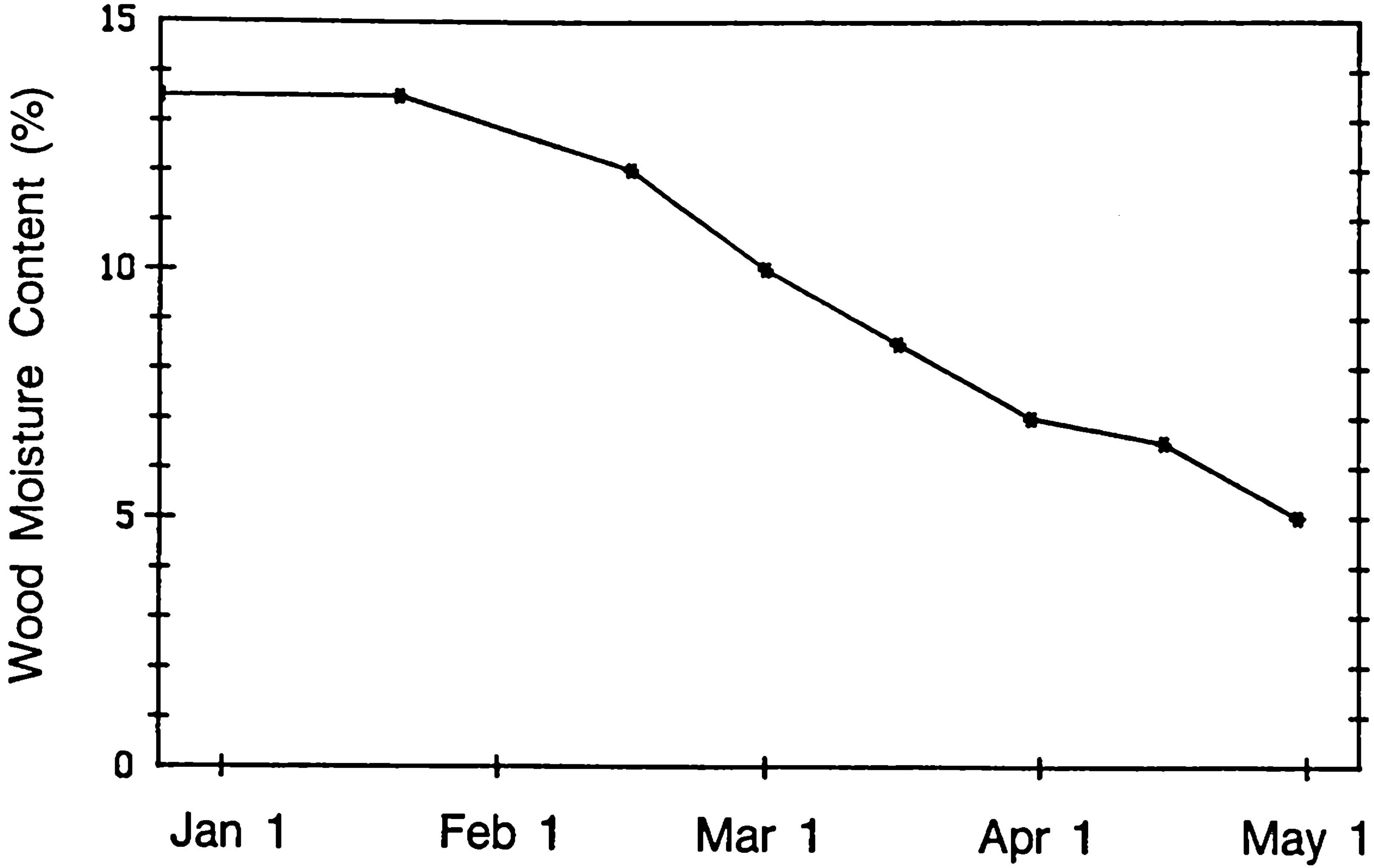

Figure 5. West Roof Sheathing Moisture Content

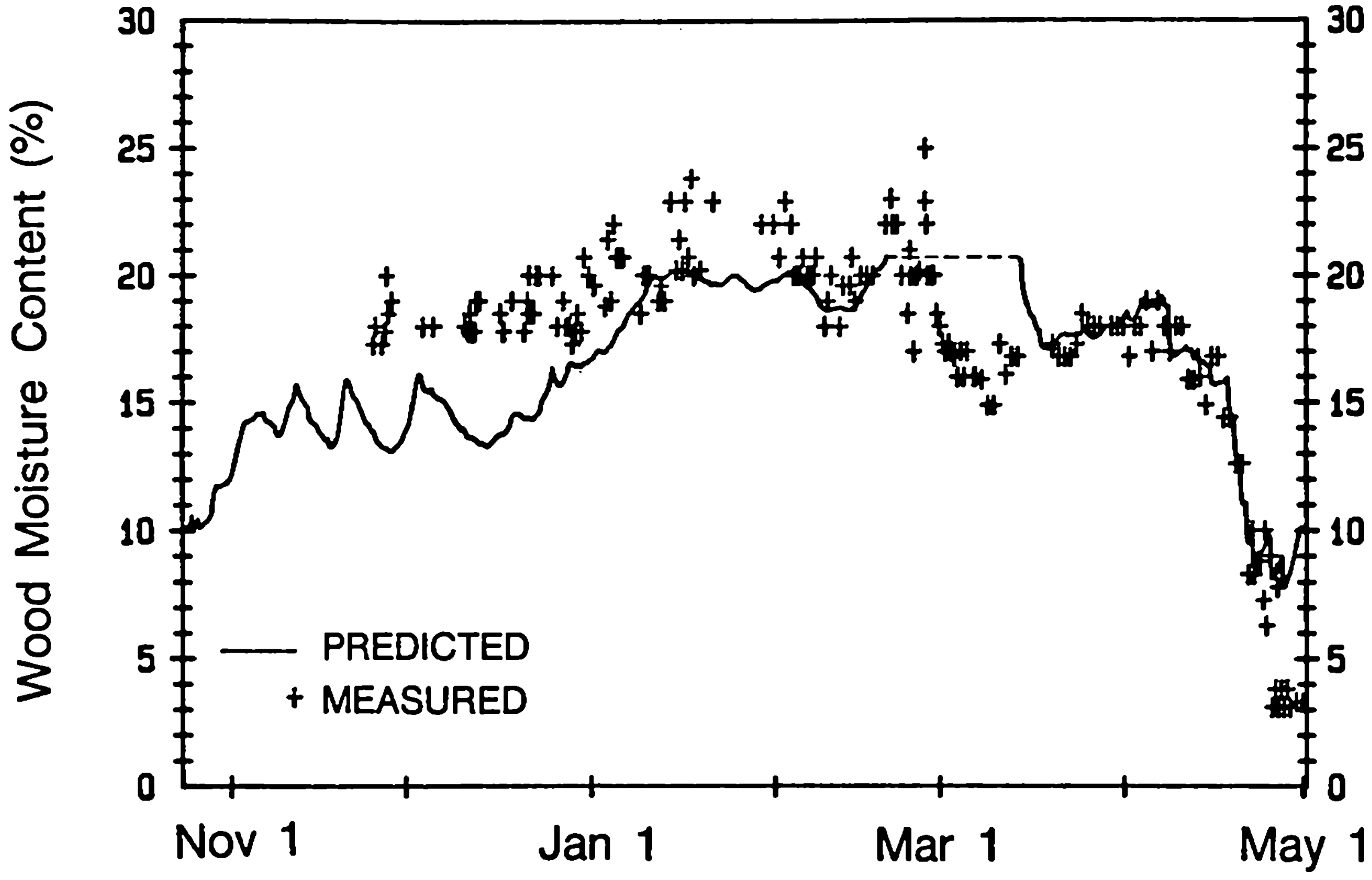

Figure 6. Wood Moisture Content In Madison, WI

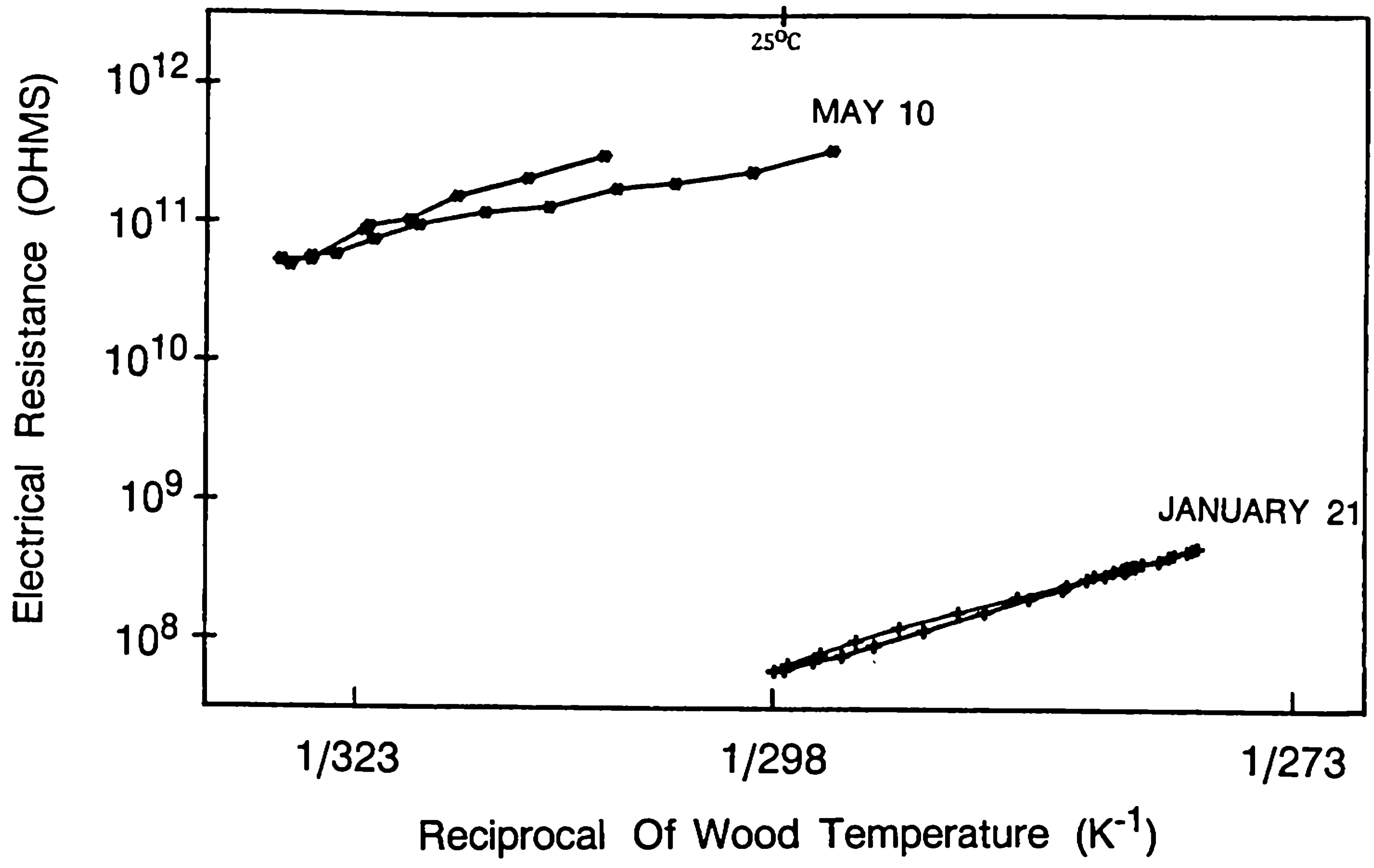

Figure 7. Resistance Of West Roof Sheathing

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP

Building Research Association of New Zealand (BRANZ)
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PAPER 3

AIR FLOW RESISTANCES IN TIMBER FRAME WALLS

M. BASSETT

Building Research Association of New Zealand
Private Bag
Porirua
New Zealand

AIR FLOW RESISTANCES IN TIMBER FRAME WALLS

M. Bassett

SYNOPSIS

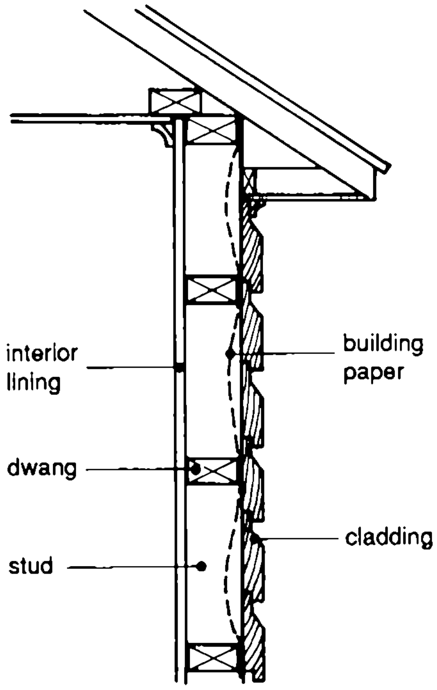
This paper deals with the air leakage paths through timber framed walls of houses built in New Zealand. It identifies three series resistances to air flow corresponding to the external cladding, the underlayer (building paper) and the interior lining. Two types of parallel resistance are identified; one connecting stud cavities to each other and another connecting cavities formed between building paper and the cladding. Various methods were used to measure these resistances to steady air pressure. Although variety in building materials and standard of workmanship contribute to variation in the air flow resistances, a picture has emerged of linings generally forming the plane of highest leakage resistance, but with certain new types of underlayer having the potential of even higher resistance. Weatherboard claddings, which have in the past contributed little to wall airtightness, tend to have become even less airtight in recent times.

1. INTRODUCTION

Little attention has been given in the past to detailed descriptions of the air flow paths in timber framed walls, but there are reasons why these details should be known. The first concerns moisture transport into or away from wall cavities by humid air. Large quantities of moisture can travel this way, which in certain conditions could lead to prolonged high moisture contents in framing timber and eventual decay. Studies of wind driven rain leakage can also make use of component airflow resistances. The trend is towards less airtight rain screen claddings that shed and deflect water without having to resist high wind forces. To be sure that air flows through the less airtight claddings do not drive water inside, many of the airflow resistances must be known. This paper gathers together as much as is known about air flow resistances in domestic timber frame walls in New Zealand.

2. CAVITY WALLS

The external walls of most New Zealand houses are a cavity construction formed by a timber frame, a lining and a cladding. In some regions a brick veneer is the favoured cladding but more generally it is timber or fibre reinforced cement weatherboards. There should be a layer of building paper under the cladding and the cavity will generally contain a thermal insulating material. A vapour barrier such as a polyethylene sheet is not normal practice in urban areas of New Zealand and no special attempt is made to seal air leaks and make buildings more airtight. Fig 1a is a cross section of a cavity wall showing studs and dwangs (horizontal framing). Dwangs are less common in new houses so that wall cavities will run from bottom to top plate unless interrupted by windows or doors.



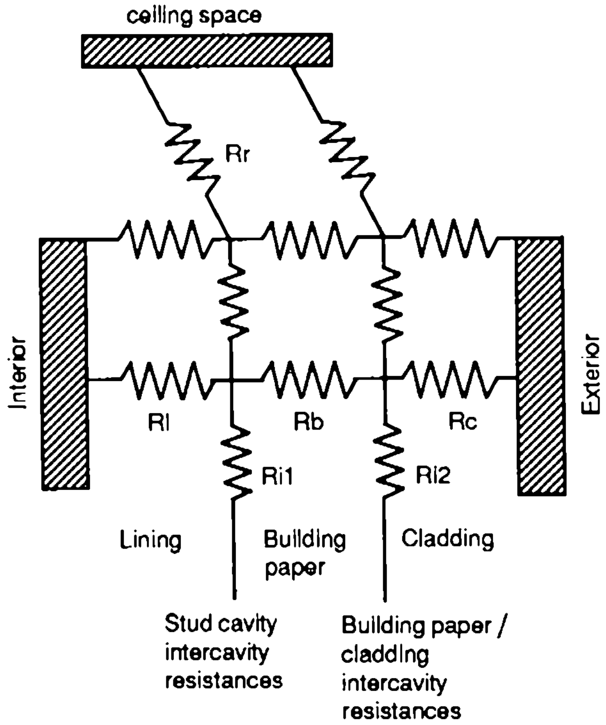


Fig.1a: Side view of wood framed cavity wall

Fig.1b Part of airflow resistance network

Also shown in Fig 1b is a schematic of the air flow resistances through the cladding, lining and the parallel resistances connecting cavities with each other and subfloor and roof space. Five main air flow path types can be identified from Fig 1.

1. Through the cladding (R_C)
2. Through the lining (R_L)
3. Diffusion through the building paper (R_b)
4. Between stud cavity (Type 1 intercavity air flows(R_{i1})
5. Between cavities formed by building paper and cladding (Type 2 intercavity air flows) (R_{i2})

Air leakage and the driving pressure are generally related by the power law equation found in the ASHRAE Handbook[1].

$$Q = C\,\Delta P^n \qquad \ldots \quad (1)$$

$$\text{and} \quad Q = \frac{A\,\Delta P}{R} \qquad \ldots \quad (2)$$

where
Q - air flow rate 1/s
C - flow coefficient
ΔP - air pressure difference Pa
A - area m^2
R - air flow resistance N.s/l
n - exponent

For physical reasons, the exponent must lie in the range $1.0 \geqslant n \geqslant 0.5$. The higher limit of n=1 characterises air flow through porous materials. In this case the resistance is conveniently independent of applied pressure. More generally, however, the important air leaks in buildings are at cracks and joints where air flow will be turbulent and the exponent closer to the lower limit n=0.5. In these cases the resistance will be a function of the driving pressure as derived from equations 1 and 2.

$$R(\Delta P) = \frac{A\ \Delta P^{(1-n)}}{C} \quad . \ . \quad (3)$$

In this paper we have elected to report an air flow rate driven by a 50 Pa pressure difference called the Q(50). This allows for easy comparison with New Zealand house airtightness data (Bassett[2]) which is also referenced to 50 Pa. The units used are litres/second (l/s) or litres/second/square meter($l/s.m^2$).

Because cavity walls are quite inhomogeneous assemblies of materials, large variations in air flow characteristics should be expected at discontinuities, such as near corners, windows and doors etc. There are also wide variations in building practice and choice of cladding and lining material. For these reasons it is unlikely that a complete set of air leakage resistances can be provided for all situations. The information in the following pages makes a start, by summarising air flow resistances (sometimes with a resolution no better than one order of magnitude) that have been measured in recent years.

3 CLADDINGS

Air leakage characteristics of claddings were measured in the course of rain leakage tests (Bishop[3]) on a wide range of new and traditional systems. The method used for these measurements is described by Bassett[4].

3.1 Cladding Airtightness results

Air flow characteristics for 16 distinct claddings types have been measured. Four were traditional timber and fibre reinforced cement weatherboards and the others were lightweight PVC, or coated aluminium or galvanised steel weatherboards new to the New Zealand market. Air flow characteristics through the cladding in the vicinity of four cavities A - D in Fig 2 were measured for each cladding.

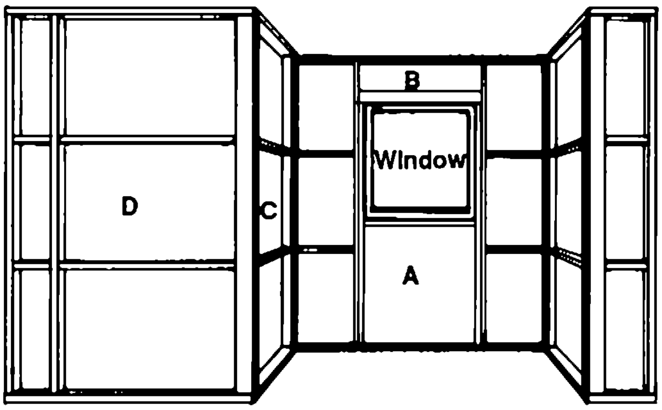


Fig.2: Experimental stud cavity arrangement

Although this arrangement gives a useful comparison of claddings, it does present some difficulty if an average leakage resistance is required for a particular section of wall. This difficulty arrises because leaks at corners and around doors and windows are a large fraction of the total leakage, and the proportions of these vary considerably from one section of wall to the next. Furthermore, the extent of leakage at edges and corners varies from one cladding to the next, which means there is little scope for a simple model of cladding airtightness in terms of wall area and building geometry. Table 1 gives Q(50) flow rates for new and traditional claddings averaged over all four cavity types. The area averaged flow rate given in Table 1 is based on the mean cavity area and should only be taken as a guide because they will include a component of intercavity flow.

Table 1 Cladding leakage rates

Cladding type	Q(50) Flow rates at 50 Pa	
	1/s.cavity	$1/s.m^2$
Wood or fibre reinforced cement weatherboards	26	42
PVC, coated metal	80	130

A histogram of Q(50) flow rates is given in Fig 3 for two classes of cladding and all cavities lumped together. It shows the traditional types to be, on average three times as airtight as the new claddings. Differences in air flow rates through the cavities were generally smaller than the differences between claddings.

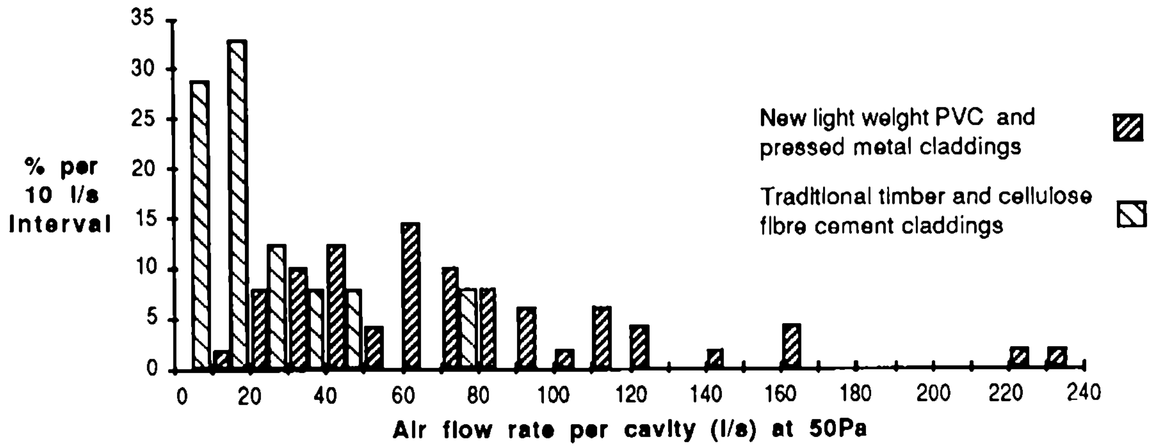


Fig 3 Cladding Airtightness

Traditional claddings are painted in situ and this could make the joints more airtight than on the unpainted laboratory examples. One rusticated timber weatherboard sample was finished with a three coat paint system and this reduced the average Q(50) flow rate by 30%.

3.2 Underlayers

A building paper underlayer must be fixed between cladding and framing in New Zealand houses. This has a large influence on wind driven airflow rates through the cladding into cavities and is seen as a second line of defence against rain leaks. New Zealand Standard 2295[5] requires building papers to have a water vapour flow resistance less than 5.8 MNs/g but the air flow resistance is not specified. A survey of building material air flow characteristics reported by Bassett[6] gives air flow resistances for several "breather papers" available in New Zealand. These appear in Table 2 expressed as Q(50) flow rates for $1m^2$ area of paper and as resistances.

Air flow rates were measured through three claddings with a building paper underlayer in place. The last entry in Table 2 gives the average Q(50) flow rate approximately corrected for $1m^2$ area. As with the diffusion resistance measurements, there were no overlap joints in the test area.

Table 2 Underlayer Airtightness

Underlayer	R MNs/m^3	Q(50) $1/s.m^2$
	Previous air flow resistance measurements	
Building paper - lightweight 0.22 kg/m^2 bitumen impregnated	0.03	2
Building paper - same sample as above but soaked in water	0.1	0.5
Building paper - another sample of lightweight bitumen impregnated paper	0.8	0.06
Roofing felt heavy weight 0.63 kg/m^2 bitumen impregnated paper	4	0.01
	Measured during cavity wall tests	
Building paper - lightweight 0.19 kg/m^2 bitumen impregnated		6

4 INTERCAVITY AIR LEAKAGE

Lateral air leaks between cavities could play a significant role in both dispersion of airborne moisture and the air leaks that can drive rain entry through claddings. Fig 4 identifies two cavities, one formed by the framing and the other between cladding and building paper. It also identifies two types of intercavity air flow labeled type 1 and type 2.

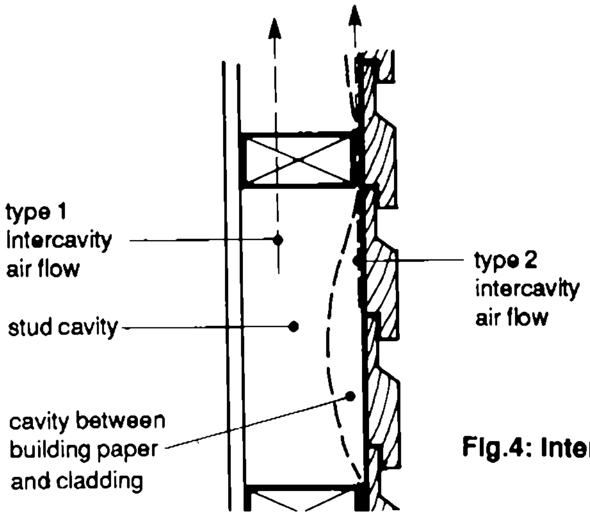


Fig.4: Intercavity air flows

Type 2 air leakage rates between the cavities labelled A-D in Fig 2 were estimated by a method given by Bassett[3]. They are approximate values, being based on an assumed exponent of n = 0.6 which is similar to the exponent found to apply to complete house air leakage[2]. Airflow resistances between these cavities were found to be higher than for leakage through the cladding itself. While cavities A and B in Fig 2 are only one cavity apart in the same wall, the other cavities were separated from each other by a corner. The arrangement of test cavities was chosen this way because there are large differences in wind pressure coefficient near corners of buildings and therefore potentially large intercavity air flows that could drive rain entry. Table 3 gives the pattern of type 2 intercavity air flow rates. These were measured as cavity leakage rates without building paper in place. Because the linings were well sealed on the framing and because the type 1 flow rates are so low, (see Table 4) this should model the cladding/building paper cavity flow rates.

Table 3 Type 2 intercavity flow rates (l/s at 50 Pa)
For cavities formed between building paper and cladding

Cavities	PVC or metal weatherboards Q(50) l/s	Timber or cement based weatherboard Q(50) l/s
In same wall separated by one cavity	36	3.7
Separated by 1 corner	7	2.5
Separated by 2 corners	7	0.4

Table 4 Type 2 and 1 Intercavity flow rates (l/s at 50 Pa) Illustrating effect of adding building paper on air flows between stud cavities

Cavities	Type 1+2 A PVC weatherboard cladding without building paper Q(50) l/s	Type 1 with building paper Q(50) l/s
In same wall separated by one cavity	25	0.03
Separated by 1 corner	16	0.37
Separated by 2 corners	10	0.31

Three significant effects emerge. The first is that type 2 air flows around corners are rather more restricted than between cavities in the same wall. The second is that type 2 intercavity air flows in PVC and pressed metal weatherboard systems were higher than for timber or cement based weatherboards. Finally, with building paper in place as a measure of type 1 air flows, much higher intercavity resistances were encountered.

5 LININGS

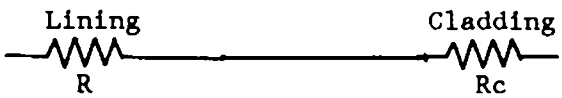
A variety of evidence is given below, in support of interior linings forming the plane of highest leakage resistance in walls and therefore determining the air infiltration rate through walls. This is perhaps to be expected as linings are generally sheet materials with a standard of finish that has to be free from cracks to be visually acceptable. Claddings, on the other hand, are generally interlocking or overlapping boards with therefore greater potential for air leaks.

5.1 Air Tightness Tests

The suggestion that linings might contribute most to wall airtightness came first from an airtightness survey of houses in three major cities in New Zealand[7] . Houses were classified into two categories: "masonry" or "other" according to the materials used for cladding. In the sample of 90 randomly selected houses "other" turned out to be mostly timber or fibre reinforced cement weatherboards and all the "masonry" types were brick or concrete block veneer over timber frame. There was no statistically significant difference in airtightness between the two classes of building, indicating that if claddings contribute to house airtightness, the difference between the two classes is less than a 10% effect. It was considered more likely that the results were similar because claddings play a minor role in wall airtightness.

5.2 Cavity Pressures During Airtightness Tests

A direct way of measuring an average ratio of air flow resistance connecting wall cavities to indoors and outdoors involves simply measuring cavity air pressures while the house is under air tightness test pressurisation. If the network of resistances in Fig 1 can reduced to an equivalent series combination as in Fig 5 then, with assumed flow exponents, a resistance ratio can be calculated from pressure differences measured across cladding and lining.



flow equality → $C_c \Delta P_c^{n_c} = C \Delta P^{n_L}$

$$\frac{C_c}{C_L} = \frac{\Delta P_L^{n_L}}{\Delta P_c^{n_c}} \quad . \; . \; . \; (4)$$

if $R(\Delta P) = \Delta P/Q$ $\quad R(\Delta P) = \dfrac{\Delta P^{(1-n)}}{C}$

then $\dfrac{R_c}{R_L} = \dfrac{C_L \Delta P_c^{(1-n_c)}}{C_c \Delta P_L^{(1-n_L)}}$

if $n_c = n_L = 0.6$ and both $R_c = R_L$ are at the same reference pressure ie $\Delta P_c' = \Delta P_L'$

then $\dfrac{R_c}{R_L} = \dfrac{C_L}{C_c}$

substituting in 4 $\quad \dfrac{R_c}{R_L} = \left(\dfrac{\Delta P_c}{\Delta P_L}\right)^{0.6}$

Fig 5 Simplified wall resistance network

Five houses in Lower Hutt were equipped with wall cavity pressure taps before the wall linings were fitted. These taps consisted of 5mm diameter plastic tubes running from the cavities to an accessible termination in the ceiling space. All houses were clad in fibre reinforced cement weatherboards and lined with gypsum plasterboard. A set of cavities of 6 types given in Table 5 were selected in each house and pressure ratios recorded while an indoor/outdoor pressure difference of 50 Pa was maintained with an airtightness test fan mounted in an external door. Pressures were measured with an MKS electronic manometer datalogged and switched between the two pressures at 5 Hz. The margin for experimental error in $\Delta P_o / \Delta P_L$ is considered to be ± 0.02.

Table 5 Cavity Pressure Ratios

Cavity description	Mean $\Delta P_C / \Delta P_L$	Range $\Delta P_C / \Delta P_L$	Mean R_C/R_L
1 Cavity - at least one cavity distant from any joint or protrusion in the lining or external corner.	0.07	0.02 - 0.18	0.2
2 Corner - As above but with one edge on an external corner.	0.03	0.01 - 0.07	0.1
3 Window - As 1 but bordering a window.	0.07	0.01 - 0.17	0.2
4 Top plate - Bordering on the top plate.	0.03	0.01 - 0.08	0.1
5 Bottom plate - A floor level cavity	0.18	0.09 - 0.24	0.4
6 Electric outlet - Containing an electrical outlet	0.05	0.01 - 0.08	0.2
7 Roof space cavity	0.02	0.01 - 0.05	0.1
8 Subfloor crawl space	0.01	0.00 - 0.01	0.1

Cavities bordering on the bottom plate had significantly higher resistance ratios. These could result from air leaks between the lining and bottom plate at a joint which is not stopped because it is covered by a skirting board. More important than this, however, is the low overall value of the resistance ratio, indicating the lining represents the plane of highest leakage resistance in this type of cavity wall construction. Another point of interest was the difference in $\Delta P_o/\Delta P_L$ between adjacent cavities, indicating that significant resistance separates the stud cavities.

5.4 Air Flow Resistances of Materials

Diffusion of air through the solid components of a building (such as its wall lining materials) has the potential to contribute to air leakage rates because the areas involved are orders of magnitude larger than the size of cracks and joints. Air diffusion resistance measurements were made in the laboratory for a range of interior and exterior lining materials and reported by Bassett[8]. A selection of the data relevant to walls is given in Table 6 together with a brief description of each material. The resolution of the data was limited to one order of magnitude by variation between materials of the same description but different batch. The airflow resistance is defined in[7] by equation 5.

$$R = \frac{A\ \Delta P\ 10^{-6}}{Q} \quad MNs/m^3 \quad . \quad . \quad (5)$$

Where

R - leakage resistance, MNs/m^3,
A - area of material, m^2,
Q - volume flow rate of air, m^3/s, and
ΔP - air pressure difference across the material, N/m^2

TABLE 6 Bulk air flow resistances of wall lining materials

Material	Coating	Density kg/m^3	Thickness mm	Resistance MNs/m^3
Paper-coated gypsum plasterboard	none	750	9.5	10
	alkyd paint system	"	"	$>10^7$
	acrylic paint system			10^5
	vinyl wallpaper	"	"	10^3
Wood fibreboard low density	prepainted	330	13	1
Wood fibreboard high density	none	1130	5	10
	alkyd paint system	"	"	$>10^7$
	acrylic paint system	"	"	10^4
	varnish	"	"	10^6
Building papers see Table 2				

5.5 Wall lining leakage data from air tightness tests

Many other leakage resistances have been gleaned from house airtightness tests. Mostly the data was obtained by selectively taping over air leaks and remeasuring the whole house leakage characteristics[2]. Table 7 is a summary of leakage resistances measured in wall linings. The data is expressed as Q(50) leakage rates at 50 Pa applied pressure.

Table 7 Leakage Openings in Wall Linings

Leakage at 50 Pa in 1/s

Location	Q(50)	Units
Bottom plate: Wood prelaid chipboard floor, Gypsum plaster board wall - Two houses.	0.08	1/s.m
Top plate: Gypsum plaster wall board, wood fibre board ceiling. Mean of two houses (unpainted).	0.3	1/s.m
Window architraves: gypsum plaster wall board overlapped by wooden architrave	0.7	1/s.m
Electrical wall outlet - average	1.0	1/s
Electrical switchboard	10	1/s
Unfinished wall lining behind kitchen joinery (most serious wall lining leak encountered)	12	1/s

On three occasions it was attempted to isolate all detectable leakage openings in a house and arrive at a background leakage rate attributed to invisible cracks and the porosity of materials used in floors, ceilings and wall linings. Table 8 summarises total and background leakage at 50 Pa achieved in 3 houses.

Table 8 Background Airtightness Characteristics of 3 Houses

Characteristic	House A	House B	House C
Total house leakage at 50 Pa in ac/h	5.05	4.64	10.0
House leakage with all locatable leaks blocked	2.47	2.12	1.62
Building enclosed volume m^3	227	210	377
Building shell area m^2	298	288	410
Shell area averaged Q(50) $1/s.m^2$	0.52	0.43	0.41

Although the buildings concerned were quite different sizes, styles and of different cladding materials, the background leakage was similar in each case.

6 SUMMARY OF WALL AIR FLOW RESISTANCES

A picture of air flow resistances in walls has emerged which can be summarised with the help of Fig 6 as follows:

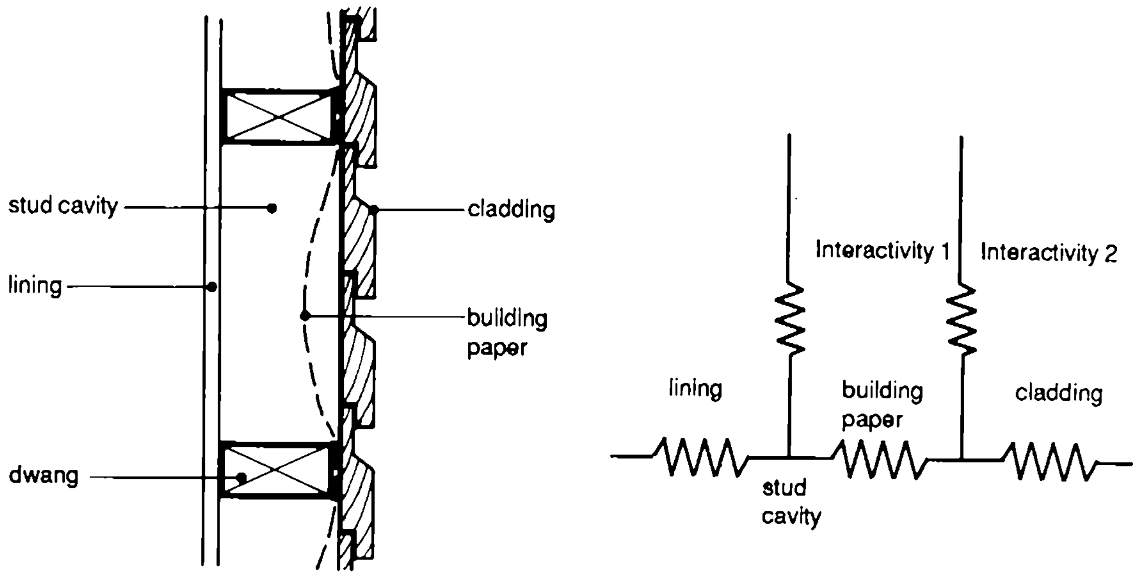


Fig.6: Arrangement of air flow resistances in timber framed wall

Table 9 gives the best estimates for components of the network of airflow resistances in walls. The units are l/s per m^2 wall area driven by 50 Pa air pressure unless otherwise indicated.

Table 9 Summary of Air Flow Path Magnitudes

Air flow path	Origin	Q(50) l/s.m^2 Max	Best estimate	Min
Wall linings	cracks	1.0	0.6	0.2
	background		0.5	
	diffusion	0.005		
	total		1.1	
Intercavity 1 (frame cavity)	adjacent		0.03 l/s	
	around corner		0.4 l/s	
Building paper (BP)	no joints	6	6	0.5
Intercavity 2 PVC or metal	adjacent		40 l/s	
(BP to cladding)	around corner		7 l/s	
Intercavity 2 timber or cement	adjacent		4 l/s	
(BP to cladding)	around corner		2 l/s	
Wall claddings	Timber, Fibre reinforced cement		42	
	PVC Metal		130	

Notes relating to Table 9

Wall linings - In the "Max" case, the area averaged Q(50) flow rates are based on all air leaks at top and bottom plate passing through the cavity. In the "best estimate" case the fraction is 50% and in the "Min" case it is 0%.

Intercavity 1 - This intercavity air leakage path has a high resistance with building paper in place and air pressure holding it against the studs. For pressure applied the other way or, with overlap joint present in the paper, the resistance could be lower.

Building paper - With heavier papers than normal, the resistance at this plane in the wall could exceed the lining resistance by orders of magnitude. More information is needed on the effect of joints and sensitivity to workmanship detail.

Intercavity 2 - These resistances depend very much on cladding type - in particular, on how tight a seal the weatherboards make against the framing.

Claddings - The air leakage resistance is more a factor of cladding type and proximity to corner and edge details than on surface area. Traditional weatherboards nailed in tight contact and with scribers at door and windows were more airtight than newer claddings in PVC or pressed metal which clip together.

7 CONCLUSIONS

First order estimates of flow characteristics have been provided for many of the air flow paths in timber framed walls. In spite of there being a wide range of building material combinations the following observations can be made.

1 The plane of highest leakage resistance for walls with weatherboard claddings, building paper, and gypsum plaster linings is the linings.

2 Building paper is the next most significant air barrier provided it can be made airtight at the joints.

3 New PVC and pressed metal weatherboards are less airtight than more traditional timber or cement based weatherboards. This need not mean the former are more prone to rain leaks.

4 Intercavity air leaks (about which comparatively little is known) tend to be blocked at corners. The resistance between stud cavities can be high enough to support appreciable pressure differences.

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AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 4

THE USE OF EQUIVALENT ELECTRICAL CIRCUITS TO DESCRIBE THE MOISTURE BEHAVIOUR OF STRUCTURES

M.J. CUNNINGHAM

Building Research Association of New Zealand
Private Bag
Porirua
New Zealand

THE USE OF EQUIVALENT ELECTRICAL CIRCUITS TO DESCRIBE THE MOISTURE BEHAVIOUR OF STRUCTURES

M J Cunningham

SYNOPSIS

Earlier work on analytical models of the moisture behaviour of structures is used to show that after suitable linearisation approximations, the models are similar in form to those describing the performance of electrical circuits. This enables the theory of electrical circuits to be used to calculate the moisture performance of the structures under any driving forces. The equivalent circuit for the performance of a structure over longer time periods (much greater than one day) is shown to be a simple series combination of a capacitor and a resistor, which implies that one parameter only, here called the drying time constant, is needed to describe the performance of the structure under these conditions. An expression is given showing how this time constant increases over the drying time of the unenclosed hygroscopic material.

LIST OF SYMBOLS

- A area (m^2)
- c_i concentration of moisture in region i (kg m^{-3})
- c_o concentration of moisture in the cavity air (kg m^{-3})
- C capacitance (F)
- F air change rate (s^{-1})
- g surface mass transfer coefficient from the evaporating surface to the cavity (kg N^{-1} s^{-1})
- i current (A)
- I Laplace transform of current (A s)
- k proportionality constant linearising the sorption curve of a hygroscopic material (m^2 s^{-2})
- m moisture concentration (kg m^{-3})
- M initial moisture concentration (kg m^{-3})
- p vapour pressure (Pa)
- $\bar{p}$ weighted mean of vapour pressures (Pa)
- p_g water vapour pressure due to evaporating surface (Pa)
- P Laplace transform of vapour pressure (Pa)
- r_{ij} vapour resistance between region i and j (N s kg^{-1})
- R total vapour resistance (N s kg^{-1} m^{-2})
- R universal gas constant (8310 J K^{-1} $kmole^{-1}$)
- R_{ae} total vapour resistance between framing material and external regions via the cavity (N s kg^{-1} m^{-2})
- R_{ao} total vapour resistance between framing material and cavity (N s kg^{-1} m^{-2})
- R_{be} total vapour resistance between framing material and external regions via the linings(N s kg^{-1} m^{-2})
- R_{oe} total vapour resistance between the cavity and the external

regions
R_{wa} total vapour resistance of a half-width of framing material facing the cavity($N\ s\ kg^{-1}\ m^{-2}$)
R_{wb} total vapour resistance of framing material facing the linings ($N\ s\ kg^{-1}\ m^{-2}$)
t time (s)
t_a unenclosed drying time constant through the edge of the framing material which will face cavity (s)
t_b unenclosed drying time constant through the edge of the framing material which will face the linings (s)
t_d drying time constant for the enclosed framing material (s)
t_w drying time constant for unenclosed framing material (s)
T Kelvin temperature (K)
v voltage (V)
V Laplace transform of voltage (V s)
V volume (m^3)
W molecular weight of water (18 kg $kmole^{-1}$)
φ phase lag (radians)
ω angular frequency (radians s^{-1})

Subscripts

a edge of the framing material which will face the cavity
b edge of the framing material which will face the linings
i,j external regions
o cavity
w framing material

1. INTRODUCTION

The traditional tools (Marsh[1],Keiper,Cammerer and Wagner[2], Glaser[3]) for predicting the moisture performance of structures have a number of deficiencies:

1. Air leakage which is usually the most important moisture transfer mechanism is not allowed for or not handled completely.
2. The hygroscopic nature of building materials is not allowed for.
3. There is an underlying assumption of steady state so that the dynamics of the structures' moisture performance is not taken into account.

In order to address these problems, the author in a series of publications (Cunningham[4-7]) has examined the moisture performance of structures by developing mathematical models based on conservation of moisture in various parts of the structure. The models are lumped and linearised which allows analytical solutions to be given.

This paper summarises these developments and places a slightly different emphasis on the topic by highlighting the value of using electrical circuit analogies to understand and predict moisture performance of structures. The differential equations of the physical model, once linearised, consist of a series of coupled first order differential equations, which can be seen to be directly equivalent to an analogous set of equations governing the performance of the corresponding electrical circuit. Although the mathematics for the two cases is the same and their performance is correspondingly similar, there exists a large body of knowledge and a well-established methodology for analysing electrical circuits that can now be tapped into directly.

The paper begins by outlining the development of two similar models developed by the author. One of these models is examined in detail to show how,after linearisation, it can be seen to be equivalent to an electrical network consisting of capacitors and resistors. It is shown that if one is interested chiefly in longer time periods, much greater than one day, then only the very simplest of circuits need be considered, namely a series combination of a capacitor and a resistor. This implies that the performance of the circuit and therefore the moisture performance of the structure, is characterised by only one parameter, namely the time constant of the circuit. An expression is given for the corresponding time constant for the moisture performance of the structure, called here the "drying time constant". The paper concludes with examples taken from earlier work demonstrating the calculation of the drying time constant and demonstrating how the structure's moisture performance under an arbitary driving force can be derived by exploiting the electrical circuit analogy. The driving force used in this example is the seasonal periodic fluctuations in climate.

2. PHYSICAL MODELS

In this section physical models are developed for two different structures taken from Cunningham[6,7]. The first most general model considered is a structure containing hygroscopic material, e.g. timber framing, and an air filled cavity as shown in Figure 1(a). In this case the hygroscopic material has a moisture flow path to the cavity but no significant flow to the linings. This model would simulate a structure such as a timber framed pitched roof where much of the framing is not in contact with any lining.

The region i shown in Figure 1(a) represents one of n moisture sources/sinks e.g. indoors, outdoors, other building cavities, extractor fans etc. The possiblity of an evaporating water surface inside the cavity is also allowed for (e.g. an open water tank or soil surface.) Two moisture transfer mechanisms are assumed, namely vapour diffusion driven by water vapour partial pressure difference p_1-p_o, and air convection characterised by a mean air change rate F_{io} (from region i to the cavity) and F_{oi} (from the cavity to region i) measured in s^{-1}. The cavity has volume Vo and the hygroscopic material has volume V_w.

The second model considered here is a flat roof or wall with a framing material which is joined to the inside and outside linings and an associated cavity filled with insulation or air, see Figure 1(b). Both framing and cavity material can store moisture but the hygroscopic properties of the linings are ignored. Any membranes such as vapour barriers, building paper, sarking etc are lumped in with the linings. In this model no evaporating surface inside the cavity has been included and for simplicity only two regions external to the structure are considered: indoors and outdoors. It is, however, straight forward to include these details if required.

A key simplication is now made. The hygroscopic material is lumped and its drying and wetting assumed to be exponential, see Cunningham[7] i.e.

$$V_w \frac{dm}{dt} = \frac{p - p_w}{R_t}$$

where
p is the vapour pressure external to the hygroscopic material (Pa)

p_w is the vapour pressure of the hygroscopically bound moisture in the framing material at moisture content m as determined by the sorption curves for that material (Pa)

R_t is the lumped total vapour flow resistance (including surface area weighting) between the hygroscopic material and the surrounding medium. ($N\ s\ kg^{-1}\ m^{-2}$)

The validity of this exponential drying approximation has been discussed elsewhere (Cunningham[7]). Cunningham[7] derives an expression giving the connection between R_t and other physical parameters such as the diffusion coefficient for moisture transfer in the hygroscopic material and the surface mass transfer coefficient for transfer in and out of the material.

The physical model of the performance of these structures is established by writing down the conservation equations for moisture in the cavity, the hygroscopic material and the air in the cavity. We have,

> Increase in cavity moisture per unit time=flow of moisture from external regions by diffusion+flow of moisture to and from external regions by air leakage-flow of moisture to the framing material

which results in the equation

$$V_o \frac{dc_o}{dt} = \frac{p_w - p_o}{R_{wo}} + g A_g (p_g - p_o) + \sum_i \left(\frac{A_{io}(p_i - p_o)}{r_{io}} + V_o (F_{io} c_i - F_{oi} c_o) \right) \tag{1}$$

for the first model and the equation and

$$V_o \frac{dm_o}{dt} = \frac{p_w - p_o}{R_{wo}} + \sum_{i=1}^{2} \left(\frac{A_{io}(p_i - p_o)}{r_{io}} + V_o (F_{io} c_i - F_{oi} c_o) \right) \tag{2}$$

for the second model.

Also

> Increase in hygroscopic moisture per unit time=flow of moisture from cavity+flow in moisture from exterior regions through the linings
>
> giving

$$V_w \frac{dm_w}{dt} = \frac{p_o - p_w}{R_{wo}} \tag{3}$$

for the first model and

$$V_w \frac{dm_w}{dt} = \frac{p_o - p_w}{R_{wo}} + \sum_{j=1}^{2} \frac{A_{jw}(p_j - p_w)}{r_{jw}} \tag{4}$$

for the second model.

Here

c_i is the moisture concentration in the air in region i (kg m^{-3})

m_i is the moisture concentration(kg m^{-3}) in the material in region i

g is the surface mass transfer coefficient from the evaporating surface to the cavity (kg N^{-1} s^{-1})

r_{pq} is the series sum of all vapour resistances between region p and q (N s kg^{-1})

A_{pq} is the area (m^2) between region p and q

F_{pq} is the air change rate (s^{-1}) between region p and q

R_{wo} is the total vapour resistance (including area weighting) between the hygroscopic material and the cavity material (N s kg^{-1} m^{-2}).

Cunningham[7] derives an expression for R_{wo} as a function of physical parameters such as the diffusion coefficient for moisture transfer in the hygroscopic material and the surface mass transfer coefficient for transfer in and out of the material.

Also since the net air flow into the cavity is zero, then for both models

$$\sum_i (F_{io} - F_{oi}) = 0$$

Note that the term $F_{io} c_i - F_{oi} c_o$ in equation (1) and (2) assumes perfect mixing of the air flows in the cavity.

From here onwards only the second (flat roof or wall) model will be developed in detail. Cunningham[6] should be consulted for detailed development of the first model.

Water vapour concentrations c_i are converted to vapour pressure by assuming water vapour to be an ideal gas i.e.

$$p = \frac{c_i R T}{W} \tag{5}$$

where R is the universal gas constant, T is the Kelvin temperature of the air and W is the molecular weight of water.

The sorption curves of the framing and cavity materials are now described by the equations

$$p_w = k_w m_w \tag{6a}$$

$$p_o = k_o m_o \tag{6b}$$

where k_w and k_o are functions of temperature and to a lesser extent of moisture content.

Note that if the cavity material is air then

$$k_o = \frac{RT}{W} \tag{7}$$

from equation (5).

Following Cunningham[7], a number of lumping definitions are now made to simplify these conservation equations, see Figure 2.

Define

$$\begin{aligned}
\frac{1}{R_{oe}} &= \sum_{i=1}^{2} \left(\frac{A_{io}}{r_{io}} + \frac{V_o F_{oi} W}{RT} \right) \\
\frac{1}{R_{be}} &= \sum_{j=1}^{2} \frac{A_{jw}}{r_{jw}} \\
R_{ie} &= R_{be} - R_{wb} \\
\bar{p}_o &= R_{oe} \sum_{i=1}^{2} \left(\frac{A_{io}}{r_{io}} + \frac{V_o F_{io} W}{RT} \right) p_i \\
\bar{p}_w &= R_{be} \sum_{j=1}^{2} \frac{A_{jw} p_j}{r_{jw}}
\end{aligned} \tag{8}$$

R_{wa} and R_{wb} are the total vapour resistances (including area weighting) to the surface (but not across it) of the hygroscopic material in the direction parallel and perpendicular to the linings respectively. An expression for these can be found in Cunningham [7].

With these definitions equations (2) and (4) become

$$\frac{V_o}{k_o} \frac{dp_o}{dt} = \frac{p_w - p_o}{R_{wo}} + \frac{\bar{p}_o - p_o}{R_{oe}} \tag{9a}$$

$$\frac{V_w}{k_w}\frac{dp_w}{dt} = \frac{p_o - p_w}{R_{wo}} + \frac{\bar{p}_w - p_w}{R_{bo}} \qquad (9b)$$

These equations as written are nonlinear, chiefly because of the strong temperature dependence of k.

Very similar equations follow for the case of the first model.

3. ELECTRICAL CIRCUIT ANALOGIES

Generally it is the long term moisture behaviour of the structure that is of interest; such details as the drying time of wet framing or the amount of moisture accumulated over the winter season. Short term moisture behaviour (say over time periods of a day or less) is usually of less concern and in any case is not well modelled by the equations developed above. Issues such as hygroscopic linings and nonuniform moisture concentrations in the hygroscopic materials are important for short term moisture behaviour and these are not modelled here.

Over the long term then (in the order of months) we can take for the temperature its mean value and therefore take the k_o and k_w constant at their mean values. This linearises equations (9) above and allows them to be solved by conventional techniques given the initial conditions, see for example Cunningham[7]. Further discussion of the implications of this linearisation can be found in Cunningham [7].

At this point the similarity between equations (9) and the corresponding equations for an equivalent electrical circuit can be exploited. Specifically, the following analogies are made in order to establish an equivalent RC electrical circuit to the physical models being used here.

voltage	$\sim$	p_i
charge	$\sim$	$m_i V_i$
current	$\sim$	$V_i \frac{dm_i}{dt} = \frac{V_i}{k_i}\frac{dp_i}{dt}$
capacitance	$\sim$	$\frac{V_i}{k_i}$
resistance	$\sim$	R_i

(10)

Using these analogies the coupled linear first order differential equations (9) become analogous to a set of equations describing the performance of an electrical circuit consisting of capacitors and resistors. The equivalent circuit to the first and second models are shown in Figure 3. The whole gamut of electrical circuit theory can now be drawn upon to describe the performance of our models under any driving (or excitation) function. The unifying concept usually used is a transfer function for the circuit in the s domain together with the theory of Laplace transforms to derive the circuit performance in the time domain.

It was stated at the beginning of this section that the long term moisture performance is of most interest to us. By considering the size of the various parameters involved, see Cunningham[7], it can be shown that once the initial transients have died down (after a few hours) the capacitor representing the cavity material in the models developed here becomes fully charged and no longer contributes to the circuit performance. In this case we are left with the capacitor representing the hygroscopic material and the resistors connected to it. These resistors can be lumped giving a value of

$$R_{ae} \tag{11a}$$

for the first model and

$$\frac{R_{ae} R_{be}}{R_{ae} + R_{be}} \tag{11b}$$

for the second model.

Hence for long term cavity performance we are left with a simple series combination of a resistor and a capacitor, see Figure 4. The differential equation describing the performance of this RC circuit is

$$v_c + iR = v$$

where
v_o is the voltage across the capacitor
v is the driving voltage across the capacitor and resistor
i is the current in the circuit
Since

$$i = \frac{dq}{dt} = C\frac{dv_c}{dt}$$

this can be written as

$$v_c + RC\frac{dv_c}{dt} = v$$

Performing a Laplace transform upon this equation gives

$$V_c = \frac{V + RC\,v_c(0)}{1 + sRC}$$

where
V_c is the Laplace transform of the capacitor voltage
V is the Laplace transform of the driving voltage
$v_c(0)$ is the initial value of the capacitor voltage.
In other words

$$V_c = \frac{V + t_c v_c(0)}{1 + st_c}$$

where t_c is the time constant of the RC circuit defined as

$$t_c = RC \tag{12}$$

This takes the form

V_c=transfer function x excitation function

where

transfer function= $\frac{1}{1 + st_c}$

and

excitation function= $V + t_c v_c(o)$

The corresponding time constant for the physical model will be labelled t_d so that the physical model analogy is seen to be

$$P_w = \frac{P + t_d p_w(o)}{1 + st_d}$$

We have now reached the point where the complete (long term) moisture behaviour of our structure is characterised by only one parameter, namely the time constant t_d (although it must be remembered that a second parameter k_w is also needed if we wish to translate from vapour pressure to moisture content within the hygroscopic material). Physically the time constant can be interpreted as the time constant for the hygroscopic material to dry from its initial moisture content (at the time of construction or, say, at the end of winter) to its long term equilibrium value over the time period of interest. However it is important to reiterate that given this single drying time constant,the moisture performance under all other driving functions can be deduced,insofar as the linearisation approximation is valid. In particular the performance can be derived under periodic seasonal variations in the climate driving forces, see Cunningham[6]. Examples are given later to illustrate this point.

4. PROPERTIES OF THE DRYING TIME CONSTANT

In the case of the second model, from equations (10), (11b) and (12) we have

$$t_d = \frac{V_w}{k_w} \frac{R_{ae} R_{be}}{(R_{ae} + R_{be})}$$

i.e.

$$\frac{1}{t_d} = \frac{k_w}{V_w}\left(\frac{1}{R_{ae}} + \frac{1}{R_{be}} \right)$$

$$= \frac{k_w}{V_w}\left(\frac{1}{R_{ae} + R_{ao} + R_{oe}} + \frac{1}{R_{wb} + R_{ie}} \right)$$

$$= \frac{k_w}{V_w}\left(\frac{1}{R_{wa}(1+\gamma)} + \frac{1}{R_{wb}(1+\delta)} \right)$$

where

$$\gamma = \frac{R_{ao} + R_{oe}}{R_{ae}}$$

and

$$\delta = \frac{R_{ie}}{R_{wb}}$$

Intuitively, one would expect that once the framing material has been enclosed its drying time constant t_d would be longer than for the unenclosed material. This can be put on a quantitative basis by comparing the value of the enclosed drying time constant t_d with the time it would take for the hygroscopic material to dry unenclosed to air under conditions where this open air drying is diffusion limited, i.e., diffusion to the surface of the material is very much slower than surface mass transfer. If t_a is the time taken for the unenclosed material to dry through the side which will face the cavity and t_b is the time taken to dry through the side which will face the linings, it can be shown, see Cunningham [7], that

$$t_a = \frac{V_w}{k_w} R_{wa} \tag{13a}$$

and

$$t_b = \frac{V_w}{k_w} R_{wb} \tag{13b}$$

The time t_w for the unenclosed hygroscopic material to dry was shown in Cunningham[7] to be

$$\frac{1}{t_w} = \frac{1}{t_a} + \frac{1}{t_b} \tag{14}$$

Therefore

$$\frac{1}{t_d} = \frac{1}{t_a(1+\gamma)} + \frac{1}{t_b(1+\delta)} \tag{15}$$

A similar expression can be derived for the first model.

Equation (15) shows how the long term time constant-physically the drying time of the framing material once enclosed in the structure-is increased over the unenclosed value,according to the air and vapour tightness construction details of the structure and the driving forces upon it.

5. EXAMPLES

The following examples are taken from Cunningham[7] and are used to illustrate the calculation of the drying time constant t_d, and the use of the equivalent electrical circuit to calculate the response of structures to seasonal driving forces.

Two structures are considered and two subcases are considered for each structure. Structure 1 has 50x50mm timber joists spaced at 500mm centres with the cavity in between filled with fibreglass. Structure 2 is similar except that the joist is 50x100mm and is orientated so that the cavity between the joists is 100mm deep and also filled with insulation.

For each structure two subcases are considered. Subcase (a) has the internal linings plus membranes with a vapour resistance of 2 GNs kg^{-1} and the external linings with a vapour resistance of 1 GNs kg^{-1}. Subcase (b) has the internal linings with a vapour resistance of 20 GNs kg^{-1} and the external linings with a vapour resistance of 10 GNs kg^{-1}.

In all cases the driving air pressures and air permeabilities are such that the air change in the cavity is 0.5 air changes per hour. (To calculate the long term time constant the direction of air movement is not needed). The mean temperature of the structure is taken as 11°C. The diffusion coefficient (vapour pressure driven) for the wood is taken as 7.32×10^{-12} s and for the insulation as 1.67×10^{-10} s. k_w is taken as $20\ m^2\ s^{-2}$.

Formulae (13a) and (13b) are used to calculate the time constants for open air drying of the joists, t_a and t_b. These time constants come to 20 days for drying through faces 50mm apart and 80 days through faces 100mm apart. Hence from formula (14) the overall drying time in air will be 10 days for a 50x50mm joist and 16 days for a 100x50mm joist.

Formula (15) is used to find how these drying times increase when the structure is enclosed.Details on how to do this can be found in Cunningham[7]. Table 1 shows the results of these calculations.

To highlight the fact that knowledge of the drying constant t_d implies complete knowledge of the longer term moisture performance of the structure (assuming linearity), the case of periodic driving forces will now be considered. Take for example the important case of seasonal variation in the moisture content of the structure.In this case the driving forces can be approximated as Cunningham[8]

$$p = \tilde{p} + \Delta p \sin \omega t$$

where

$\tilde{p}$ is the mean value of p and Δp is the maximum deviation of the driving force from this mean

and ω is the angular frequency of the driving forces.

The moisture content of the framing material can be simply determined by examining the RC circuit analogy in Figure 4. From circuit analysis the voltage v_c across the capacitor for this circuit is

$$v_c = \frac{v}{\sqrt{1 + (\omega \bar{t}_d)^2}}$$

where v is the driving voltage and $\bar{t}_d$ is the time constant appropriate to the mean of the driving conditions over the time period being considered, see Cunningham[6].

The phase φ of the voltage across the capacitor lags the phase of the driving voltage by

$$\varphi = \tan^{-1}(\omega \bar{t}_d)$$

Taking the driving period as 1 year, Table 2 contains the amplitude response and phase lag of the framing material vapour pressure and hence moisture content compared to the driving forces for each of the four cases analysed in the examples above. For example in the case of the structure with a 100x50mm joist and high vapour resistance linings, the maximum seasonal moisture content in the joist occurs 1.35 months later than the peak driving forces, and the value of the deviation of the moisture content from the yearly mean value is only 77% of that which would be predicted from assuming the timber was in moisture equilibrium with the driving forces. In fact as pointed out elsewhere (Cunningham[6]), the amplitude response and phase lag is only significant for tight structures, that is, structures in which the enclosed drying time constant is significantly longer than the unenclosed time constant.

6. CONCLUSIONS

Earlier work (Cunningham[4-7]) on mathematical models of the moisture performance of structures has been summarised. Once these models have been linearised their equivalent electrical circuit has been found. This enables the large body of knowledge on electrical circuit theory to be utilised to give quick and easy calculation of the moisture performance of the structure under any driving force.

For the approach to be useful it is necessary to understand the range of validity of the linearising approximations used. It has been argued that, provided the longer term performance of the structure is of chief concern, the mean value of the parameters k_w and k_o used to describe the sorption curves of the cavity materials can be used.

Furthermore if only the longer term performance of the structure is of concern it has been shown that the equivalent circuit is a series combination of a capacitor and a resistor, characterised by its time constant. In turn this means that the long term moisture performance of the structure can be completely understood with just one parameter, the drying time constant of the hygroscopic material. An expression showing how this time constant increases over the drying time of the unenclosed hygroscopic material has been given.

It has not been the intention of this paper to examine the experimental validity of this approach. However some preliminary experimental work is being done which tends to point to the usefulness of this approach. Cunningham[8] has shown that framed roofing structures exhibit exponential drying and can thus be associated with a time constant, while in Cunningham[6] field results from a group of houses in Invercargill, New Zealand, were shown to have attic moisture contents in phase with the annual climate driving forces, implying that for these houses the roof timber drying time constant was much less than one year.

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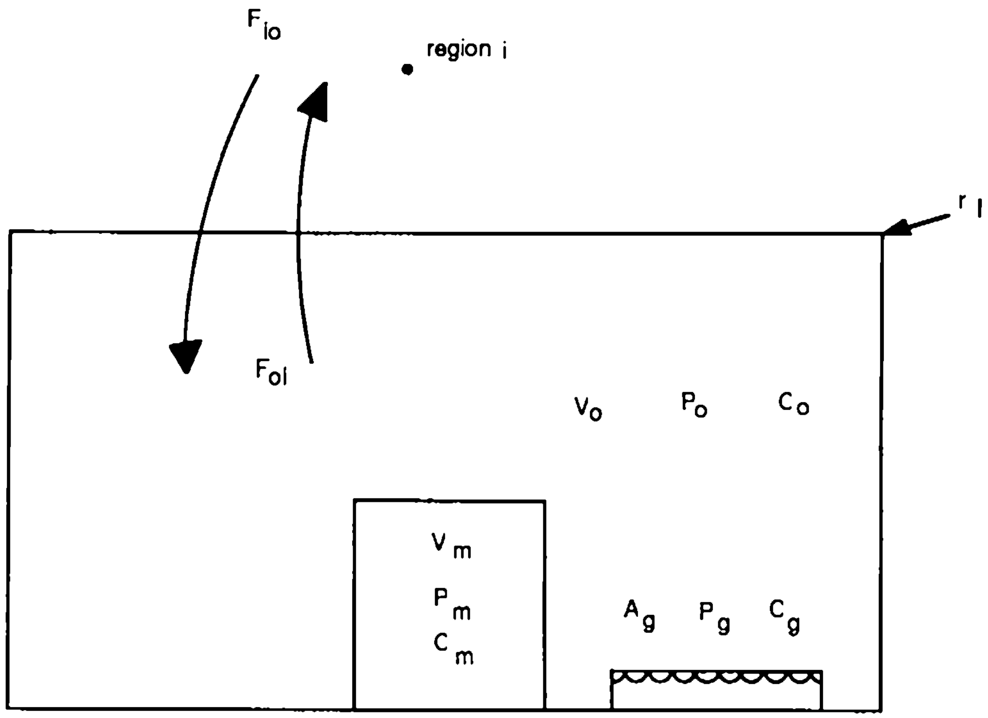
Quantity	1. 50x50mm Joist		2. 100x50mm Joist	
	1(a) Low resistance linings	1(b) High resistance linings	2(a) Low resistance linings	2(b) High resistance linings
Drying time constant for unenclosed framing, t_w	10.0 days	10.0 days	16.0 days	16.0 days
Drying time constant for enclosed framing, t_2	17.2 days	36.4 days	25.5 days	47.8 days
Drying time constant for enclosed framing from earlier work.	22.1 days	35.9 days	24.0 days	45.0 days

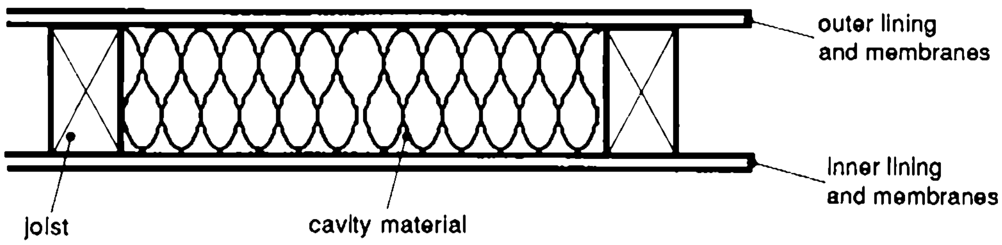
Table 1: Drying time constants for various structures.

Quantity	1. 50x50mm Joist		2. 100x50mm Joist	
	1(a) Low resistance linings	1(b) High resistance linings	2(a) Low resistance linings	2(b) High resistance linings
Drying time constant for enclosed framing, t_2	17.3 days	36.8 days	25.8 days	48.5 days
Phase Lag	0.56 months	1.10 months	0.81 months	1.35 months
Amplitude response	0.96	0.84	0.91	0.77

Table 2: Seasonal moisture behaviour for various structures.



1(a) first model



1(b) Second model

Figure 1: Physical models

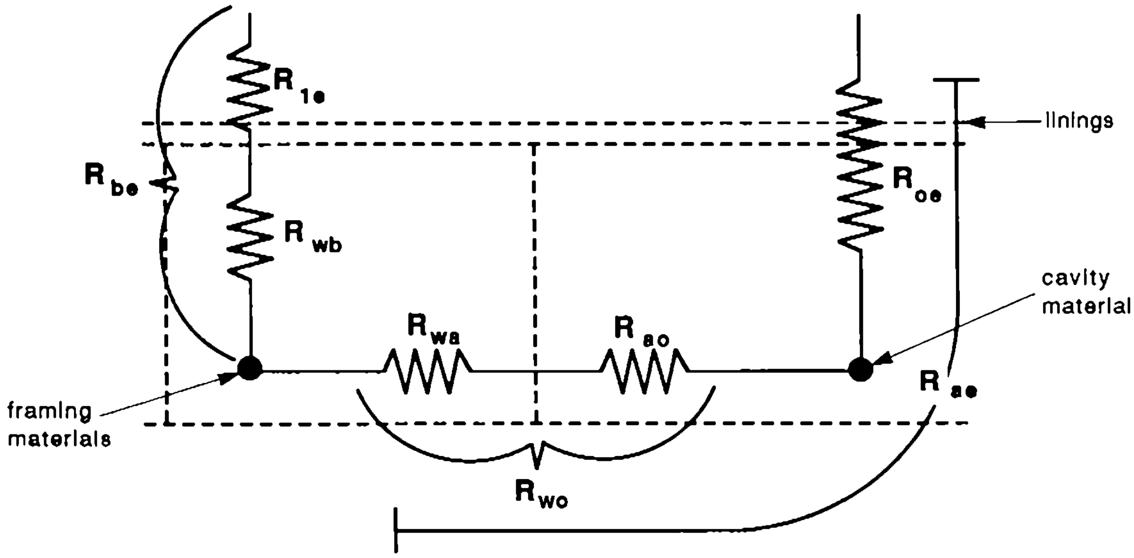
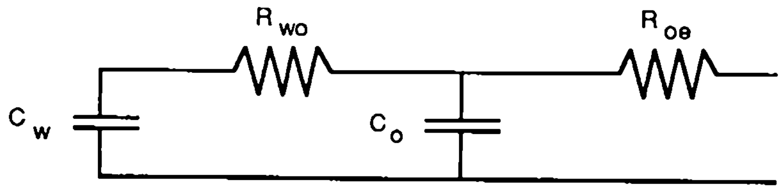
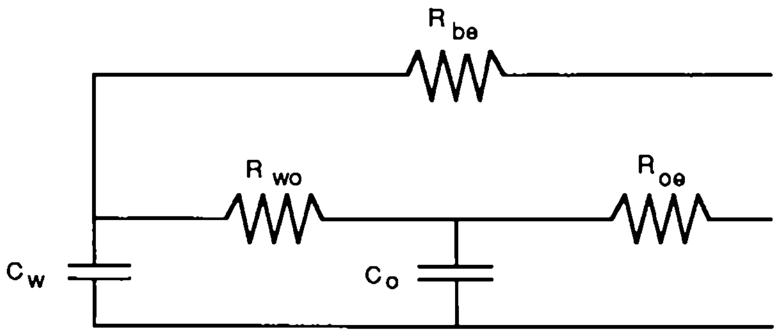


Figure 2: Definitions of the lumped total vapour flow resistances.



3(a) First model



3(b) Second model

Figure 3: Equivalent circuits for each model

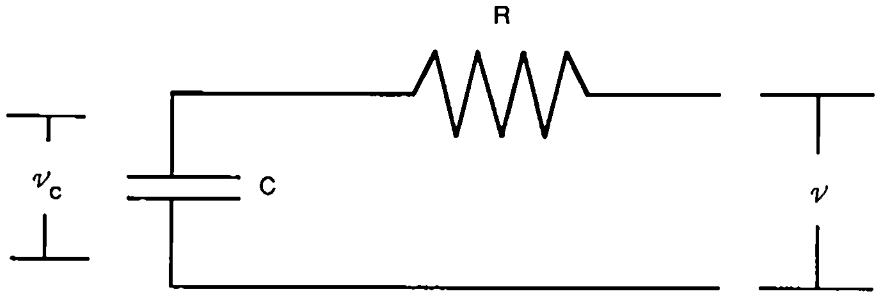


Figure 4: RC equivalent circuit

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PAPER 5

MOISTURE RESEARCH IN SWEDEN

J. KRONVALL

Dept of Building Science
Lund University
Sweden

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Johnny Kronvall

Dep. of Building Science, Lund University, Lund, S
Div. of Energy Technology, National Testing Institute, Borås, S

1 RESEARCH INSTITUTIONS

Within the area of moisture research the following institutions in Sweden could be listed:

Research institution	Research profile
The moisture group at Lund Institute of Technology/ Lund University (Appendix)	Moisture in air (especially in dwellings) Moisture transfer Moisture in materials
National Testing Institute Borås and Lund	Thermal conductivity influenced by moisture Moisture and mould
Chalmers Institute of Technology, Göteborg	Moisture in materials (especially concrete Moisture in roofs Moisture in PU-sandwich walls
Royal Institute of Technology Stockholm	Moisture in low-slope roofs (additional insulation) Moisture transer coefficients for wood materials
Wood Technology Centre of Sweden, Skellefteå and Stockholm	Moisture in wood materials Moisture in building components
SWEDISOL	Moisture conditions in attics (esp. after additional insulation)

2 MOISTURE IN AIR

Lars Erik Harderup at the moisture group in Lund, (Appendix 1), has completed a study on indoor moisture conditions in dwellings (Appendix 2). The research work has dealt with field measurements, laboratory tests especially on the influence of moisture capacity of surface-, clothing- and furnishing materials, and theoretical studies on moisture flow and moisture generation within the dwelling.

Kronvall(1986) discusses the influence of indoor moisture conditions on ventilation strategies for houses in different climates in order to avoid mould growth and indoor surface condensation. In Kronvall(1986A) the study is concentrated on such problems in connection with retrofit measures in UK. (Appendix 3).

3 MOISTURE IN MATERIALS AND BUILDING COMPONENTS

3.1 Material properties

Several researchers are working with determination of material properties for moisture transfer.

Lars Olof Nilsson, Dep. of Building Materials at Chalmers Institute of Technology, has devoted much of his research on moisture properties of concrete and theories of moisture transfer in concrete.

Dan Gaffner at the moisture group of Lund Institute of Technology has developed a method for determination of moisture transfer properties of different materials - the moment method (Appendix 4).

The influence of moisture content in insulation materials on the thermal conductivity is studied by Per-Ingvar Sandberg at the National Testing Institute in Borås. (Sandberg(1985).

At the Wood Technology Centre of Sweden and at the Royal Institute of Technology research is going on concerning moisture properties of wood and how these properties are changed under influence of different wood treatments, for example impregnation.

3.2 Moisture distribution in materials and building components

Several researchers works in the field of determination of moisture conditions in materials and building components. This can be seen in part 1 of this paper.

A certain interest has been devoted to the moisture conditions in building components i high insulated structures. Lars-Erik Nevander has given a brief over-view of the problem (Appendix 5).

The spatial distribution of moisture in wood is investigated by Owe Lindgren at the Wood Technology Centre of Sweden by means of a computerized axial tomography method (Lindgren 1986).

Mould problems in new Swedish buildings are reviewed by Ingemar Samuelson, National Testing Institute, (Appendix 6).

4 MOISTURE TRANSFER

Most of the research work within this field deals with calculation methods for determining the moisture conditions in building components under different climatical loads.

Work concerning moisture transfer in concrete has been mentioned above.

A computer program for the moisture balance of building components in natural climate, developed by Per-Ingvar Sandberg in the beginning of the 70's, is run quite often nowadays by researchers, consultants etc in order to pre-investigate the moisture behaviour of new-developed building components or to check the real behaviour against theory. (Sandberg(1973)).

A computer program package for combined calculations of heat and moisture transfer in building components and ground is under development at the Moisture Group at Lund Institute of Technology. The program is developed and intended to be possible to run on a PC-computer.

An attempt to verify different calculation methods for moisture transfer in building materials has been done by Ann-Charlotte Andersson at the Moisture Group in Lund (Andersson(1985).

5 AIRBORNE MOISTURE TRANSFER

The airborne moisture transfer - or moisture convection - may be of a special interest to people working within the field of AIVC-activities.

In a number of on-going research projects moisture convection problems are treated.

In a research project run by Lars Erik Harderup at the Moisture Group in Lund entitled "repair methods for damaged floors on ground" the influence of ventilating a layer above (or below) the concrete slab in order to remove moisture is investigated. Convection of moist air from the dwelling to the attic has been investigated in several research projects (see part 1 above).

The general conclusions that can be made point out some important factors for avoiding moisture problems in attics:

- The intermediate floor between the dwelling and the attic space must be very air tight. Special attention must be drawn to openings around pipes etc penetrating the floor.

- Over-pressure in the dwelling must be avoided. When using mechanical exhaust/supply ventilation systems it is very important to balance the system in order not to create indoor over-pressure.

- When retrofitting. including additional attic insulation at the bottom of the attic space it is very important to tighten up the existing intermediate floor before making the insulation measure.

6 REFERENCES

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Lindgren, O. 1986. Computerised axial tomography (to be published)

Sandberg, PI, 1973, Moisture balance in building elements exposed to natural climatic conditions, (in Swedish, English summary), Report 43, Div of Building Technology, Lund Inst of Technology, Lund, Sweden, 1973.

Sandberg, PI, 1985, Moisture content and thermal conductivity in soil insulation, Contribution to the CIB W 40 Holzkirchen meeting 1985, National Testing Institute, Borås, Sweden, 1985.

APPENDIX 1

THE MOISTURE GROUP AT LUND INSTITUTE OF TECHNOLOGY
- a short presentation

A research group was formed at Lund Institute of Technology in 1981 for intensified research into moisture problems and moisture damage in buildings. The Group is principally financed by the Swedish Council for Building Research. The reason for this is that moisture damage has caused both society and the individual large sums of money in recent years. In addition, moisture damage in many cases gives rise to hygienic problems for the occupants, and in some cases even to health hazards.

Moisture research at LTH has been going on ever since the middle of the sixties. Several important problem areas have been treated over the years, such as moisture problems in roofs, in floors laid directly on the ground, and in conjunction with plaster on walls. Hitherto, moisture research at LTH has been carried out in the form of individual projects at different departments. In order to make overall planning possible and to broaden contacts and collaboration, moisture researchers from three departments, Building Science, Building Materials and Building Technology, have combined work in the Moisture Group at LTH. A research program was drawn up in 1981 in consultation with the Swedish Council for Building Research which allocated the group about SEK 7 million for the six-year period 1981/82-1986/87. The program was renewed in 1984.

The subject areas in the research program include both applied problems and matters of a more fundamental character. For instance, windows damaged by decay are at present one of the most common maintenance problems. Decay has therefore been studied in greater detail. Another problem of interest is moisture in foundations, and the group has examined problems in floors laid on the ground. Moisture in external walls due to driving rain is another area which has been dealt with. The renewed program also includes moisture in attics and moisture in brick walls.

Among work of a more fundamental nature may be mentioned the study of the correctness of analytical models used in conjunction with damage investigations. Material data of different types has been collected.

In order to expand external contacts and to disseminate information regarding current projects, seminars to which those concerned in the building industry will be invited will be held continually. In 1982 two seminars were held, one on moisture problems in ground slabs, and one on moisture problems in flat roofs. In 1983 two seminars were held concerning moisture in high-insulated structures and moisture balance in rooms and buildings. These seminars have been documented. In 1984 a conference was held on moisture problems with about 50 researchers invited from the Scandinavian countries.

The Moisture Group is under the direction of a reference and coordination group appointed by the Swedish Council for Building Research (BFR). The chairman of this group is Dage Kåberger, board member of BFR. Members include Professors Bo Adamson, Arne Hillerborg and Lars Erik Nevander, all of LTH, professor Lars-Olof Nilsson of Chalmers University of Technology in Gothenburg and research secretary Jan Lagerström, BFR.

Members of the Moisture Group (May 1986)

Göran Hedenblad,	Building Materials
Kenneth Sandin,	-"- -"- -"-
Sture Sahlén	-"- -"- -"-
Dan Gaffner,	Building Science
Ingrid Wilhelmsson,	-"- -"- -"-
Håkan Håkansson,	-"- -"- -"-
Lars-Erik Harderup,	Building Technology
Olle Åberg,	-"- -"- -"-
Lars Ohlsson	-"- -"- -"-

The entire activity of the Moisture Group is reported in greater detail in "Fuktgruppen informerar 1984:1, Verksamheten 1981-84", which is published by the Department of Building Science.

APPENDIX 2

LUND UNIVERSITY
Division of Building Technology
Moisture Research Group

THE MOISTURE BALANCE IN A BUILDING DEPENDS ON MORE THAN JUST THE HOUSE

Lars-Erik Harderup

Lund 1985

Contribution to the CIB W40 Holzkirchen meeting 1985

Postal address	Office address	Telephone	Telex
PO Box 118 S-221 00 LUND Sweden	John Ericssons väg 1	+ 46-46 10 70 00	LUNIVER (Telexnr S-33533)

THE MOISTURE BALANCE IN A BUILDING DEPENDS ON MORE THAN JUST THE HOUSE

Introduction

Indoor air-humidity depends on a number of factors: air-humidity out of doors, production of moisture insida the building, ventilation rate, length of time since the production of moisture changed and humidity on the indoor surfaces- and fittings. Leakproof houses with little ventilation - intentional or unintentional - cause higher air humidity and greater risks for condensation and a low rate of drying. Thick thermal insulation results in small heating surfaces and small temperature differences. Whereby the mixing of the indoor air is reduced and a higher air hunidity may occur locally. The air humidity is closely related to the air temperature so that high air humidity is more troublesome at higher temperatures. Consequently it is now more urgent than previously to know the air humidity indoors and analyse the moisture sources that are of importance for the moisture supply to the building.

The following items are dealt with in the report "Luftfuktighet i bostäder", sponsored by the Swedish Council for Building Research:

- Measurements in building in order to investigate size, variation and distribution of the moisture supply to buildings from different moisture sources.

- The moisture capacity for a number of different surface-, clothing- and furnishing materials that can be found inside a building.

- Non-steady moisture-flow calculations.

- Amount of moisture from people and from moisture producing activities.

Field tests

During the winter 82/83 measurements of temperature, relative humidity and ventilation rate were carried out in five buildings in the south of Sweden. The buildings were not chosen at random. The selection is therefore very heterogeneous where the age of the buildings, size of the household, ventilationsystem, net living area etc are concerned.

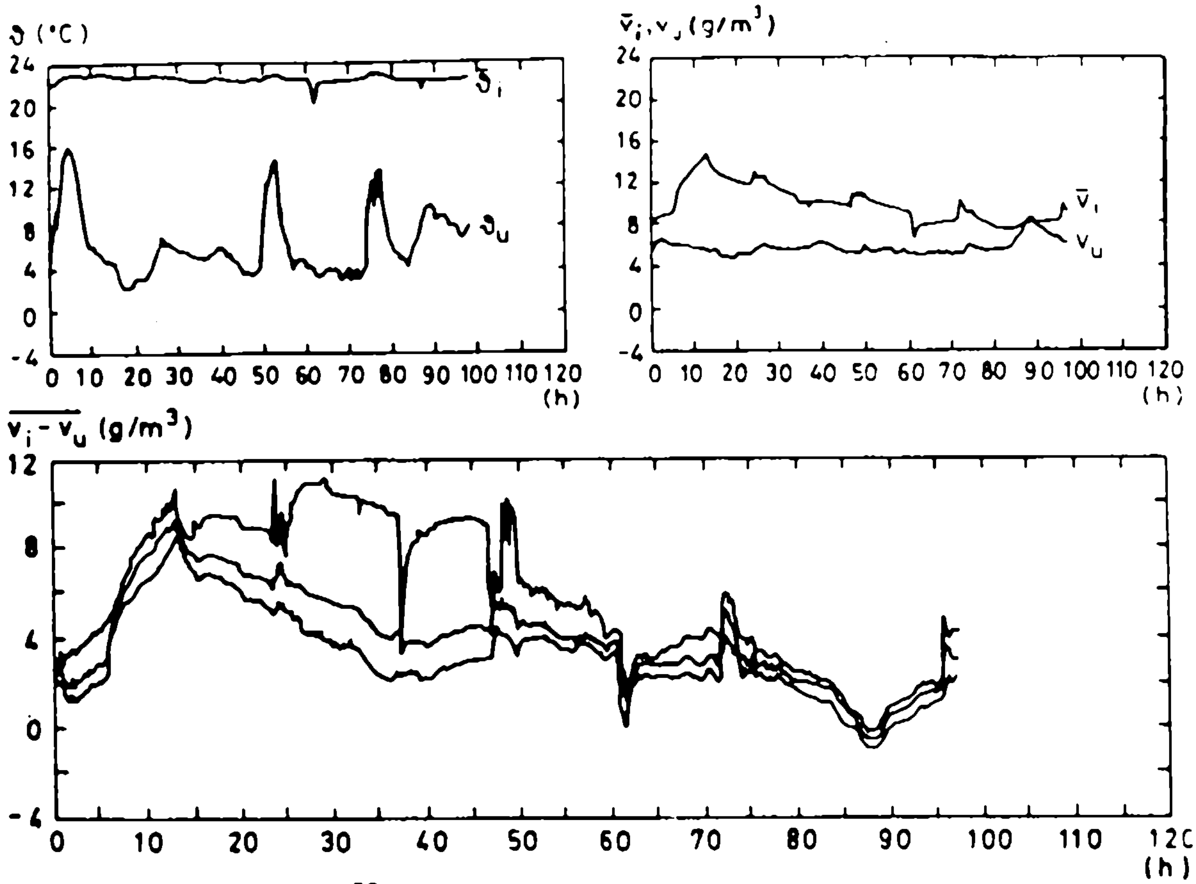
Temperature and relative humidity were registered with eight combined temperature- and relative humidity sensors, of which seven were placed inside the building and one outside the building. The information was registered every ten minutes on a cassett tape. The air change rate was checked with trace gas, at least once in every building. As a complement to the measurements the people that lived in the houses kept a diary on all activities that might influence the moisture supply or the temperature in the building.

The results from one of the measurements are shown in FIG 1. The apartment, about 75 m^2, comprises three rooms and a kitchen. It is situated in a multiple-unit building, built in the early 1970's, in a suburb of Lund. The building has exhaust air ventilation in the kitchen and the bathroom and a normal air change rate of about 0.66 air changes per hour.

From FIG 1 it can be seen that the mechanical ventilation was completely shut off during the first 24 hours of the measurements which resulted in an air change rate of about 0.065 air changes per hour, which is a very low value. At thw same time there was a hunidifier in the building which was used during these extreme ventilation conditions. As can be seen from FIG 1 this resulted, not unexpectedly, in a very high supply of moisture. When the mechanical ventilation in the kitchen was restarted 24 hours after the beginning of the measureing it can be seen that the average moisture supply is beginning to reach normal values, in spite of the extra moisture supply in the kitchen. The moisture supply in the bathroom (maximum in FIG 1) continues however to stay at a very high level for a long period of time.

By systematic comparison between diary notes and measurements from figures, like those shown in FIG 1, one arrives at the following general conclusions

- A shower is one of the moisture sources that results in the greatest changes in the moisture climate in a house. If the door to the shower is closed it will result in a very rapid and great increase in vapour concentration in the shower. The measurements show an almost instant increase in the vapour concentration of about 7-16 g/m^3. With a normal mechanical air-change rate this effect will disappear completely after a few hours. The effects outside the bathroom are



Start: 82-11-15, 07^{50}

End: 82-11-19, 08^{30}

Time from start	Activity
00^{40}	Mechanical ventilation shut off
05^{10} - 12^{50}	Humidifier 1 below balcony window
15^{10} - 23^{10}	Sleeping
23^{10}	Shower, bathroom door open
24^{10}	Valve over kitchen stove re-opened
24^{50} - 32^{30}	Humidifier 1 on kitchen stove
38^{50} - 46^{30}	Sleeping
46^{30}	Shower, bathroom door open
47^{40} - 58^{40}	Humidifier 2 in the bathroom
60^{30} - 61^{30}	Airing of the living-room
62^{30} - 71^{10}	Sleeping
71^{10}	Shower, bathroom door open
72^{40}	Valve in bathroom re-opened
86^{00} - 86^{20}	Airing of the living-room
86^{40} - 95^{10}	Sleeping
95^{20}	Shower, bathroom door open

FIG 1. Measurement of temperature and vapour concentration in a house. $\overline{v_i - v_u}$ shows the moisture supply as a mean value and pertaining variation and deviation during a measuring period.

very small but are generally measureable. If the door to the bathroom is open the situation becomes different. Now the vapour concentration increases 3-8 g/m^3 while other parts of the apartment on the same level receive a moisture supply of about 0.5-3 g/m^3.

- Effects from cooking naturally vary greatly, 0-2 g/m^3 in the kitchen. As expected the kitchen fan is of great importance in preventing the spreading of moisture from the kitchen to other parts of the apartment.

- Intentional humidification always results in an increase in vapour concentration inside the apartment. The location of the humidifier in relation to the exhaust air terminal device has a great influence on how great the average moisture supply to the dwelling will be on the whole.

- The effect of airing depends, apart from how long the airing continues, on where the airing takes place and on the moisture content of the air in the apartment when the door or the window is opened. If only one window or door is opened the best effect is obtained if this is situated a long way away from the exhaust air terminal devices.

- From the detailed results that exist for every room one can see a clear increase in vapour concentration when there are people in the room. Increases can for example be seen in the bedroom during the night and in the TV-room in the evenings. The moisture supply from an adult who is resting is considered to be about 40-60 g/h according to literature. During sleep the moisture supply from people decreases to about 30 g/h. The temperature affects the evaporation in such a way that for every degree over 20^{0}C evaporation increases by about 10 g/h, person according to literature.

- The difference in vapour concentration between the outside and the inside is normally 2-4 g/m^3, in normal ventilation conditions, in spite of occasional humidification arrangements that increased the average moisture supply. Lowered ventilation intensity naturally increases the vapour concentration in the indoor air because the production of moisture and number of air changes are directly proportional to each other.

Moisture buffers and surface condensation

In general no consideration is paid to the buildings ability to absorb moisture after a change in the moisture supply or in the ventilation rate. This means that adsorption and absorption of moisture on and in material that are normally found in our houses, for example interior wall materials, curtains, furniture, carpets etc are neglected. When the steam content increases, these materials will absorb moisture in varying degrees according to their properties. When the steam content of the air decreases vapour is released to the air instead. In this way these materials can compensate for variations in the vapour concentration of the air. Condensation and evaporation respectively on windows for example also have an equalizing effect on the climate of the apartment. Surface condensation is not however especially desirable.

FIG 2 shows two examples of the deviation obtained between measured and calculated values if the moisture buffering capacity and surface condensation are neglected. Measured values are from field tests when the building was exposed to a known quantity of moisture supply by intentional humidification.

The difference between calculated and measured curves varies rather much on the whole. The main reasons for the variations seem to be the placing and capacity of the humidifier, surface condensation, moisture buffering capacity and ventilation intensity that can also vary within the house.

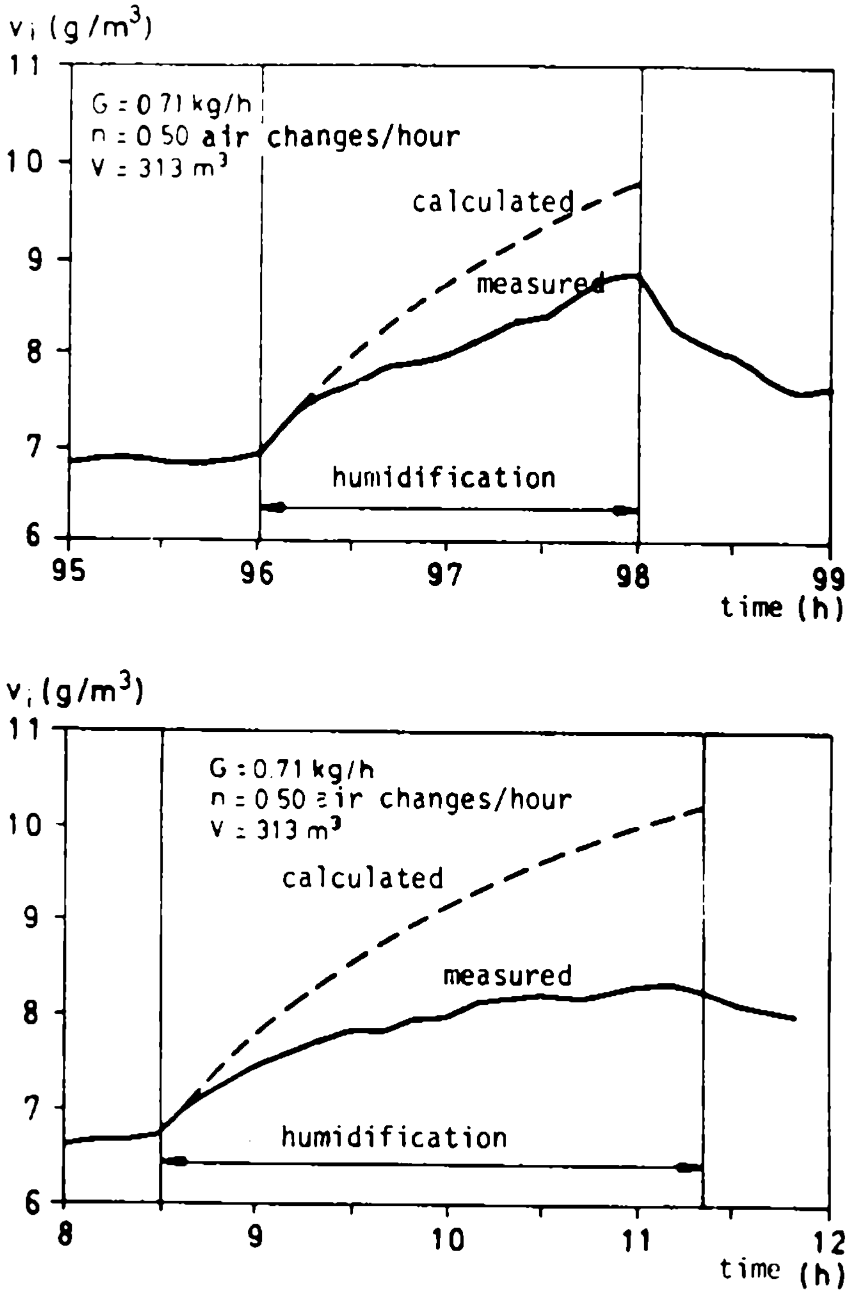


FIG 2. Difference between calculated and measured vapour concentration after an instantaneous change in moisture production. Calculations have been carried out without any consideration being paid to absorption and surface condensation.

Laboratory tests

In order to come to an understanding about the importance of clothing-materials as moisture buffers, resistance to water vapour migration and absorption capacity must be known for the materials. During the absorption tests the relative humidity was changed instantaneously around the test material where a change in weight could be registered when the material adapted to a new state of equilibrium with its sursoundings. FIG 3 illustrates such a test. This particular test was stopped before the final state of equilibrium was reached. The temperature during the tests was about 21^{o}C in the room while the relative humidity could vary very quickly from 35% up to 80% during the absorption process and decrease again to 35% during the desorption process.

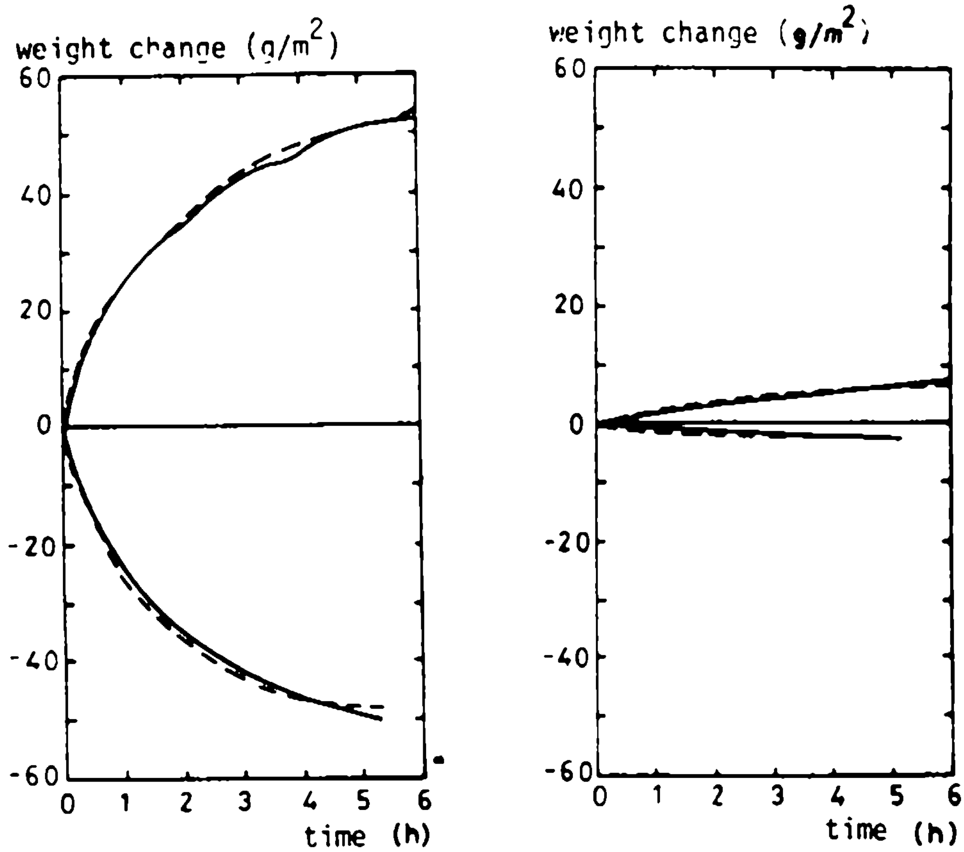


FIG 3. 13 mm gypsum board a) uncoated, b) coated with wallpaper of vinyl. ——— Test ------ Adapted C-value.

On the left is shown an uncoated 13 mm gypsum board and to the right the same type of gypsum board but coated with wallpaper of vinyl. The continuous line shows the measured value and the line of short dashes shows the result from an analytic model. A summary of the results from the tests with uncoated and painted or coated boards of gypsum and chip, fitted carpets, parquet, curtains and furnishing fabrics gives the following results:

- With a given step-change in the surrounding climate, uncoated gypsum board and chipboard achieve the greatest change in weight followed by boards coated with wallpaper of textile material. Many board materials have however a considerable hysteresis loop which reduces their moisture absorbing ability during repeated variations in the surrounding climate.

- There were considerable differences in weight change between different samples of the same material. The standard deviation is in general greater during desorption than absorption.

- Regarding surface resistances, i e paint and wallpaper , and hysteresis it is primarily curtains, furnishing fabrics, textile wallpaper different kinds of textile carpets and surface materials with coatings open to diffusion that can function as buffers to the short and rapid changes in the vapour concentration that can occur locally inside a building.

- Also after a rather short time, for instance 3 hours, in a different climate the weight change might be considerably greater if the wallpaper is attached to a gypsum board or chipboard in comparison to a test with wallpaper only. The results show that it is wrong to neglect the properties of the board behind the wallpaper in spite of rather short vapour pulses.

- For very thin textile materials, for instance curtains, the whole weight change is caused by adsorption on the surface which takes place independent of the properties of the material. Moisture absorption inside the material is now of secondary importance. For these materials it is correct to apply a constant absorption coefficient and give the time to equilibrium after a change in the surrounding vapour concentration.

Non-steady moisture-flow calculations

A computer program for non-steady moisture-flow calculations has been developed where both moisture buffering and possible surface condensation on windows have been taken into account. The calculations are intended for a family of four persons who live in an apartment of about 110 m^2. The outdoor climate is assumed to be valid for the south of Sweden (Lund) in February and the inside temperature is $21^{o}C$. The calculations are carried out with 0.25 and 0.5 air changes per hour. The total window area is 15 m^2. The family have a weekly schedule according to TAB 1 that results in an indoor vapour concentration presented in FIGS 4 and 5.

TABLE 1. Assumed moisture production (g/h), during a week for a family of four persons.

Hour	Mo-Fr	Hour	Sa	Hour	Su
0-7	290	0-9	290	0-9	290
$7\text{-}7^{30}$	1690	9-10	1690	$9\text{-}9^{30}$	1690
$7^{30}\text{-}8$	370	10-13	430	$9^{30}\text{-}11$	370
8-15	130	13-14	550	11-13	430
15-17	310	14-17	1090	13-14	550
17-18	550	17-18	370	14-15	1190
18-20	430	18-20	430	15-18	190
20-22	330	20-24	550	18-19	430
22-24	290			19-21	390
				21-22	330
				22-24	290
Total per 24 hours: 7240 g			11740 g		9300 g
Average per hour: 302 g			489 g		388 g

Mean value per hour during a whole week: 341 g

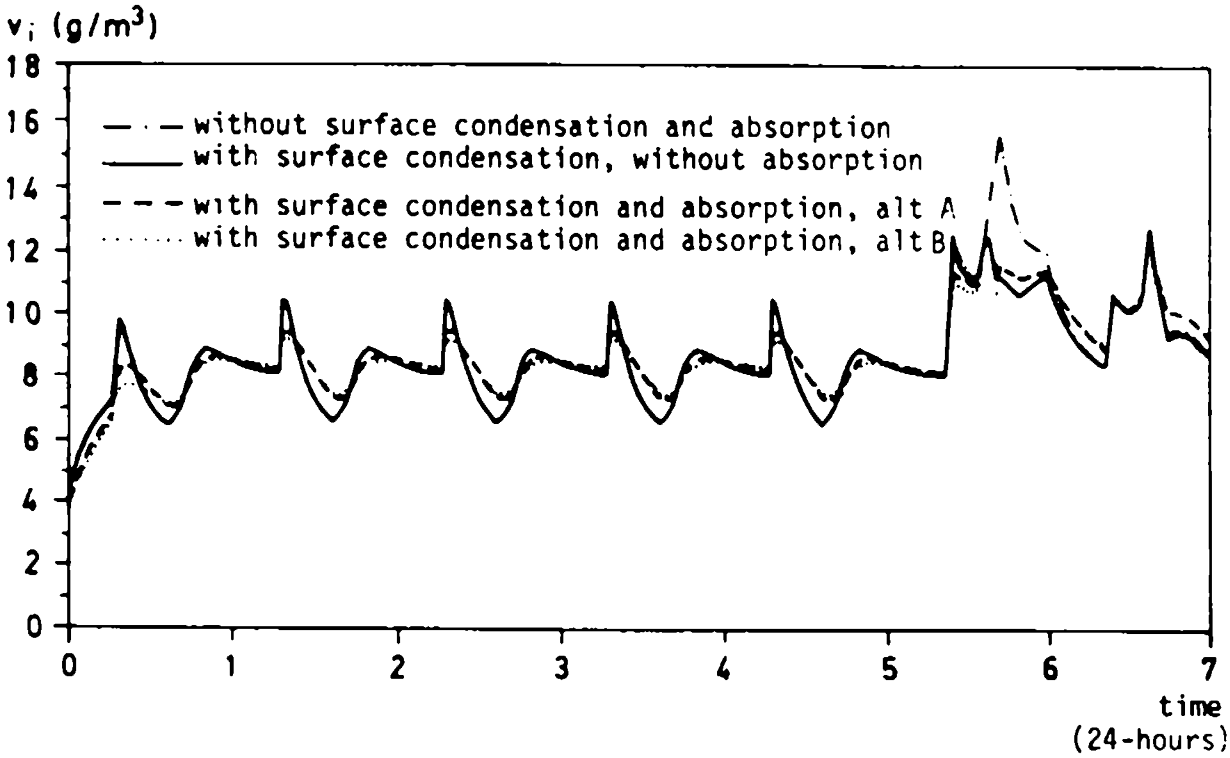


FIG 4. Non-steady moisture-flow balance, double pane windows, 0.25 air changes per hour. Surface condensation only occurs on Saturday evenings which means that the continuous line and the line of short dashes coincides during the rest of the week.

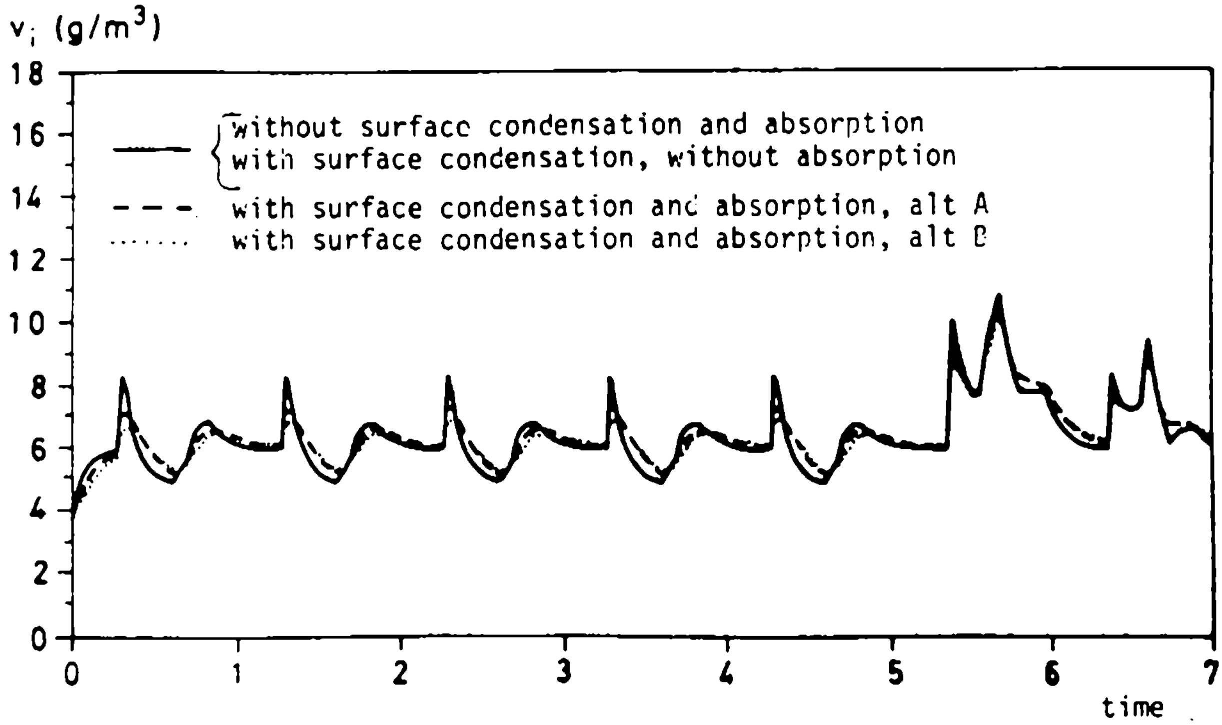


FIG 5. Non-steady moisture-flow balance, double pane windows, 0.5 air changes per hour.

The calculations show that absorbing materials and surface condensation result in a more uniform indoor climate by eliminating all extreme values. They do not however give a drier indoor climate. Observe that in the surface condensation model no attention has been paid to sunshine, placing of the windows, the radiators or window sills. However if conditions for surface condensation exist these give a considerable, if unwanted, contribution to the total moisture absorption capacity in the apartment.

Two alternative combinations of absorbents are shown in FIGS 4 and 5. Normal equipment is assumed for both alternatives. In alternative A only the moisture capacity of the textile wallpaper is taken into account while in alternative B the moisture ability of the gypsum board behind the wallpaper is also taken into account. As seen from the Figures the difference is rather small after the introductory period. However alternative B shows a somewhat smoother climate.

APPENDIX 3

SEMINAR ON THE REPAIR, MAINTENANCE AND ENERGY CONSERVATION IN COUNCIL HOUSING AND HOSPITALS

LONDON

MOISTURE AND MOULD

by

JOHNNY KRONVALL

Professor
Dep. of Building Science
Lund Institute of Technology
Lund, Sweden

Postal address:
P.o. box 118
S-221 00 LUND Sweden

Tel. +46 46!07000

CONTENTS

1	MOISTURE	... 1
1.1	Moisture sources	... 1
1.1.1	Moist air	... 1
1.1.2	Damp after the erection of a building	... 5
1.1.3	Rain and moisture from the ground	... 6
1.2	Moisture transfer	... 7
1.3	Air humidity and ventilation	... 8
2	RISK ANALYSES	...16
2.1	Surface phenomena	...16
2.1.1	Condensation and mould growth	...17
2.1.2	Examples on surface related moisture problems	...17
2.2	Moisture problems in building components	...24
3	CONCLUDING REMARKS	...24
4	LITERATURE	...25

1 MOISTURE

Moisture considerations are important in building design. A main reason for this is the severeness and, normally, high repair costs connected with curing buildings from moisture damages. Especially the durability of organic building components and materials is in danger if the building is not properly designed from moisture points of wiev.

1.1 Moisture sources

Moisture could be added to a building component due to precipitation, moist air, capillary water from the ground or leakage. Furthermore, all material in contact with the water vapour absorbs certain amounts of water. During the erection of a building certain quantities of water are added too.

Most building failures - approximately 80 % or more - are more or less due to the the moisture conditions in and around the building.

The moisture condition of a building or a building component is settled by the environmental and climatic conditions, the building design and the materials in the building components.

The analysis of moisture conditions is normally based on the "moisture stresses" of the building, most often called moisture sources.

These are:

- moist air
- damp after the erection
- rain
- moisture from the ground

1.1.1 Moist air

Air is a mix of gases and one of the gases is water vapour. A way of characterizing the humidity of an air volume is simply to specify the amount of water per volume. This quantity is called the <u>vapour concentration, v.</u>

$$v = \frac{m_v}{V} \quad (kg/m^3) \qquad \text{... 1.1.1 a}$$

where m_v is the mass of water vapour (kg) and V the total volume (m^3) of the gas mix. At a certain temperature, air can not hold more than a certain quantity of water vapour. This maximum quantity is called the <u>vapour concentration at saturation point, v_s</u> (kg/m^3). v_s is depending on the temperature of the air. Figure 1.1.1 a.

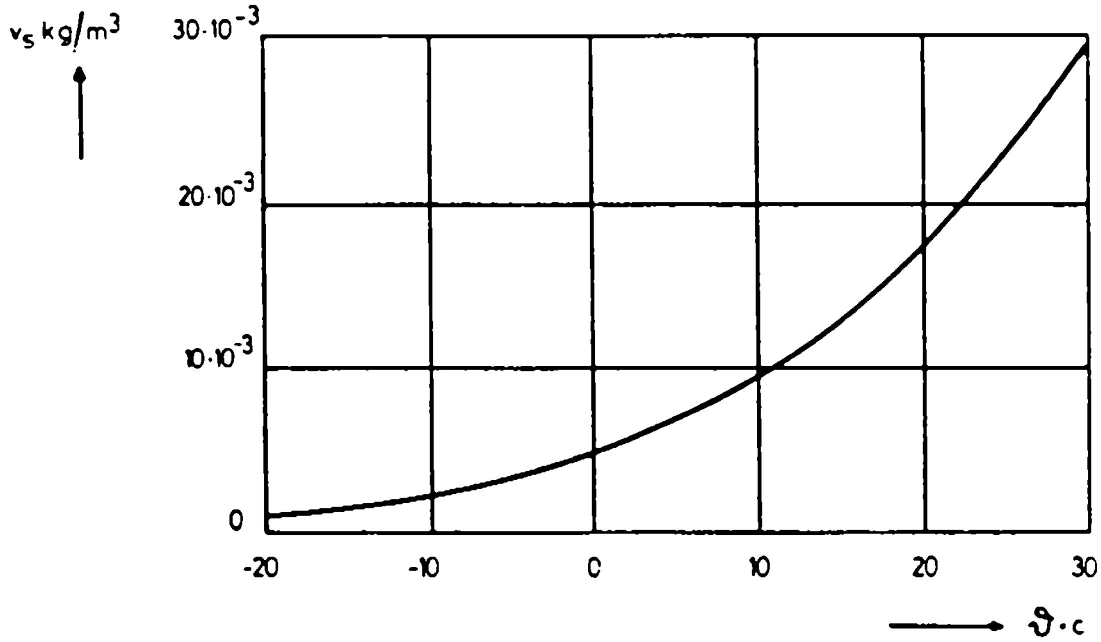


FIGURE 1.1.1 a. The water vapour concentration at saturation point plottet vs. air temperature (dew point).

Another commonly used way of specifying the moisture condition of air is to give the relative humidity (RH), which is the ratio between the actual vapour concentration and the vapour concentration at saturation point.

$$RH = \frac{v}{v_s} \quad (-) \text{ or } (\%) \qquad \ldots 1.1.1\text{ b}$$

Often, the relative humidity is given in percent.

Thus, the moisture content in air could be characterized either by the vapour concentration or the relative humidity and the temperature. Figure 1.1.1 b.

The realative humidity, RH, is the qauntity that, together with material properties unique for each material, will settle the moisture content (kg/m^3) the material will reach if placed in moist air with constant vapour concentration. The equiljblium condition is called the hygroscopic moisture content w (kg/m^3). An example of the relationship between relative humidity and hygroscopic moisture content of a material is shown in figure 1.1.1 c.

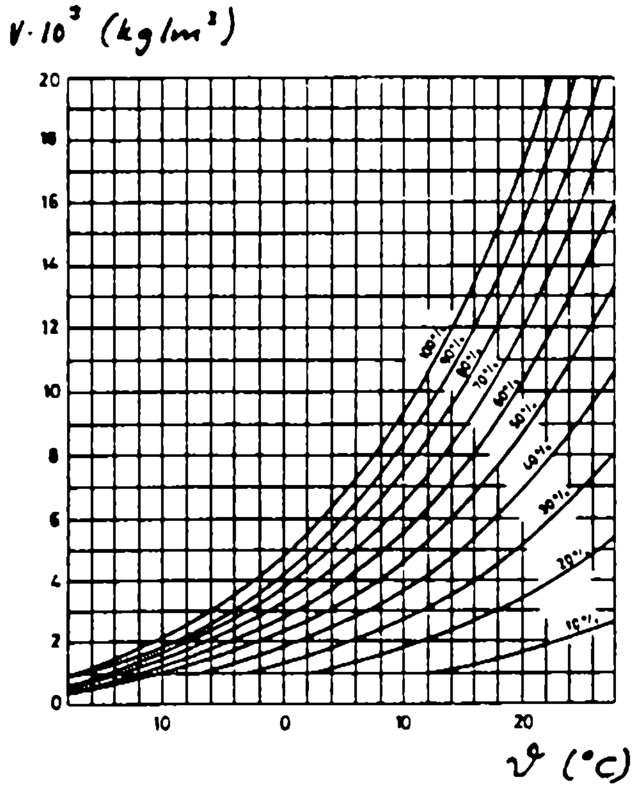


FIGURE 1.1.1 b. The relationship between temperature, water vapour concentration and relative humidity.

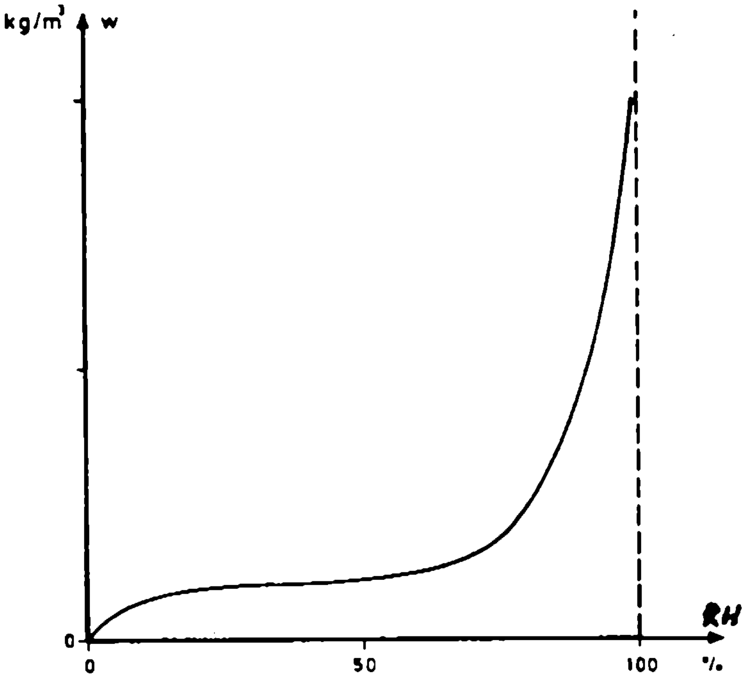


FIGURE 1.1.1 c. Relationship between relative humidity and hygroscopic moisture content, so called sorption isotherm curve, for a certain material.

The indoor relative humidity is settled by the air temperature and relative humidity of the outdoor air, the indoor air temperature, the indoor moisture supply and the ventilation intensity. Equation 1.1.1 c gives an exprsssion for the vapour concentration in the indoor air at the time t (h) after that a moisture supply G (kg/h) has started.

$$v_i(t) = v_o + \frac{G}{n \cdot V}(1 - e^{-nt}) \quad (kg/m^3) \qquad \ldots 1.1.1\text{ c}$$

where:

v_o = vapour concentration in outdoor air, kg/m^3

n = ventilation intensity, air changes / hour
V = room volume, m^3

Under stationary conditions, i.e. an even moisture supply and an even ventilation intensity, the expression e^{-nt} equals zero and 1.1.1 c could be written:

$$v_i = v_o + \frac{G}{n \cdot V} \quad (kg/m^3) \qquad \ldots 1.1.1\text{ d}$$

The corresponding indoor relative humidity (RH) is:

$$RH_i = \frac{v_i}{v_s(\vartheta_i)} = \frac{v_o + \frac{G}{n.V}}{v_s(\vartheta_i)} \qquad \ldots 1.1.1\text{ e}$$

$v_s(\vartheta_i)$ is the vapour concentration at saturation point at the indoor temperature ϑ_i.

The moisture supply G in a volume, flat etc. could be separated into three parts:

Continuous supply

Intentional humidification, evaporation from plants, aquariums etc and diffusion through the envelope of the volume.

Discontinuous but recurrent supply

Peoples 40 - 50 g/h and person at low activity level (up to ten times this figure at lively activity, dancing etc).
Cooking and washing up.
Use of toilet, shower and bath.

Discontinuous supply

Washing, drying clothes, cleaning etc.

The quantity G/(n·V) is sometimes called moisture addition (kg/m^3). Often suggested values are:

$2 \cdot 10^{-3}$ kg/m^3 for office buildings

$3 \cdot 10^{-3}$ kg/m^3 for living rooms etc.

$4 \cdot 10^{-3}$ kg/m^3 for bathrooms, laundries and kitchens

Other phenomena affecting the indoor moisture conditions are absorption and desorption in the materials in rooms, for example furniture, carpets, wall coverings etc. These materials act levelling at the indoor moisture condition. The magnitude of the influence is however studied very little.

The following example will conclude and illustrate the section on moist air:

Example

The inner of a building is heated to +20°C and ventilated with 0.5 airchanges/hour (outdoor air). The building volume is 300 m^3 and the moisture supply indoor due to people, pets and plants is 0.6 kg/h. Outside the temperature is ± 0°C and the relative humidity is 90 %.

Calculate the relative humidity indoors!

Solution:

Eq. 1.1.1 e, $$v_i = \frac{v_u + \frac{G}{n.V}}{v_s(\vartheta_i)}$$

where:

$v_u = 4.3 \cdot 10^{-3}$ kg/m^3 $(= 0.9 \cdot v_s(\pm 0^0C)$ (fig 1.1.1 a))

$G = 0.6$ kg/h
$n \cdot V = 0.5 \cdot 300\ m^3 = 150\ m^3/h$

$v_s(+20^0C) = 17.3 \cdot 10^{-3}$ kg/h (fig 1.1.1 a)

gives:

$$v_i = \frac{4.3 \cdot 10^{-3} + \frac{0.6}{0.5 \cdot 300}}{17.3 \cdot 10^{-3}} = 0.48 \quad (48\ \%)$$

So, the indoor relative humidity is 48 % in the room air at 20°C

1.1.2 Damp after the erection of a building

Many materials placed in a house in connection with the erection of it contains more moisture than the corresponding equilibluim level of moisture in the material during later periods of the house age.

This excess amount of moisture, during the first time of the age of a building could be called erection moisture.

The amounts of erection moisture to dry out from different materials until the equilibrium level is reached can be seen in table 1.1.2 a.

Material	Moisture content (kg/m^3)			
	At erection	Chemically bound	Hygroscopic at 50 % RH	Erection moisture to dry out
Concrete	170 - 200	70	30-50	50 - 100
Lightweight concrete	100 - 200	0	10-20	80 - 190
Lime mortar	300	- 30	10	320
Lime cement mortar	250 - 350	20	10-20	220 - 320
Brick stone	10	0	10	0
Brick masonry	60 - 80	- 5	5-10	45 - 70
Wood	max 100	0	40-60	max 60

Table 1.1.2 a. Erection moisture in some materials and components.

The drying out of on-site cast concrete building components is of primary interest as far as the contribution to the moisture content of indoor air is concerned. According to Nilsson (1978) an evaporation of appr. 2 $g/(m^2.h)$ during a buildings first years is normal if the concrete surface is exposed to the air (at $+20^oC$). The moisture supply is of course at a lower level in connection with more or less vapour tight coverings on the surfaces.

1.1.3 Rain and moisture from the ground

Under influence of driving rain vertical parts of a building can be wetted. Horisontal parts, such as roofs, terraces etc are normally made as water tight constructions.

Moisture from the ground could be ground water or rain water on the ground.

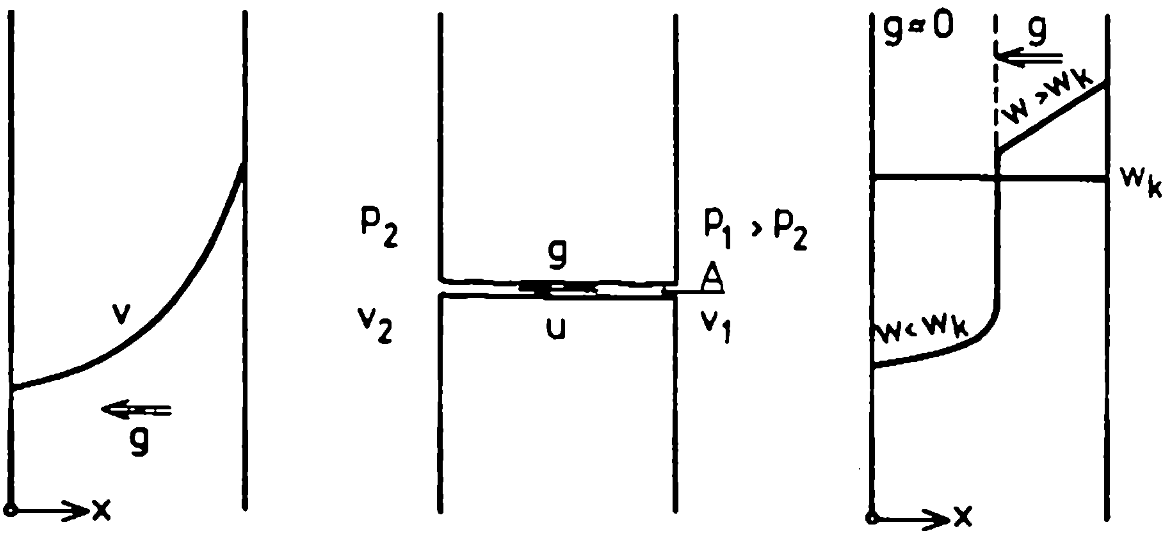
These moisture sources will not be discussed in this paper.

1.2 Moisture transfer.

Moisture could be transferred in materials in vapour phase or in liquid phase. In vapour phase it is essentially either of the diffusion och convection transfer mechanism that is involved. In liquid phase the transfer is governed primarilly by capillary forces or gravity force.

Figure 1.2.a shows schematically the different transfer mechanisms.

DIFFUSION	MOISTURE CONVECTION	CAPILLARY TRANSFER



Governed by differences in:

vapour concentrations	pressure of air and vapour concentrations	moisture content
$g = -\delta \frac{dv}{dx}$	$g = u \cdot A(v_1 - v_2)$	$g = -k \frac{dw}{dx}$

FIGURE 1.2. a. Moisture transfer mechanisms

Hence, diffusion is governed by differences in vapour concentrations while convection is governed by differences in air pressure. Capillary transfer is possible when the moisture content in a material exceeds a certain moisture content value, the so called critical moisture content, w_k (kg/m^3).

1.3 Air humidity and ventilation.

According to eq. 1.1.1 d, the water vapour concentration indoors, v_i, could be written (steady state case):

$$v_i = v_o + \frac{G}{n \cdot V} \ (\text{kg/m}^3) \qquad \text{... 1.1.1 d}$$

The expresson G/(nV), the moisture addition, increases with increasing G, i.e. the indoor moisture supply and with decreasing n, i.e. ventilation intensity at constant volume, V.

Two questions must be answered:

- what magnitude of moisture supply
and
- what ventilation intensity

could be expected in practice?

The magnitude of the moisture supply in dwellings is far from well known and, in many cases, so is the ventilation intensity.

However, the consequences on the moisture addition due to different levels of moisture supply and ventilation intensity for different building volumes could be illustrated. That is done in figure 1.3 a-c for a flat as a whole (300 m^3), a kitchen (37.5m^3) and a bath room (20m^3).

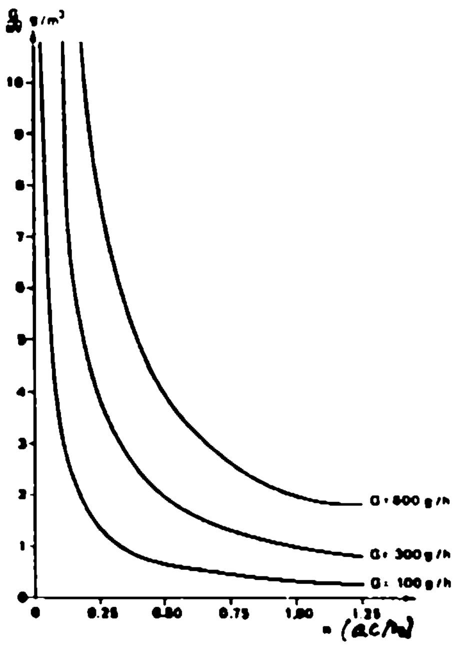


FIGURE 1.3 a Ventilation intensity vs. moisture addition for different moisture supply levels. Flat, 300m^3.

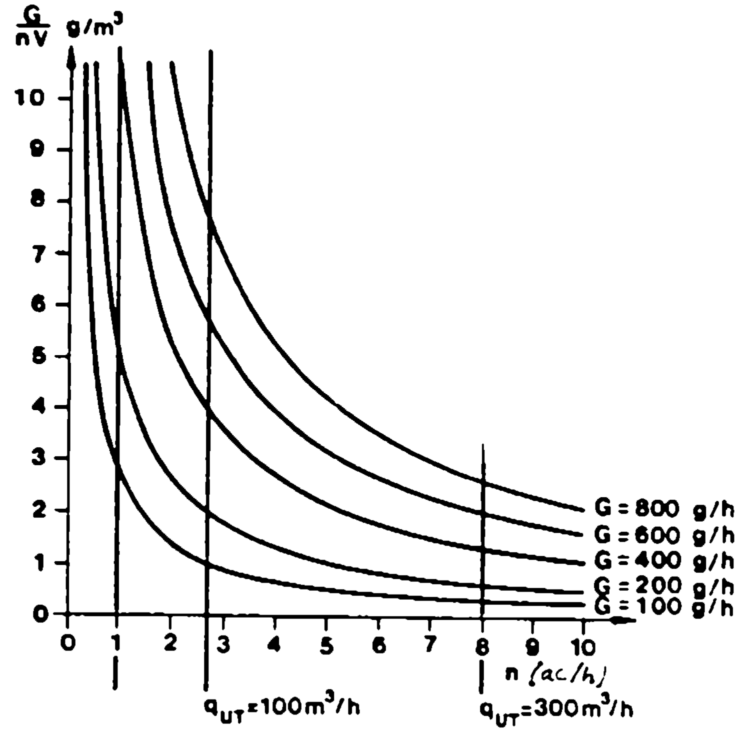


FIGURE 1.3 b Ventilation intensity vs. moisture addition for different moisture supply levels. Kitchen, 37.5 m^3

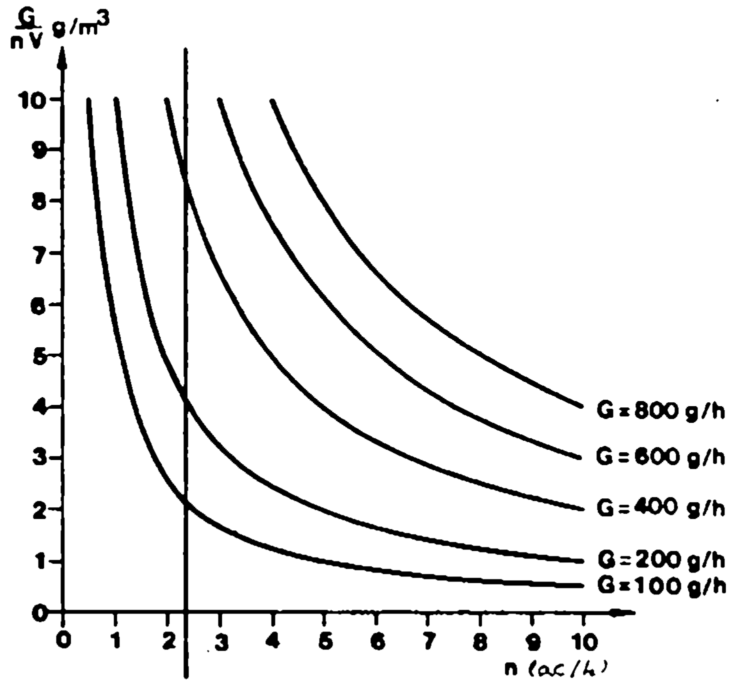


FIGURE 1.3 c Ventilation intenity vs. moisture addition for different moisture supply levels. Bath room, 20 m^3

It is also important to take into account where the moisture is supplied and if there are any ventilation devices there, taking care of the moist air. In Sweden flats are normally equipped with exhaust ventilation devices in kitchen and in bath/toilet rooms, i.e. rooms where moisture supply is high and frequent.

Sandberg (1973) states that if air is exhausted from a room where moisture is supplied, the water vapour concentration in other rooms around will not be noticeably risened. Hence, it is possible to study the moisture behaviour of each room separately.

At low ventilation intensities the expression $(1-e^{-nt})$ in 1.1.1 c, which stands for a non steady state development, will not eqaals one until a certain time has elapsed. Figure 1.3 d shows how the expression varies with time for different ventilation intensities.

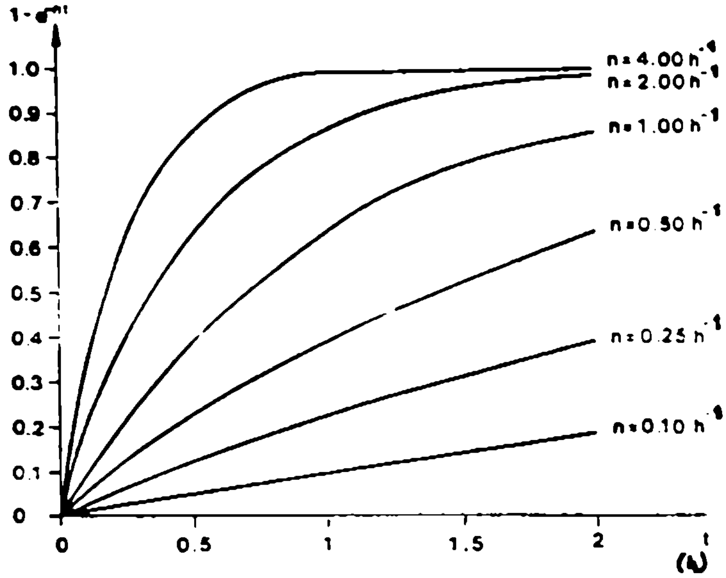


FIGURE 1.3 d $(1-e^{-nt})$ vs. time for different ventilation intensities.

What directly could be seen from the figure, is that at higher ventilation intensities the expression $(1-e^{-nt})$ rapidly approaches the value one. For such cases the simplified equation $v_i = v_o+G/(nV)$ could be applied directly. For lower ventilation intensity cases it takes quite a time for $(1-e^{-nt})$ to reach the value one.

By writing eq. 1.1.1 c in a somewhat different way:

$$v_i = \frac{G}{V} \cdot \frac{1 - e^{-nt}}{n} + v_o \qquad \text{... 1.3 a}$$

the total influence of the ventilation intensity can be studied. Figure 1.3 e.

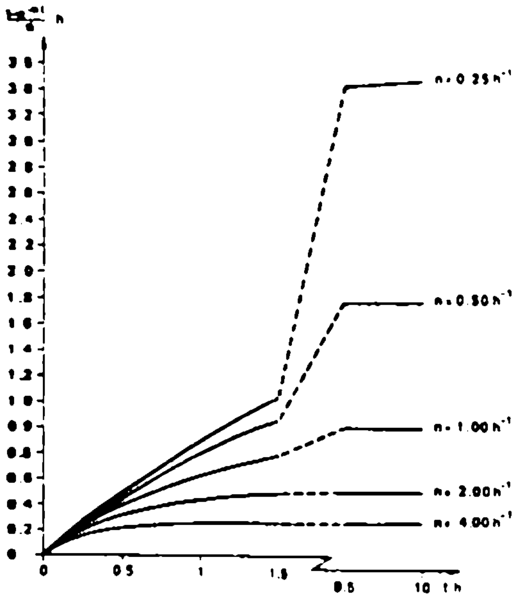


FIGURE 1.3 e $(1-e^{-nt})/n$ vs. time for different ventilation intensities.

Some examples may illustrate the non steady state behaviour:

Example 1

In a bath room (volume 20 m^3) bathing takes place and this results in a moisture supply of 0.6 kg water vapour per hour. The supply air to the bath room is indoor air, +22°C, RH=42%. Calculate the water vapour concentration in the bath room air after 0.1, 0.25 and 0.5 hour if the ventilation intensity is 2 air changes per hour.

Solution:

v_o (in this case indoor air) = $0.42 \times 19.4 \cdot 10^{-3} = 8.2 \cdot 10^{-3}$ kg/m^3

Eq. 1.3 a yields:

$$v_i = 8.2 \cdot 10^{-3} + 0.6/20 \cdot (1-e^{-nt})/n = 8.2 \cdot 10^{-3} + 0.03 \cdot A$$

where A can be read from figure 1.3 e

time (h)	A (h)
0.10	0.09
0.25	0.20
0.50	0.32

Result:

time (h)	$v_i \cdot 10^3$ (kg/m^3)
0.10	10.9
0.25	14.2
0.50	17.8

Example 2

In a bed room (volume 30 m^3) two persons go to bed at 22.00. The moisture supply from the persons is 50 g/(person·h). For some reason the room is badly ventilated (0.1 air changes per hour).

Calculate the water vapour concentration in the bed room, hour by hour, during the night. Outdoor climate: + 10°C, RH=80%. Moisture buffering in textile goods does not have to be taken into account.

Solution:

$v_0 = 0.8 \times 9.4 \cdot 10^{-3} = 7.5 \cdot 10^{-3}$ kg/m^3 (fig 1.1.1 b)

Eq. 1.1.1 c gives the solution:

Time	22	23	24	2	4	6
$v_i \cdot 10^3$ (kg/m^3)	7.5	10.7	13.5	15.1	22.5	25.8

The value at 06.00 is here, by pure calculation, higher than the saturation value at + 25°C ($\approx 23.0 \cdot 10^{-3}$kg/$m^3$).

From practical point of view, this it not possible. Probably, condensation on window glasses has taken place before. A certain moisture buffering in textile goods is also possible.

The two examples show that in some cases the expression $(1-e^{-nt})$ must be considered.

If ventilation devices for exhausting air from rooms with high moisture supply do not exist or are not used, the moisture situation in the dwelling as a whole will be much more critical. The anticipation of no (or just a little) influence on the moisture condition in adjecant rooms does not hold any longer.

A proper estimation for a non-intentionally ventilated flat (only "natural ventilation" due to leaky walls, windows etc.) is that all the rooms in the flat will get about the same ventilation intensity. This could vary due to wind, air tightness, temperatures etc in the range between 0.5 to 5 air changes per hour.

Table 1.3.a gives approximate values for possible moisture supplies to a flat.

Supply source	Moisture supply kg/h
People, low activity	0.03 - 0.06
medium work	0.12 - 0.30
heavy work	0.20 - 0.30
Bath room, tub bath	0.7
shower	2.6
Kitchen, cooking etc	
electrical stove	0.6 - 1.5
gas fired stove	2 - 3
daily mean electrical	0.1
gas	0.2
Wash-drying	0.05 - 0.5
Plants, small (per plant)	0.005 - 0.01
medium	0.007 - 0.015
large	0.01 - 0.02
Aquarium	0.01

Table 1.3 a Possible moisture supplies in a dwelling. Mainly from Erhorn & Gertis (1986)

An accumulative calculation of the moisture supply to a dwelling follows:

	Supply kg/h	Accumulated min	max
Plants, 20 small	0.1-0.2	0.1	0.2
10 medium	0.07-0.15	0.17	0.35
5 large	0.05-0.1	0.22	0.45
Aquarium	0-0.01	0.22	0.46
2 persons low to medium work	0.06-0.60	0.28	1.06
Kitchen electrical stove (E)	0.1	0.38	1.06
gas stove	0.2	0.38	1.26
Bath room, rough estimate	0.1	0.48	1.36
Washing, drying clothes, cleaning etc	0-0.25	0.48	1.61

Thus the total moisture supply to a dwelling could be estimated to

0.4 - 1.6 kg/h

For a flat with a volume of 250 m^3 this corresponds to moisture additions (G/(nV)) of the following magnitude:

G = 0.4 kg/h

n (ac/h)	$G/(nV)\cdot 10^3$ (kg/m^3)
0.5	3.2
1	1.6
2	0.8
5	0.32

G = 1.6 kg/h

N (ac/h)	$G/(nV)\cdot 10^3$ (kg/m^3)
0.5	12.8
1	6.4
2	3.2
5	1.3

In order to form a proper basis for risk analyses presented in the next chapter, some meteorological data concerning British inland climate (Manchester airport) from Wallén (1970) are quoted in table 1.3 b. The table also includes some calculated values of the indoor relative humidity for two indoor temperatures and different moisture additions.

	jan	feb	mar	apr	maj	jun	jul	aug	sep	okt	nov	dec
Air temperature daily mean	3.4	3.9	5.9	8.4	11.4	14.6	16.2	16.0	13.7	10.1	6.7	4.7
daily minimum	1.1	0.8	2.2	3.9	7.0	9.7	11.7	11.5	9.8	7.0	4.3	2.9
Relative humidity daily mean	89	89	82	78	74	77	79	81	82	84	86	86
Water vapour concentration daily mean	5.4	5.6	5.9	6.6	7.6	9.6	10.9	11.0	9.7	7.9	6.5	5.7

Relative humidity indoors, 20°C

$G/(nV)\cdot 10^3$ (kg/m3)

0	31	32	34	38	44	56	63	64	56	46	38	33
2	42	44	46	50	56	67	75	75	68	58	49	45
4	54	56	57	61	67	79	86	87	79	69	61	56
6	66	67	69	73	79	90	98	98	91	80	72	68

Relative humidity, indoors, 16°C

$G/(nV)\cdot 10^3$ (kg/m^3)

0	40	41	43	48	56	70	80	81	71	58	48	42
2	54	56	58	63	70	85	95	95	86	73	62	56
4	69	70	73	78	85	££	££	££	££	87	84	71
6	84	85	87	93	££	££	££	££	££	££	92	86

££ = moisture saturation in the indoor air

In this chapter we will deal with combined effects of moist air, cold surfaces on the inner side of the dwelling envelope and risks for condensation, mould growth etc.

2.1 Surface phenomena

The surface temperatures of different parts of the inner side of the building envelope (walls,roofs,windows etc) are of essential interest in order to analyse the humidity conditions for a building.

The thermal analysis could be simplified by using a local formulation of the heat transmission coefficient of a building component, U_{loc} ($W/(m^2K)$). This formulation implies that there is only one-dimensional heat flow in a surrounding of the local "spot". (No cross-conduction.) The indoor surface temperature, ϑ_{si} of a building component etc. could be written:

$$\vartheta_{si} = \vartheta_{ai} - \frac{U_{loc}}{\alpha_i} (\vartheta_{ai} - \vartheta_{ao}) \qquad \text{... 2.1 a}$$

where

ϑ_{ai} and ϑ_{ao} = air temperature indoors resp. outdoors, ^{o}C

α_i = indoor surface heat transfer coefficient, $W/(m^2K)$

In a given climatical situation

$$\vartheta_{si} = \vartheta_{si}(U_{loc}, \alpha_i) \qquad \text{... 2.1 b}$$

The local U-values for some building components are given in table 2.1 a.

Building component	U_{loc} ($W/(m^2K)$)
0.25 m masonry (brick)	1.7
0.15 m concrete	3.0
0.15 m wood	0.7
0.15 m steel	4.0
Window, single-glazed	5.0
double-glazed	3.0
triple-glazed	2.0

Table 2.1 a Local U-values for some building components

The indoor surface heat transfer coefficient, α_i, is by definition:

$$\alpha_i = \frac{q}{\vartheta_{ai} - \vartheta_{si}} \qquad \text{... 2.1 c}$$

where

q = heat flow density, W/m^2

The magnitude of the indoor surface heat transfer coefficient in different situations has been studied by several authors.

Gertis (1983) gives the following approximate values suitable to practical design:

Situation	α_i (W/(m^{2}K))
Undisturbed, free vertical surface	8
Corner, no furniture	6
Corner, behind furniture	4

Table 2.1 b Practical design values of indoor surface heat transmission coefficient. Gertis (1983)

2.1.1 Condensation and mould growth

Condensation is the phenomenon when water in vapour phase is transferred into liquid phase. Generally, this occurs on a cold surface with a surface temperature lower than or equal to the dew point temperature (corresponding to RH=100%).

Mould growth on a surface is possible if there exist:

- an organic material to grow on (substratum)
- a suitable temperature (generally greater than appr. +5°C)
- a suitable humidity level (most often quoted to be RH=70% or more)

The mould growth is generally of low intensity at lower temperatures but the activity is strongly stimulated by increasing temperature. Sometimes it is also claimed that mould growth is possible only if the surrounding air is still. This, however, seems not to have been proved.

Analyses of risks for surface condensation or mould growth on the inner part of a building's envelope thus involves estimations of local surface temperatures and the moisture condition of indoor air.

2.1.2 Examples on surface related moisture problems

The analysis, however, is rather complex. A number of parameters must be set and/or calculated:

- volume of room or dwelling
- ventilation intensity
- moisture supply
- outdoor and indoor temperature and relative humidity
- risk criterion on inner surface (set critical value of RH)
- indoor surface heat transfer coefficient
- local heat transmission coefficient

Possibilities to study the sensitivity, in different aspects, due to changes of levels of one or more parameters, could be done in a rather simple way by means of a multi-diagram (figure 2.1.2 a).

Some examples may illustrate the use of the multi-diagram:

Example 1

Investigate the ventilation need for a dwelling, volume 250 m^3, in order to avoid condensation on the inner glass of the windows at medium (0.4 kg/h) and very high (1.6 kg/h) moisture supply. Climatical conditions: Outdoor +2.2°C, RH=82% i.e. $v_0=5.9\cdot10^{-3}$ kg/m^3 (Manchester, march, mean daily minimum temperature). Indoor temperature = +18°C. Indoor surface heat transfer coeff. = 8 $W/(m^2K)$, i.e. free vertical surface. Heat transmission coefficient for window acc. to table 2.1 a.

Solution:

Study figure 2.1.2 b !

Result:

Window type	Minimum ventilation intensity (ac/h) at medium (0.4 kg/h)	very high (1.6 kg/h) moisture supply
single-glazing	0.60	more than 2
double-glazing	0.25	1.25
triple-glazing	0.15	0.95

Example 2

Investigate the ventilation need for a dwelling in order to avoid moisture conditions suitable for mould growth on the wall-paper behind a corner sofa, placed in a way so that the room air can pass freely behind the sofa. Weather conditions are the same as in example 1. Medium and high moisture supplies are investigated. Wall: 0.25 m brick masonry ($U = 1.7$ $W/(m^2K)$).

Solution:

Study figure 2.1.2 c

Result:

The minimum ventilation rate is 0.60 ac/h in the medium and 1.20 ac/h in the high moisture supply case.

Example 3

investigate the ventilation need for a dwelling, 250 m^3, in Manchester climate under different seasons. Moisture supply = 0.8 kg/h (high). U_{walls}=1.0 W/m²K. No situation with a higher relative humidity than 75% is allowed in outer wall corners with furniture in front of them. Indoor temperature: Summertime + 20°C, else +18°C.

Solution:

Climatical conditions acc. to table 2.1.a
Definitions: Winter = January, Spring = April, Summer = Jule,
Autumn = October.

Study figure 2.1.2 d !

Result:

The ventilation need is in the range 0.7 ac/h (winter) to 1.3 ac/h (summer).

Example 4

Calculate the highest permissable moisture addition (kg/m^3) for a dwelling with rather well insulated walls, roofs etc. (U=0.6 $W/(m^2K)$) and with double-glazed windows.
Design criteria: No condensation on window glasses.
No higher RH than 70 % in outer wall corners with furniture.

Solution:

Study figure 2.1.2 e !

Result:

The highest permissable moisture addition ranges from $1.1 \cdot 10^{-3}$ kg/m^3 (wall, summer) to $6.0 \cdot 10^{-3}$ kg/m^3 (window, summer).

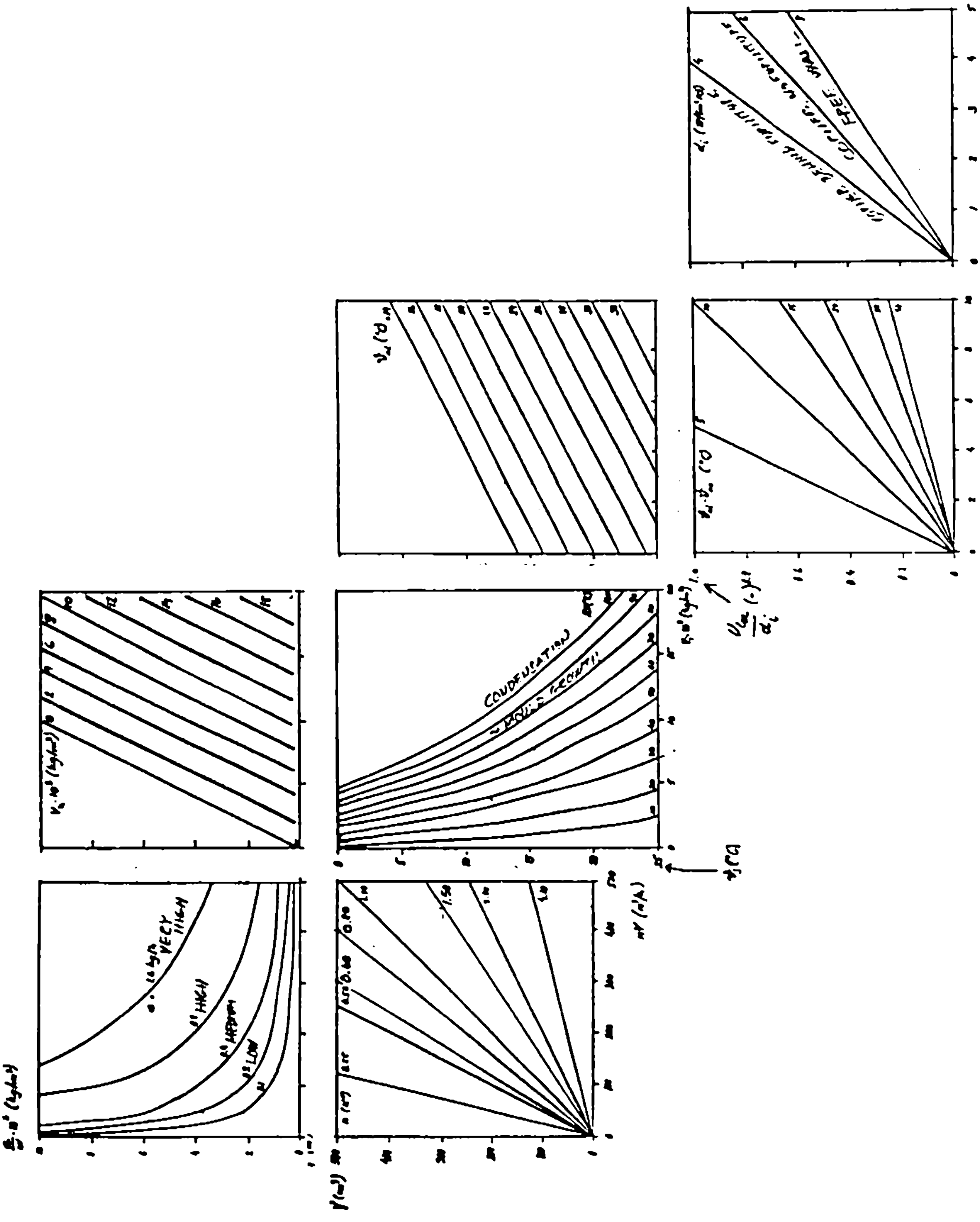


FIGURE 2.1.2 a Multi-diagram for moisture risk analyses

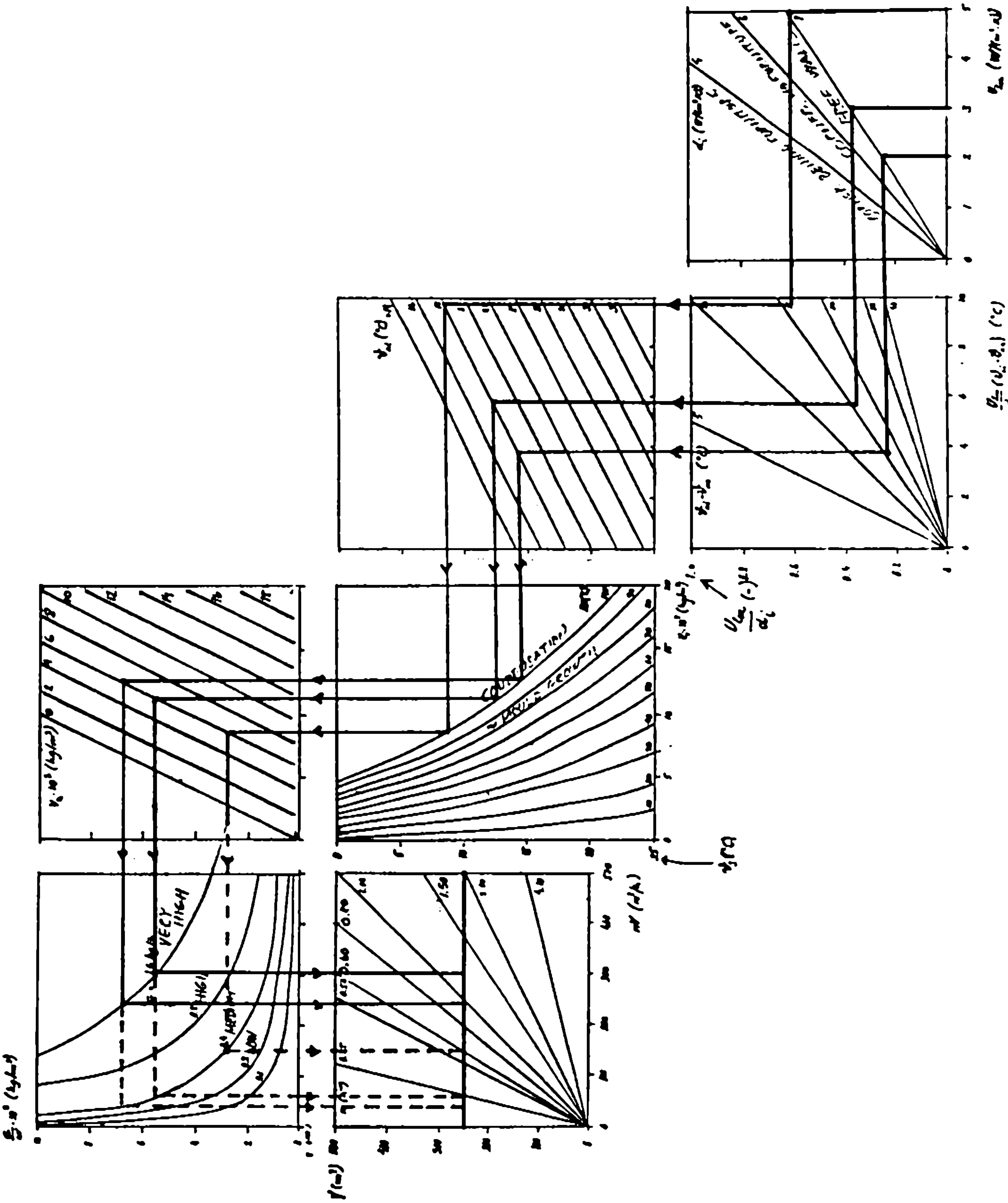


FIGURE 2.1.2 b

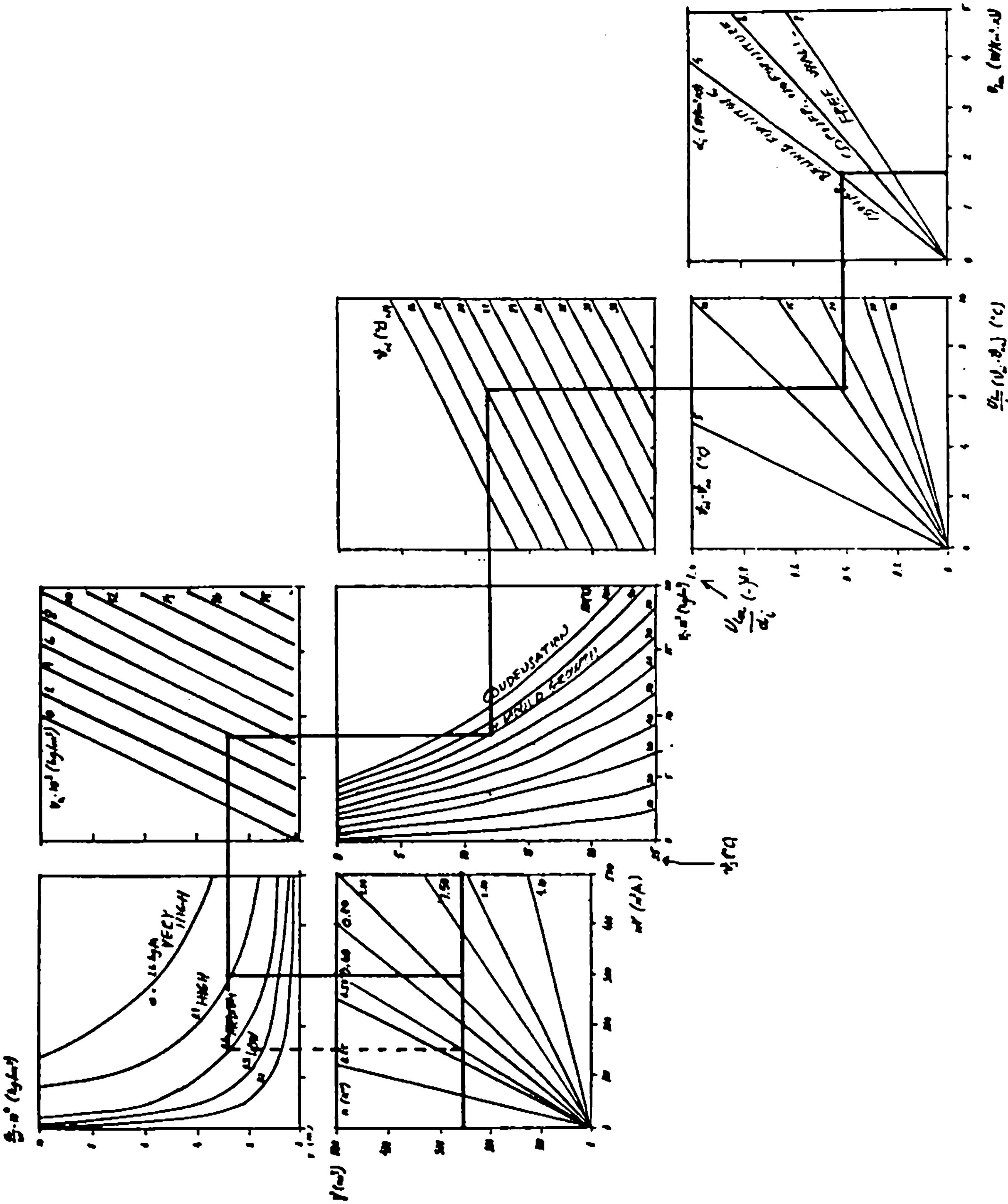


FIGURE 2.1.2 c

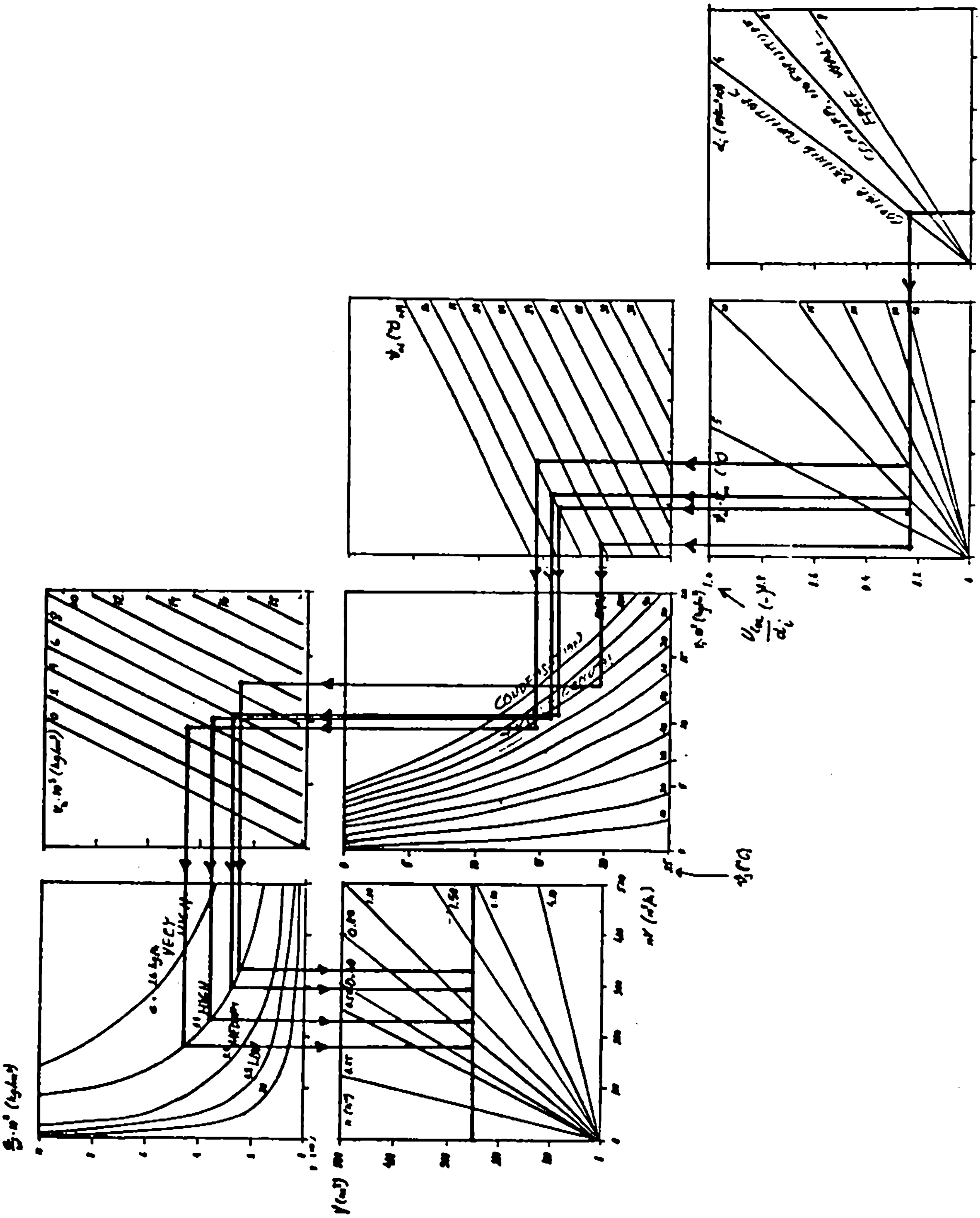


FIGURE 2.1.2 d

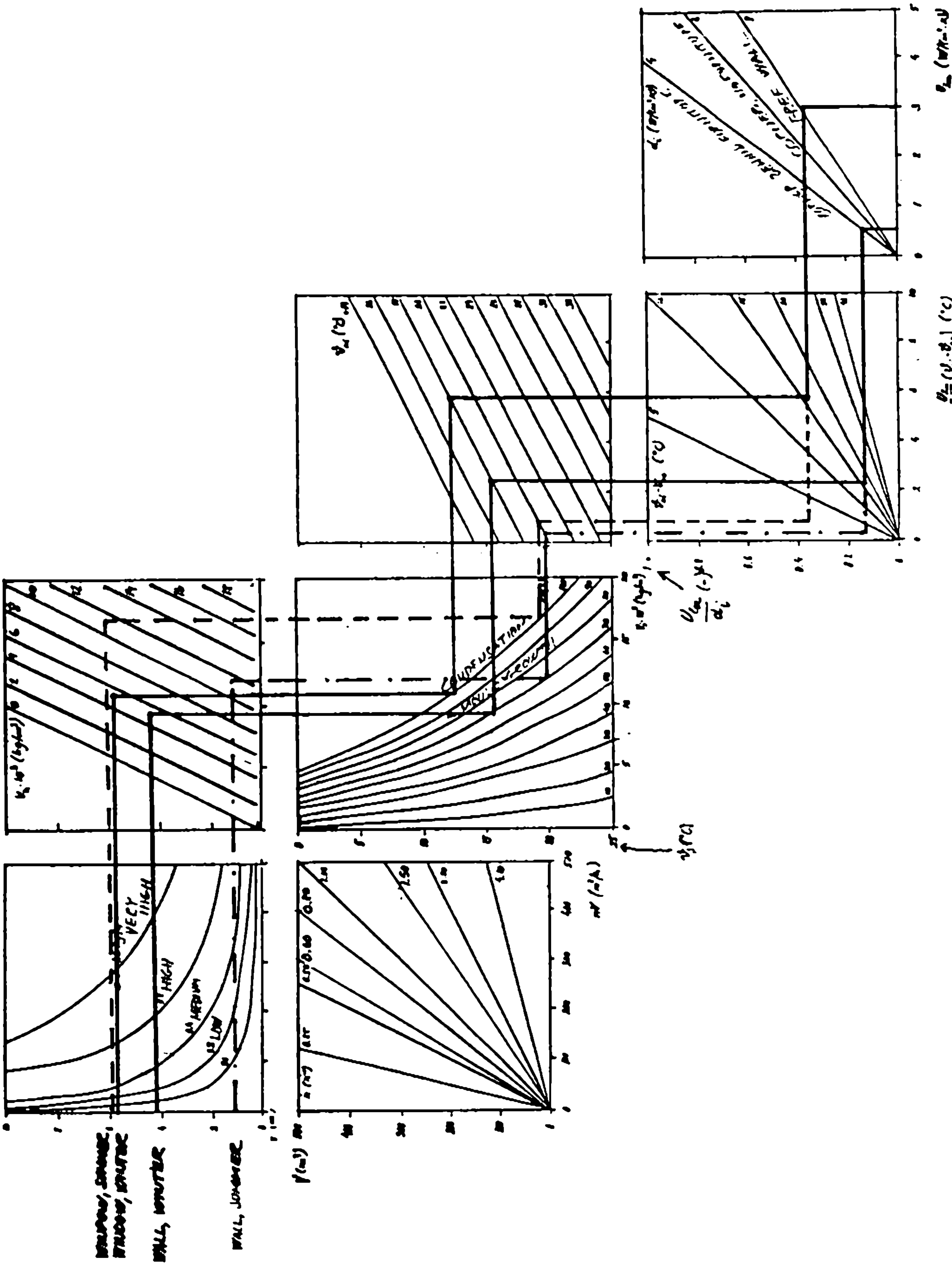


FIGURE 2.1.2 e

2.2 Moisture problems in building components

In the same manner as mould can grow and condensation can occur on inner surfaces of a building, these phenomena may happen within a building component or an adjecent space, for example an attic.

The risk criteria are likely to be the same, i.e. moisture conditions above a relative humidity of appr. 70 %, at certain temperatures, under longer periods, may be harmful to organic material.

Out of the two transfer mechanisms explained in part 1.2, moisture diffusion and moisture convection, the latter one is without any doubt the more harmful one. Except for very special cases, such as freezing-houses etc., moisture diffusion in fact in most cases could be neglected in the design procedure. This is due to the fact that diffusion is a very slow prcess and possible condensation amounts are small.

However, conditions with higher air pressure inside a building than outside, may create very unfavourable moisture convection problems. The moist air is trnsferred out from the building through cracks etc and creates high relative humidities or condensation when the heated and moist air meets parts in the construction with lower temperatures.

Exemples of severe moisture damages caused by moisture convection are moisture accumulation, mould and rot in roof constructions and attics.

3 CONCLUDING REMARKS

From the discussions and analyses carried out in this paper, these general recommendations for building physics design can be given:

- Reduce the moisture supply in dwellings as much as possible. Try to avoid such activities in the dwelling itself as drying clothes, using water vapourproducing local heaters without chimney etc.

- Install a ventilation system - preferably a mechanical one but at least pipes for natural ventilation - which can exhaust moisture where it is supplied (kitchen, bath room etc) and give the whole dwelling a good air quality.

- If using mechanical ventilation, recover heat from the exhaust air.

- Ensure a maximum level for heat transmission through the building envelope for moisture and energy conservation reasons.

- Ensure a good air tightness of the building in order to avoid moisture convection problems, to give the ventilation system a chance to produce a good and even air quality in the whole dwelling and to save energy.

4 LITERATURE

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APPENDIX 4

Lund University/Lund Institute of Technology
Department of Building Science
Moisture Research Group

Contribution to the CIB-W40-meeting in
Holzkirschen 1985

DETERMINATION OF MOISTURE FLOW COEFFICIENTS FOR POROUS MATERIALS BY USING THE "MOMENT METHOD"

Dan Gaffner, Ingrid Wilhelmsson

Background

The porous building materials (concrete, lightweigt concrete, timber, etc) contain an extensive and complicated system of pores in which moisture in the form of ice, water or water vapour may be present. The amount of moisture in the pores is governed both by the structure of the pore system and by the moisture conditions around the porous material. Transfer of moisture through a porous material is also dependent on the pore system, but also on the moisture gradient and other factors.

Fundamental and experimental research into the moisture conditions in porous materials has been going on at Departement of Building Science since the beginning of the seventies. This research has been carried on in collaboration with the Departement of Mathematical Physics at Lund Institute of Technology (LTH), and has been reported by Claesson-Gaffner (1977) and Adamson-Gaffner (1977). The first report discussed, inter alia, certain fundamental relationships for moisture processes in porous materials, and put forward proposals for methods of measuring different moisture processes. These were included in the programme of the Moisture Research Group at LTH, and resulted in a research project commencing in 1981. This project relates, inter alia, to development of a new method called the moment method for measurement of moisture transfer coefficients and determination of hysteresis effects for equilibrium moisture curves. A more detailed description of these methods is given below. The project also comprises production of material data regarding moisture properties for some common building materials. These material data have partly been used for calculation of moisture processes in a computer program made by of the Department of Building Technology in the Moisture Group. The calculations have then been compared with laboratory experiments to check the calculation methods , se Andersson (1985).

The absence of material data and measuring methods for different moisture properties constitutes a considerable impendiment to meaningful calculations of various moisture problems. Such calculations are of great significance, both for reliable moisture design of new structures and for analyses of moisture damage.

The moment method

In the moment method, the moisture flow coefficient D_w for a porous material can be measured at a moisture content gradient w under isothermal conditions. A bar of the porous material is placed on two supports, one of which is carried on a precision balance. The bar is moistened in advance so that a definite moisture gradient exists along the bar. An equalisation of moisture movement takes place and is recorded by the precision balance as change in weight per unit time. The value of D_w can be easily determined from this change in weight. In general, D_w is not constant but varies with w. See FIG 1.

In the project we are engaged on a development of the moment method so that measuring method of practical application may be obtained. Measurements will further be made for the whole of the "practical" range of moisture contents and for different materials. The expected result is a well defined measuring method which can be used by test institutes etc, as well as measurement data for some typical building materials.

The moment method has so far been used in measurements on lightweight concrete of early date (γ =520 kg/m^3), on hydrophobic lightweight concrete of recent manufacture (γ =320 kg/m^3) and on brick (γ =1800 kg/m^3). For the old lightweight concrete and brick we obtained curves of D_w which are in good agreement regarding appearance and magnitude with curves obtained with other (and more complicated) methods. For the hydrophobic lightweight concrete the results are more irregular. The irregularity is probably due to the process which rendered the lightweight concrete hydrophobic. See FIG 2.

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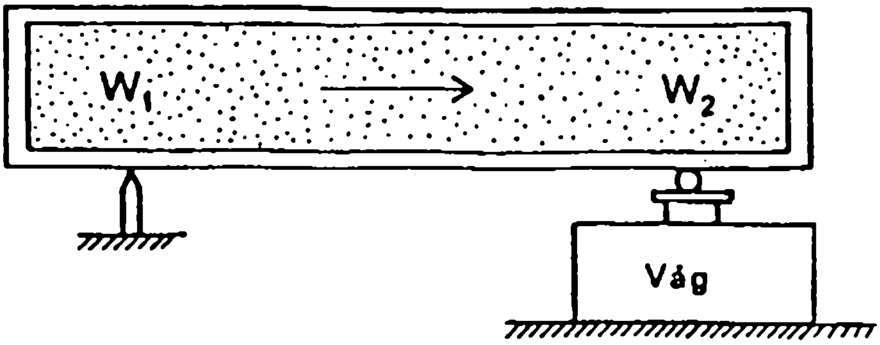

FIG. 1. In the moment method a porous bar is enclosed in a tube. The moisture contents w_1 and w_2 at the ends of the bar are different. Moisture transfer takes place, and this is recorded by the precision balance (in swedish: våg).

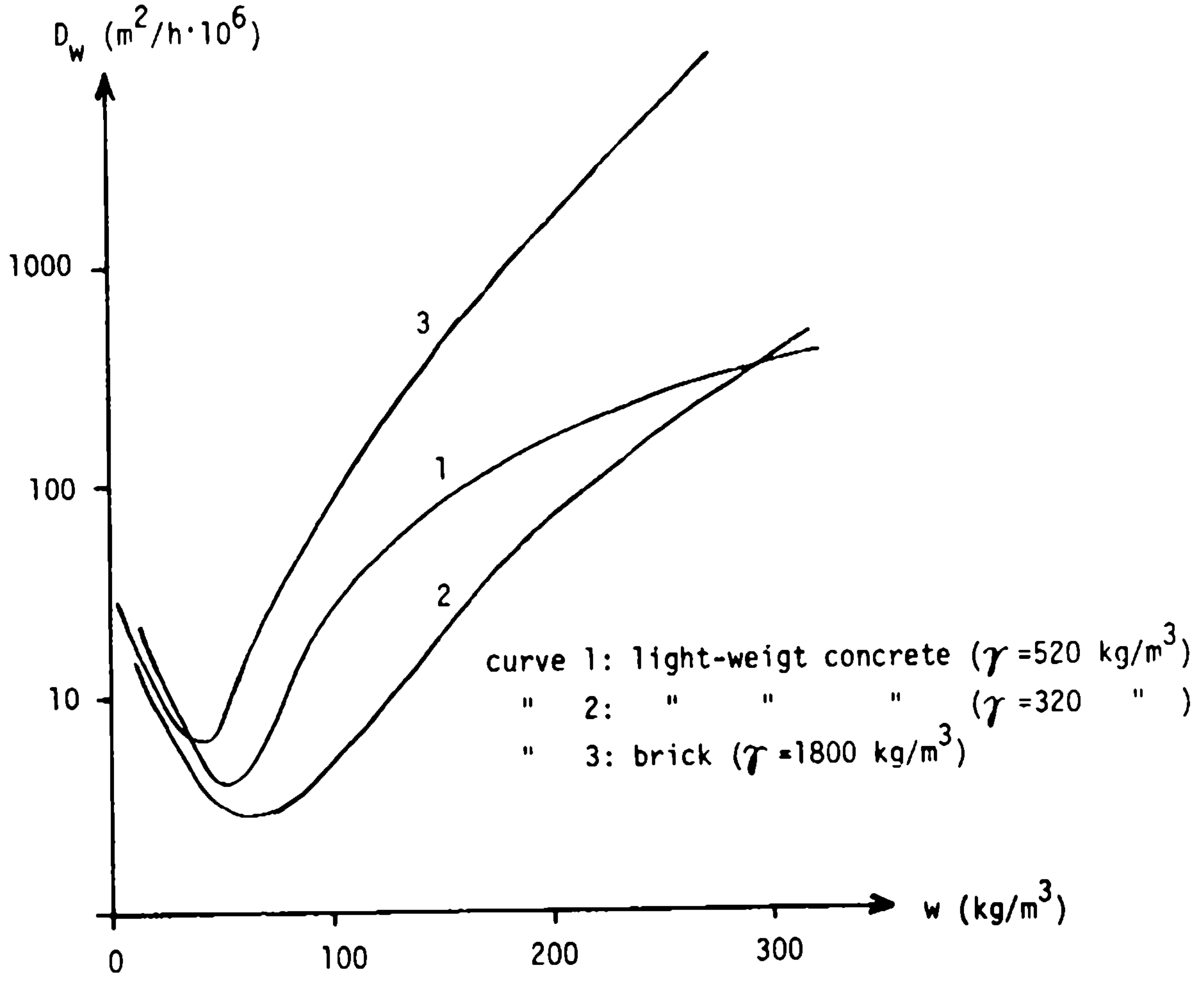

FIG. 2. The moisture flow coefficient D_w as a function of the moisture content w for different materials obtained by the moment method

APPENDIX 5

CIB W40 Holzkirchen 850903-05

Moisture problems in high insulated structures - an outline of Swedish experiences.

L E Nevander

In the typical Swedish wood stud wall, figure 1 there was 100 mm insulation in the 50's, now the building code requires a minimum of 170 mm and 300 mm is often used in well-insulated houses. The aim is of course to decrease the heat flow through the wall but this influences also the moisture conditions.

A simple diffusion calculation under steady conditions for the wall with an efficient vapour barrier shows that the outer part of the wooden parts in winter time is exposed to higher relative humidity (RH) the thicker the insulation is. This means that also the moisture content increases, which has been confirmed by field measurements, Bergström (1), figure 2.

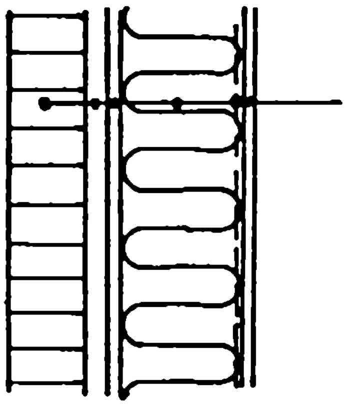

Figure 1. Typical Swedish exterior wall with mineral wool insulation between wood studs.

Postal address
PO Box 118
S-221 00 LUND
Sweden

Office address
John Ericssons väg 1

Telephone
+ 46-46 10 70 00

Telex
LUNIVER
(Telexnr S-33533)

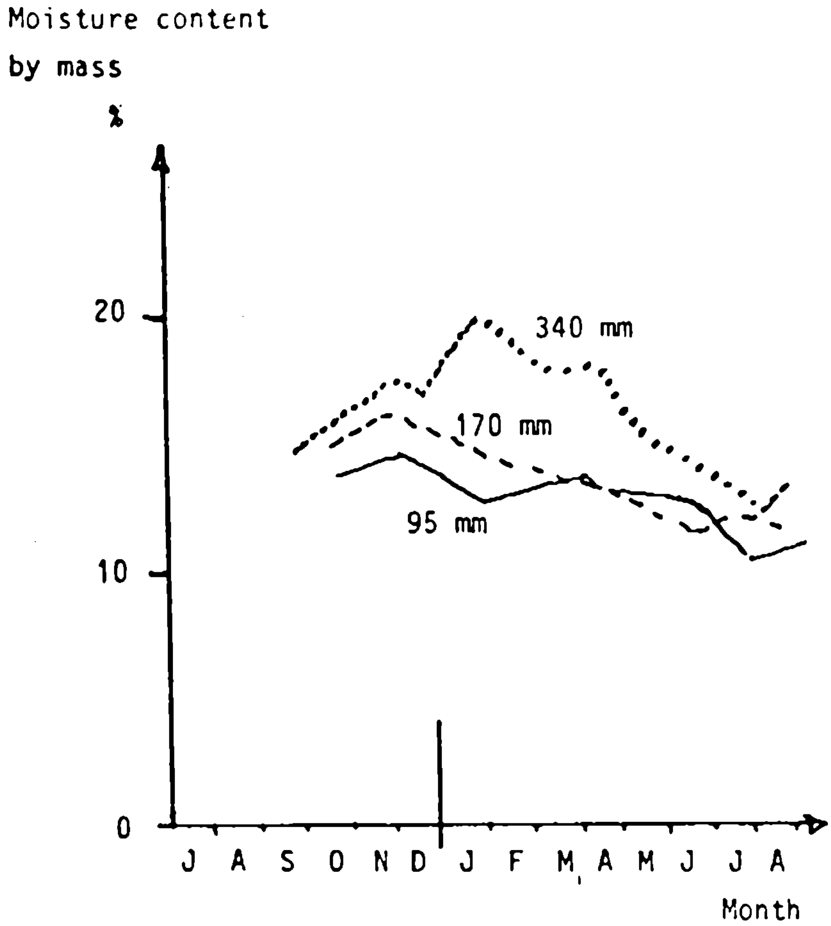

Figure 2. Moisture content of wood dummies placed at the outmost part of the wood studs in walls with 95, 170 and 340 mm insulation thickness.

So far we have not had any damages by that reason even though the RH is higher than what we generally accept for wood. This probably depends upon that the temperature at the same time is rather low which keeps back the growth of fungus or mildew.

It has also been claimed that the low heat flow through a wall should give reason to more frost damages of the facing material, e.g. bricks, renderings. Theoretically it is correct but in practice we have not been able to find the effect. It is likely that the stochastic behaviour of the climate overrules such small differences in temperatur of the facing.

The attic floors generally have thicker insulation than the walls. The heat supply to the ventilated attic is therefore very small and the increase in temperature of the ventilation air is low. This means that the moisture absorbing capacity of the air is low and that the ventilation is not so efficient for taking away water vapour. Thus, the construction is getting very sensitive to moisture convection from below and for evaporation of initial construction moisture. We have had a number of damages both in new buildings and in retrofitting.

In an office building with a roof according to figure 3 the wooden roof panel buckled out the first winter. The attic was supplied with mechanical ventilation which gave 1.0 air changes per hour. However, the construction moisture in the concrete slab evaporated through the 280 mm thick insulation into the attic. The attic air could not ventilate away the water vapour and it condensed on the wooden roof panel. The engineer had suspected something to happen and had put in a fan, but he had not calculated the effect of the ventilation. The lesson was to put in a vapour barrier on top of the concrete floor.

In efforts to save energy it is very common to increase the insulation on the attic floor. On some occasions it has happened that a roof which has performed well before gets damaged after the new insulation. The explanation is the same as before: the attic is getting colder, the ventilation cannot take away so much moisture. Before the insulation is installed one has to check the air tightness of the floor and the air pressure conditions. It has always been water vapour convection and not diffusion that has caused the problems.

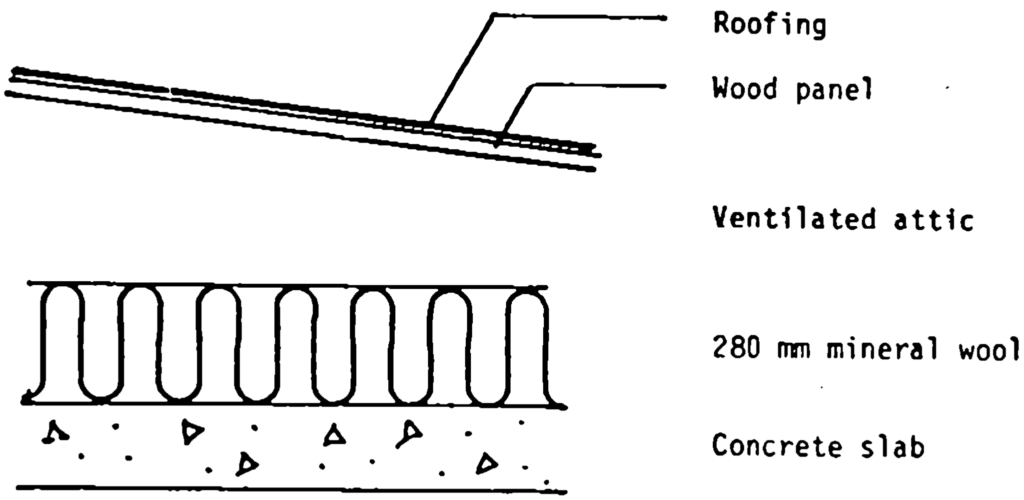

Figure 3. Roof construction of an office building.

Soon after the energy crises started there was a campaign in Sweden for tightening your house by stripping the windows and similar measures. This sometimes led to that the ventilation rate was too low and thus the RH too high with condensation on the windows as a first result. If walls and roofs are less insulated or include thermal bridges the condensation can occur also on other places.

Most of the moisture damages in Sweden during the last 15 years are related to windows and foundation by slab on the ground. In neither of these cases one can claim that the increased thermal insulation has had any influence.

It is, however, popular to say that the new building technic with air tight and well insulated buildings has led to the increase in moisture damages but in fact there is only a limited number of damages which can be related to this technic. - As we know of so far!

Ref.

1. Bergström, U: Högisolerade konstruktioner aktualiserar fuktforskning. Byggmästaren 1984, nr 2. p 27-29.

APPENDIX 6

NATIONAL TESTING INSTITUTE
BUILDING PHYSICS
P.O. BOX 857, S-501 15 BORÅS, SWEDEN
TEL. INT. + 46 33 16 50 00
TELEX 36252, TESTING S

Ingemar Samuelson

MOULD PROBLEMS IN NEW SWEDISH BUILDINGS

Borås 1985

Contribution to the CIB W 40 Holzkirchen meeting 1985

MOULD PROBLEMS IN NEW SWEDISH BUILDINGS

Mould in buildings

Mould growth on walls and ceilings has for a long time been a big problem in dwellings with high moisture content and high relative humidity. This type of mould growth can cause diseases for persons in the dwelling. The problem has decreased when buildings are better insulated. The more insulation in the wall and roof the higher surface temperature on the inside and the less risk for condensation and mould. Only if the ventilation rate is very low there is still a risk for high moisture content in the indoor air and condensation.

During the last 10-15 years these problems however seem to increase in Swedish dwellings depending on the fact that many new buildings have no ventilation at all. These houses are very airtight but have no mecanical ventilation. Although this is a big problem for the persons who live in the houses we think that the problem is easily solved. A better ventilation will give an acceptable indoor climate.

But during the last ten years another type of building defect has appeard in Sweden. The occupants of such buildings are troubled by an offensive odour, and suffer from various degrees of medical complaints. Schools and nurseries have been particularly affected, and it has not always proved possible to determine the cause.

During the last five years, we at the National Testing Institute have experienced a rapid increase in this type of damage, predominantly in the form of mould odour, although the occupants have also been affected in other ways.

We lack expertise in the evaluation of the effect on health of residing in buildings that smell, but we are able to note that the majority of buildings so affected also suffer from problems of moisture. We examine possible damage due to moisture and attempt to determine its cause. A normal investigation involves both determining the degree of the damage and putting forwards proposals for remedial action.

Since 1979 we have undertaken measurements in 394 buildings suffering from mould growth, odour or other complaints. The vast majority of cases involved single-family houses, both detached and terraced, although flats in multi-story buildings were also included. In addition, some 30 day nurseries and schools were examined.

The most common type of damage takes the form of an unpleasant odour caused by mould. In order for its fungi to grow and an odour to develop, the presence of moisture, among ohter factors, is required. Mould growth can take place with a relative humidity of 70-75 % and above. In the majority of foundation structures these levels are reached at least as long as there is residual built-in moisture. Figure 1 shows sketches of two common methods of laying foundations for single-family houses and nurseries. These structures are frequently affected by mould growth and odour.

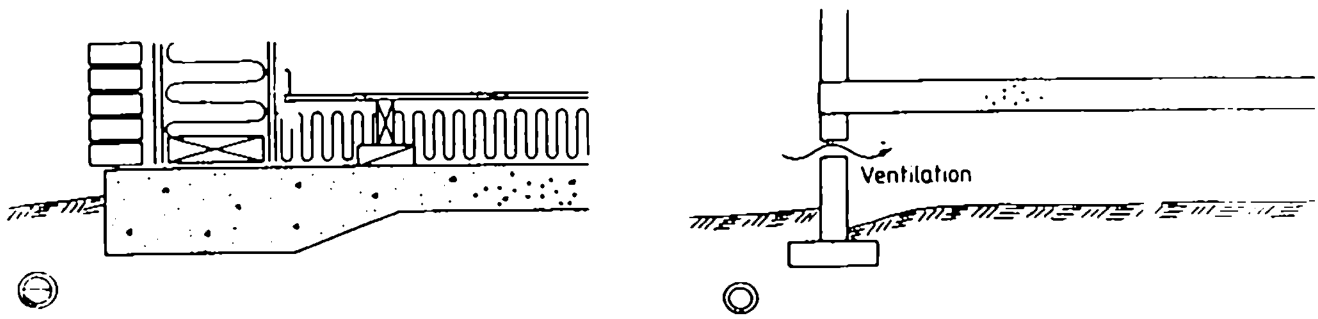

Fig 1 Slab on ground and crawl space. Two structures which often suffer from mould problems

Cause of odour

The reason for the growth of mould in floors or crawl spaces is most often underlying moisture. Since the concrete slab is laid directly on the ground, a fully functioning vapour barrier is required in order to be completely certain of avoiding ground moisture. Such vapour barrier is absent in the majority of structures. The cause of this damage may however also be completely different from ground moisture, as can be seen in figure 2 which is a list of the causes of damage in buildings suffering from mould odour which we examined.

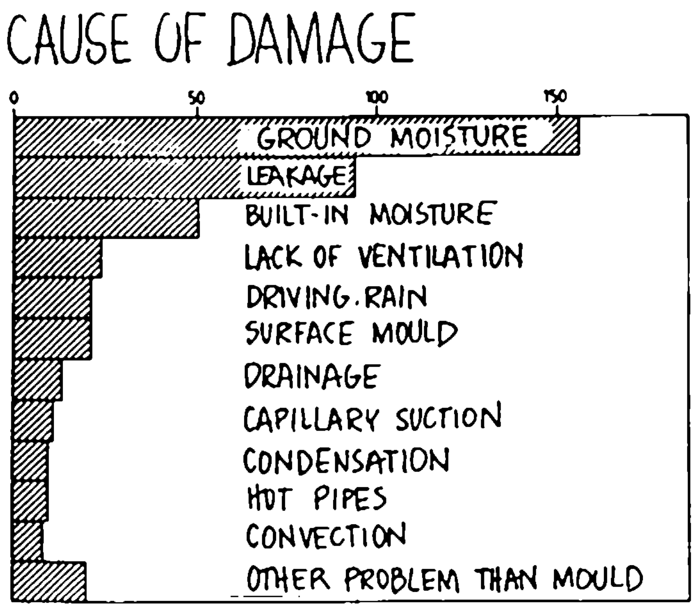

Fig 2 Cause of high moisture content in floors with mould odour

It should thus not be taken for granted that all problems come from below. If measures are taken to deal with an incorrect cause of damage, no improvements are attained.

Mould odour in buildings is a phenomenon which has occurred during the 1970's. Previously at any rate there was no mention of the fact that buildings could be affected by mould odour in the same manner as is common today. Figure 3 shows the year of construction of those buildings which we have examined. As can be seen, there are very few that pre-date 1970, and in the majority of cases where the buildings are of earlier age, mould odour has occurred after recent renovations or rebuilding.

YEAR OF CONSTRUCTION

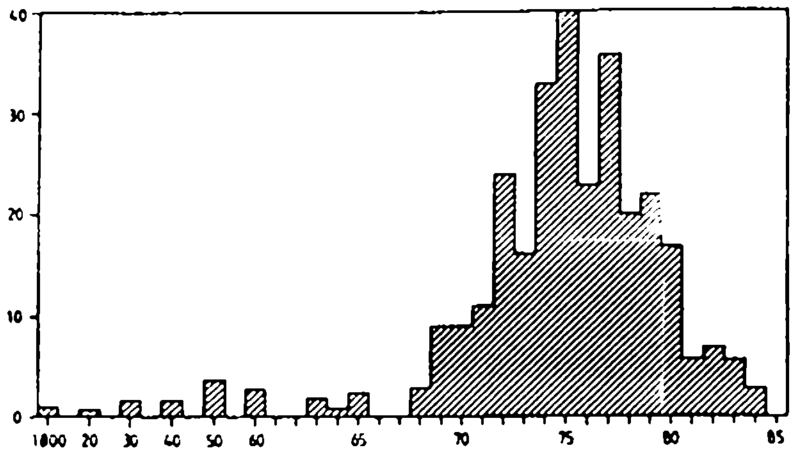

Fig 3 Year of construction of buildings with mould odour. The figure refers to those inspected by the National Testing Institute

Figure 3 may give the impression that Swedish buildings that were constructed during the 1970's are considerably inferior to those that were built prior to this date. This is probably an erroneous impression. On the contrary, the amount of serious damage to buildings in the form of attack by rot or collapse has declined, although this has been replaced by the problem of sick houses.

The question arises as to the reason why this should be so. Is this a completely new form of damage which was previously unknown, and against which no safeguards thus needed to be taken? Or is it known damage which should have been avoided? Much progress was made during the 1970's which either in its individual aspects or collectively has resulted in considerable alternations to building designs. An increased amount of thermal insulation improved air tightness, rapid and rational construction, short construction times, new materials and designs, may have all resulted in changes necessary to the emergence of this kind of damage.

Measures

The odour problem is related to moisture. Without moisture there would be no problems of mould growth. Even if the quantities of moisture in new buildings are not particularly great, they are nonetheless sufficient to cause problems. Careless use of the building may promote this damage and a susceptible or faulty structure will often cause damage. Both occupants and builders must be conscious of the fact that the problems of sick houses are nearly always caused by dampness, and they must therefore take reasonable precautions to reduce the risk of damage. On the part of the occupants this means ensuring a constantly high indoor temperature as well as adequate ventilation. On the part of the builder this requires reliable structures. Above all, one should avoid those methods of laying foundations that are often associated with problems. Figure 4 shows the most commonly affected structures which should be avoided as far as possible in new buildings under construction.

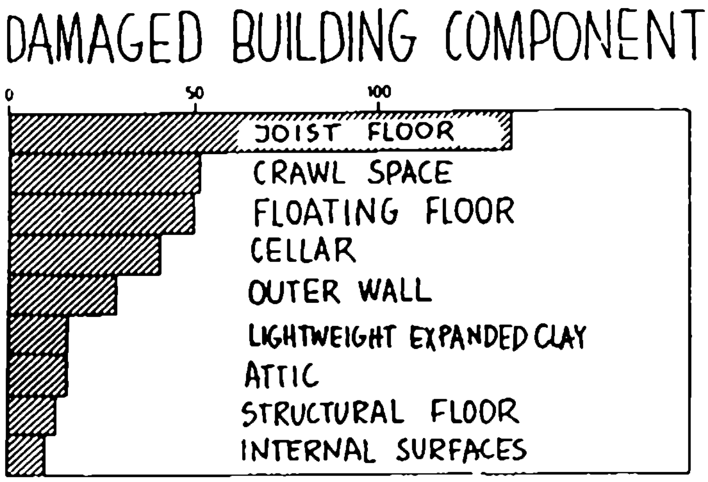

Fig 4 Damaged building components with mould odour

Different individuals experience mould odour differently. What may seem like a strong odour to one person may be less offensive to another. The evaluation of the degree of odour in a building is problematic. Should one use one's own sense of smell as a criterion when problems arise or rely on the testimony of the occupants?

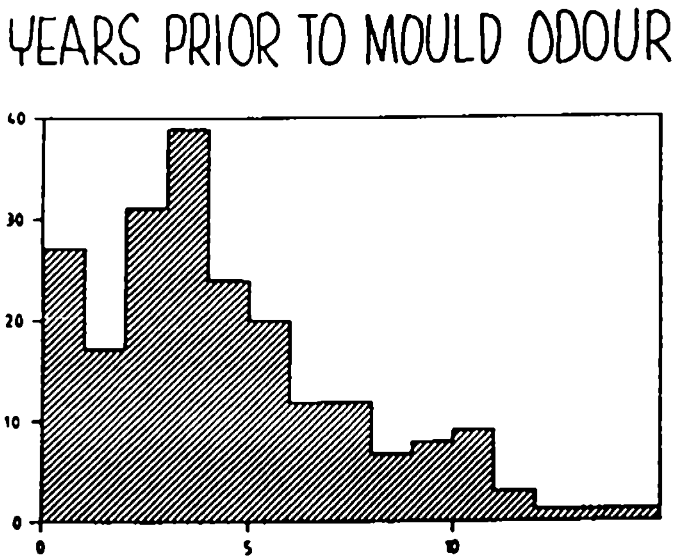

Fig 5   Number of years before mould odour is detected in the building

Figure 5 shows the length of time which elapses before the occupants begin to detect an odour in the building. Many already do so during the first year, although this sometimes takes considerably longer. By this time a change of ownership has occured, and the new owner usually notices the odour immediately after moving in, despite the fact that the previous owner had not detected any odour, or at least had not admitted that this had been the case.

It is our opinion that the problems relating to mould ododur in buildings are new problems that were previously unknown some 10-15 years ago. We can point to a number of changes in building techniques which may have caused this, but we are still not certain which is the most important cause. Until this matter is clarified however, one should always endeavour to maintain a low moisture content, since low levels of moisture do not allow those ciritical areas to be reached, at which damage occours.

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 6

SHORT PRESENTATION OF THE AIRBORNE MOISTURE PROBLEMS AND RESEARCH ACTIVITIES WITHIN THIS FIELD IN NORWAY

J. BRUNSELL

Norwegian Building Research Institute
Box 322
Blindern
N-0314 Oslo 3
Norway

SHORT PRESENTATION OF THE AIRBORN MOISTURE PROBLEMS AND RESEARCH ACTIVITIES WITHIN THIS FIELD IN NORWAY

Problems

Airborne moisture can cause two kinds of problems in buildings.

1) Condensation of moisture on surfaces which can result in mould growth.
2) Condensation of moisture inside the building construction which can result in mould growth and wood rot.

Condensation on surfaces

Whether or not condensation occurs on a surface depends upon several parameters:

- indoor temperature
- outdoor temperature
- thermal resistance of the construction
- moisture content in the indoor air
- air flow

In Norway the most common problem of this type is condensation on windows. We mostly use triple-glazed or coated double-glazed windows The situation for many people can be described as follows:

In order to make their old dwellings or houses more energy efficient and modern they start replacing old windows with new double or triple glazed windows. The old ones are usualy two pane in two frames coupled together. Except that they are often leaky, these windows are good (U-value $\approx 2.7\ W/m^2K$). The new windows, however, are usualy more airtight, especially between the frame and the wall. The old dwellings and houses have a simple ventilation system, natural ventilation with fresh air through leaks. If they do not do anything with the ventilation system the tighter windows result in less infiltration and ventilation and more moisture content in the indoor air. This very often results in condensation on the windows and of course the inhabitants will complain about their new windows.

We have also from time to time seen condensation and mould growth on walls in new dwellings. The location is very often close to the floor and behind furniture or curtains. It also occurs on the the surface where there is a thermal bridge in the wall. The temperature on the wall surface at these locations can be quite low but the moisture content in the air is the same as in the rest of the room, sometimes resulting in condensation. This kind of damage is a minor problem in Norway because of the insulation level of the constructions, the indoor air temperature and the ventilation level in the buildings.

Condensation in the construction

The last 10 years we have seen a significant number of new houses with damage caused by condensation inside the constructions. This almost always occurs in the roof. This type of damage began about 10 years ago with a change in construction practice in Norway. Instead of insulating the ceiling from the attic we started insulating the roof itself so the "attic" could be used for "indoor activities". We also started using more wooden panelling instead of boards as the interior finish. After doing this, the condensation problems started to occur. The reasons were these:

We had the same situation in the new house as in the old one. Warm, humid air was pressed out through leakages in the vapor barrier because of the stack effect. But instead of comming up to a big volume in the attic where the moisture could be spred out, the humid air in the new house came up to the ventilation space which had a very little volume and possibility to store moisture. Therefore the moisture condensed at once on the first cold surface it met. On cold days the moisture turned into ice that melted when the outdoor temperature rose.

The use of the panelling resulted in less airtight constructions and the stack effect increased because of the height of the buildings. Both these parameters increased the moisture transport.

At the Norwegian Building Research Institute we have made a field investigation on houses with pitched roofs with parallel ceilings. We found that 17 out of 25 new houses had leakage in the vapour barrier that could lead to damage.

Although we know that the walls are often more leaky than the roofs we have not found the same damage here. This knowledge, together with the fact that damage in roofs allways occurs where there is a leak in the vapor barrier, tell us that this is an airborne moisture problem and not a diffusion problem.

Experience from old cavity walls tell us the same. If we insulate a wall by blowing mineral wool into the cavity no damage occurs, even though the wall does not have a vapor barrier. (This has been done for 25 years.) But if we blow mineral wool into the cavity in the roof, which does not have a vapour barrier, we often get condensation problems.

Research activites

At the moment we have little research activites in this field. However, I want to say a few words about a computer intensive statistic method used for moisture transfer calculations. This method is developed by Dr.ing. Anker Nielsen at the NBRI.

Almost all calculations of moisture transfer are made today with mean climate conditions and fixed moisture transfer coefficients. This is sometimes supplemented with additional calculations in extreme cases. But this gives no information on how often the extreme will occur. It is important to know if we get damage from condensation in 5 % or 50 % of the cases. This can be solved by taking into account the variations in each of the parameters in the calculation. The resulting variation can be calculated if the parameters are normally distributed. But that is not the case for many of the parameters. It must be solved with another statistical method where we need to know the distributions and how to simulate them.

We have also some diffusion measurements for different materials going on at the moment.

In addition to this we are continuously doing projects in order to improve our construction details in our building details sheet series.

Oslo, March 11, 1987

Jørn T. Brunsell

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 7

THE CONTROL OF CONDENSATION WITHIN BUILDINGS IN THE UNITED KINGDOM

A. WILSON

Oscar Faber Consulting Engineers
Marlborough House
Upper Marlborough Road
St Albans
Herts
AL1 3UT
United Kingdom

The control of condensation within buildings in the United Kingdom

Anthony Wilson
Oscar Faber Consulting Engineers

Synopsis

Last year saw the release of an important new document in the United Kingdom. The Chartered Institution of Building Services Engineers (CIBSE) completely revised Section A10 of the Design Guide dealing with moisture transfer and condensation. The section was also extended in scope to include more detailed design calculations. 1986 also saw the circulation of a new draft of British Standard BS 5250 "The Control of Condensation in Buildings". The new draft British Standard is design orientated and includes many design details. This paper will review these two new documents and outline the way the control of condensation is handled within the British construction industry.

Introduction

Within the United Kingdom condensation within buildings is widespread effecting some 3.5 million homes to some degree. A recent MORI survey for London Weekend Television reported that 96 percent of the UK population described damp free housing as essential. This was the second highest response after 97 percent stated that provision of heating to warm living areas of the home was essential. It is estimated that 8 percent of the UK population lack damp free homes. The awareness of condensation in buildings seems to be fairly high and last year two new documents were published. The Chartered Institute of Building Services Engineers (CIBSE) produced a new section A10 to their design guide entitled Moisture Transfer and Condensation. The British Standards Institution also circulated a draft for public comment of the new BS 5250 British Standard Code of Practice: The Control of Condensation in Buildings. This paper will look at the old IHVE section A10 (Ref. 1.) and the improved CIBSE section A10 (Ref. 2.) and the 1975 BS 5250 Ref. 3.) and the improved draft BS 5250 (Ref. 4.).

1970 IHVE Guide Section A10 Moisture Problems

This document was only five pages long and covered condensation and evapouration, vapour diffusion using diffusion resistance factors and permeance values, and general condensation in buildings. Most of the information is based on work by Billington (Ref. 5.) and Krischer (Ref. 6.) in the 1950's.

1986 CIBSE Guide Section A10 Moisture Transfer and Condensation

This document has been extended to include a much more thorough examination of the problems with condensation and includes sections on Hygroscopic Materials, Vapour Difusion within Materials, Prediction of Moisture Condensation, Sources of Moisture, Controlling and Eliminating Condensation and Algorithms for Interstitial Condensation.

This new document was seen as a major step forward by the Institute and has seen the section triple in size. Section A10 concentrates on vapour resistivity and resistances and gives guidelines for converting permeabilities and diffusion resistance factors into appropriate units. The new method still keeps with the overall concept of vapour diffusion but deals with it in a more sophisticated manner. The guide follows the BRE recommended method based on the work of Glaser (Ref. 7.).
Consideration is given to the sources of moisture within buildings and the guide quotes typical daily moisture production rates of 7 kilogrammes for a 5 person family with peak moisture generation of 20 kilogrammes.
A more detailed breakdown can be seen in Figure 1 which shows details on the sources of moisture in buildings.

There are different causes of condensation in buildings and therefore the way to illiminate those problems require different treatment. Figure 2 shows another tables summarising the properties of the various forms of condensation and lists the possible causes.

Surface condensation is the major problem in housing within the UK and a flow chart is included in the CIBSE Guide to show if surface condensation is likely to occur. This flow chart is shown in Figure 3.

The calculation of interstitial condensation is dealt with in detail and proposes certain conditions to be analysed. It stresses that surface vapour resistances are generally small and may be ignored and it suggests that the following conditions be assumed to exist for a period of 60 days when considering interstitial condensation. An inside air temperature of 15 degrees C with 65 percent relative humidity with corresponding outside air temperature of 5 degrees C with 95 percent relative humidity.
Section A10 is illustrated with worked examples showing how to use the calculation procedures that are outlined.

British Standard BS 5250:1975

The general sections within the 27 page long 1975 British Standard are outlined below.

1. General
2. The occurrence of condensation and mould growth.
3. Basis of design for the control of condensation
4. Recommended design assumptions.
5. Design and construction details
6. Work on site.
7. Remedial work in existing buildings
8. Conversion, modernization and change in use of buildings.

There then follows appendices, tables on relavent values of vapour resistivites of air and figures on interrelationships with moisture contents and temperature. The aim of the British Standard is to represent a standard of good practice and therefore takes the form of recommendations. It is emphasised within the document that the designers are recommended to take particular care in the detailed constructional design. The 1975 document outlines in general the four following aspects of design that control condensation in buildings.

1. Heating which maintains a higher inside surface temperature and improves the moisture carrying capacity of the ventilating air.

2. Ventilation which removes the moisture produced within space.

3. Thermal insulation which raises an inside surface temperature.

4. Permeability of building construction which influences moisture conditions within the thickness of the building element.

New BS 5250 (Draft)

This document at present must not be regarded or used as a British Standard but was released for public comment. Once all comments are sent to the committee secretary they are then given due consideration. The main aim of the British Standard is identical to the 1975 document and provides guidance for building designers, contractors and occupiers and includes recommendations for heating, ventilation and construction. These recommendations should control condensation in all but the most exceptional circumstances with methods of calculation to help assess and quantify the risk of condensation. The main sections of the standard are listed below.

1. General
2. The nature of condensation
3. Design to control condensation
4. Existing Buidling
5. Precautionary measures during building work
6. Tenant/user

The main inprovement in the new Draft is the detailing of constructions This is the final part of section 3 "Design to Control Condensation" entitled Design Details where various wall, floor and roof constructions are considered. The general element type is considered under four headings.

1. General design guidance
2. Specific design guidance
3. Comments
4. Warnings

Typical comments to be found in each section are:-

General Design Guidance
On masonary cavity walls the following points are considered essential weep holes to drain Damp Proof Courses and cavity trays and stop ends to cavity trays.

Specific Design Guidance
On solid floors a damp proof membrane also acting as a vapour control layer is to be 1000 gauge polyethylene.

Comments
On pitched roofs care is necessary to avoid a thermal bridge at the wall roof junction and to ensure that ventilation paths are not blocked at this point.

Warnings
On concrete flat roofs of warm deck type construction the provision of additional insulation at ceiling level will radically alter the condensation characteristics of this roof type.

Other general information is given in relation to general construction types for walls:-

To minimize interestitial condensation within a wall designers should aim to specify materials of decreasing vapour resistance from inside to outside. As a guide the materials on the warm side of any insulation should have a total vapour resistance of at least five times the sum of the vapour resistances on the cold side of the insulation.

The calculation procedures outlined in appendix B and C follow the same calculation procedures as given in the CIBSE guide A10 and worked examples are included within draft BS 5250. There are also useful tables provided on moisture generation, vapour properties, thermal properties and maximum permissable moisture due to winter condensation.

The draft British Standard provides an excellent design document for the control of condensation in buildings and should be of great use in the design of building within the United Kingdom.

Table A10.12. Sources of moisture within buildings.

Source	Amount of moisture
Combustion in flueless room heaters/cookers	
Paraffin	0.1 kg/h per kW
Natural gas	0.16 kg/h per kW
Butane	0.12 kg/h per kW
Propane	0.13 kg/h per kW
Household activities:	
Cooking (3 meals)	0.9 to 3.0 kg per day
Dish washing (3 meals)	0.15 to 0.45 kg per day
Clothes washing	0.5 to 1.8 kg per day
Clothes drying indoors	5.0 to 14.0 kg per day
Baths and showers	0.75 to 1.5 kg per day
Floor washing	1.0 to 1.5 kg per $10m^2$
Indoor plants	up to 0.8 kg per day
Perspiration and respiration of building occupants	0.04 to 0.1 kg/h per person
Direct penetration of rain, groundwater or moist ambient air	Variable
'Drying out' of water used in construction of building	4000 kg in one year for medium sized office building

Figure 1

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Table A10.11. Forms of condensation.

Nature	Type	Cause
Visible - prolonged	Permanent	Element surface temperature below the dew-point temperature. Normally occurs in winter through accumulation of moisture in space, poor thermal insulation of element, lack of heating.
Visible - spasmodic	Temporary	Element surface temperature below the dew-point temperature. Normally caused by build-up of excessive moisture in space such as kitchen or bathroom. Poor thermal insulation aggravates the precipitation of condensation. Can occasionally be caused by warm humid weather rapidly following a cold spell, the air coming into contact with cold building elements.
Invisible - if prolonged can become visible	Interstitial	Dew-point above temperature within element. Often caused by the mis-application of thermal insulation layer or vapour barrier. Interstitial condensation can appear on the surfaces of an element as a result of capillary penetration.

Figure 2

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Conclusion

Both of the new documents discussed have shown great steps forward in our understanding of moisture related problems in buildings. It is my personal view that the draft document should be released in the not too distant future as much of the design detailing will be of great use. The calculation procedures however can already be found within the 1986 CIBSE Design Guide. Many of the computer programs available for predicting condensation utilise these methods. Figure 4 and 5 show typical output from such programs.

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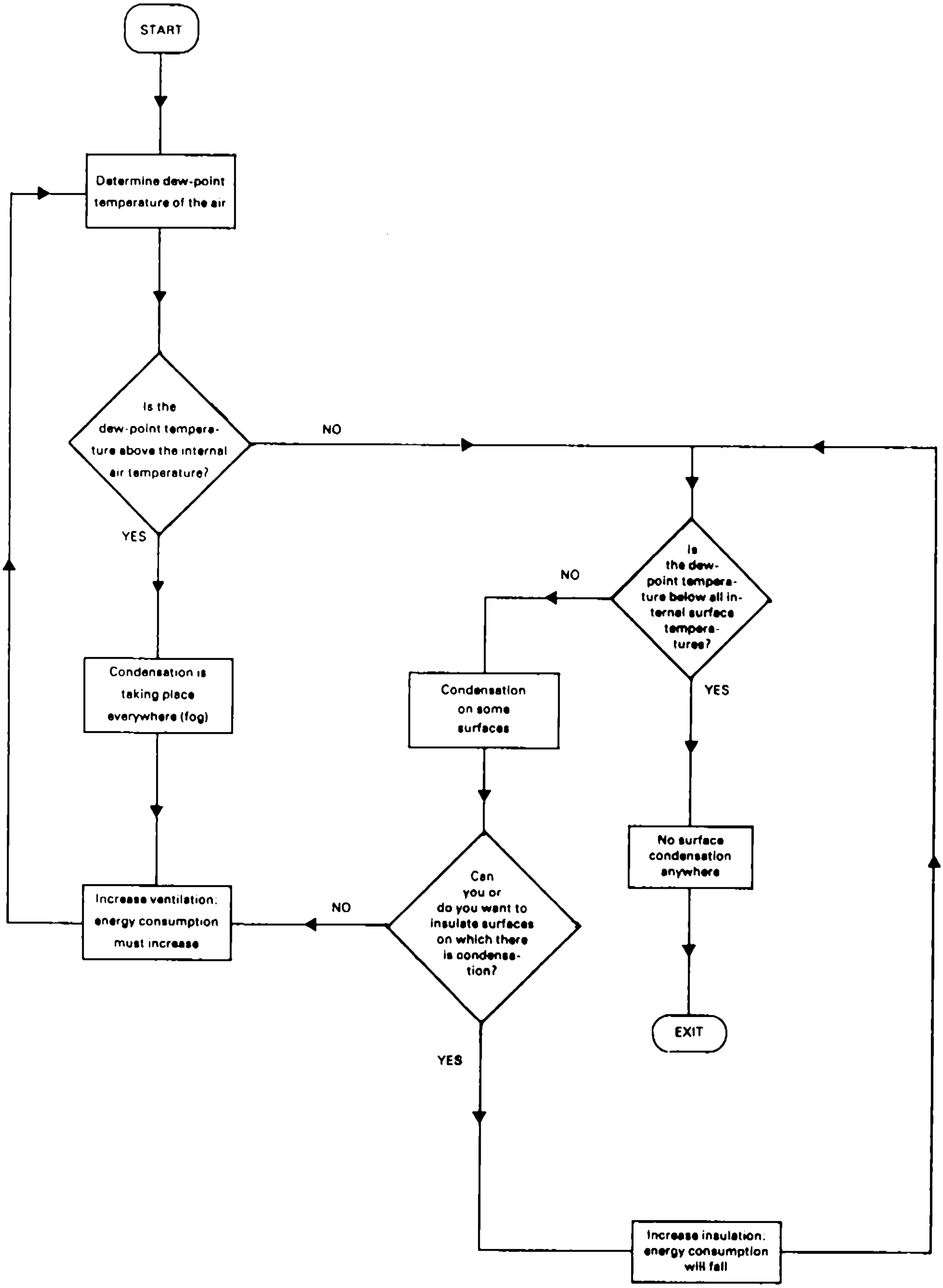

Fig. A10.5 Flow chart for prediction of surface condensation.

Figure 3

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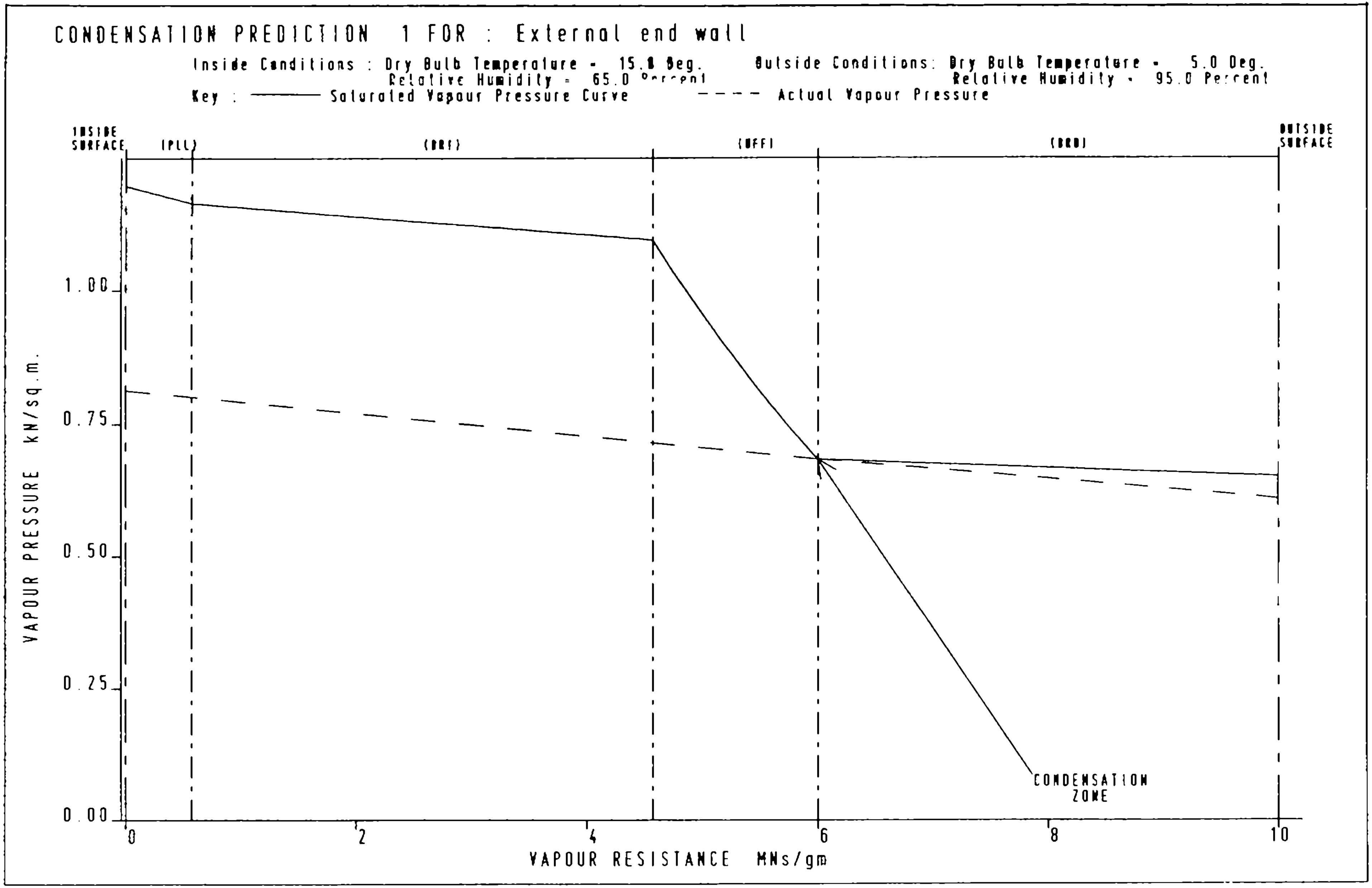

Figure 4 Condensation Prediction plot showing vapour pressure against vapour resistance for a wall.
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CONDENSATION PREDICTION 1 FOR : External end wall (EEW).

INSIDE DRY BULB TEMPERATURE = 15.0 Deg.C INSIDE RELATIVE HUMIDITY = 65.0 Percent
OUTSIDE DRY BULB TEMPERATURE = 5.0 Deg.C OUTSIDE RELATIVE HUMIDITY = 95.0 Percent NORMAL WIND EXPOSURE

Name of layer	Thickness metres	Conductivity W/m K	Permeance Kg/Ns 10**11 or Diff. Res. Fact.	Dry Bulb Temperature Deg. C	Vapour Pressures N / sq.m. Saturated	Vapour Pressures N / sq.m. Actual	Vapour Flowrate gm/sq.m sec
- - - - - - - -				5.00	871.9		
OUTSIDE SURFACE		(Res.=0.040)					
- - - - - - - -				5.23	885.7	828.3	0.24E-04
BRICKWORK (OUTER LEAF)	0.105	0.840	40.000 (R)				0.24E-04
- - - - - - - -				5.93	930.1	930.1	**
UF FOAM	0.050	0.040	30.000 (R)				0.28E-04
- - - - - - - -				12.97	1493.7	972.4	0.28E-04
BRICKWORK (INNER LEAF)	0.105	0.620	40.000 (R)				0.28E-04
- - - - - - - -				13.92	1589.4	1091.0	0.28E-04
PLASTER (LIGHTWEIGHT)	0.012	0.160	50.000 (R)				0.28E-04
- - - - - - - -				14.34	1633.5	1108.0	0.28E-04
INSIDE SURFACE		(Res.=0.117)					
- - - - - - - -				15.00	1704.5		

U - value for fabric = 0.56 W / sq.m K

****
* CONDENSATION IS PREDICTED FOR THIS FABRIC, AS SHOWN BY STARS ON ABOVE TABLE *
****

The Condensation Zone lies on the boundary between layers 2 and 1, 0.167m from the inside surface.

The rate of condensation = 0.40E-05 gm/sq.m s
The vapour flow into the element = 0.28E-04 gm/sq.m s, and out of the element = 0.24E-04 gm/sq.m s
(Flow is from the inside to outside surface).
Values assuming constant conditions for a 60 day period...
Condensation = 0.0207 kg/sq.m
Vapour into element = 0.1464 kg/sq.m, and out of element = 0.1256 kg/sq.m

NOTE: These calculations have been based on the inside and outside conditions and physical properties of the materials as stated in the condensation prediction summary. There can be wide variations in the actual value of these properties, and the user of this information should ensure that the selected values of this data are appropriate to the particular application.
NO RESPONSIBILITY CAN BE ACCEPTED FOR SELECTION OF MATERIALS, METHOD OF CONSTRUCTION OR QUALITY OF WORKMANSHIP.

Figure 5 Condensation prediction for an external end wall.
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AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 8

FIELD EXPERIENCES OF BUILDING MOISTURE

A.R. BONGARD

(Member NZ Institute Refrigeration and Airconditioning Engineers)

Technical Services Manager
Armafoil Industries
PO Box 11 - 052
Ellerslie
New Zealand

SYNOPSIS

This report contains a number of case histories of moisture problems in residential buildings in the mild and moderate temperature zones of New Zealand, where the majority of our population reside.

These cases represent the pattern of technical service enquiries over a period of some twenty years.

They all concern timber framed structures, as this is the form of construction most used for housing in this country.

About half the number of cases concern buildings with suspended timber floors and continuous concrete perimeter foundations with limited ventilation.

The balance fall into three categories:

1. Moisture absorbent claddings
2. Poor building practices
3. Occupant activities

All investigations were carried out with the objective of determining the source of the offending moisture before applying remedial procedures.

The wisdom of this strategy is indicated by a success rate of over 100%.

1. ANALYSIS OF CASE HISTORIES

1.1 Breakdown of 27 Dampness Problems

1.1.1. Table 1

Ground being moisture source (2.1 to 2.15)	15
Other moisture sources (2.16 to 2.27)	12
Total number of cases	27

1.1.2. Table 2

Ground Being Moisture Source

Natural high moisture content (2.1 to 2.7)	7
Avoidable high moisture content (2.8 to 2.12)	5
Heat stimulation of wet ground (2.13 to 2.15)	3
Total	15

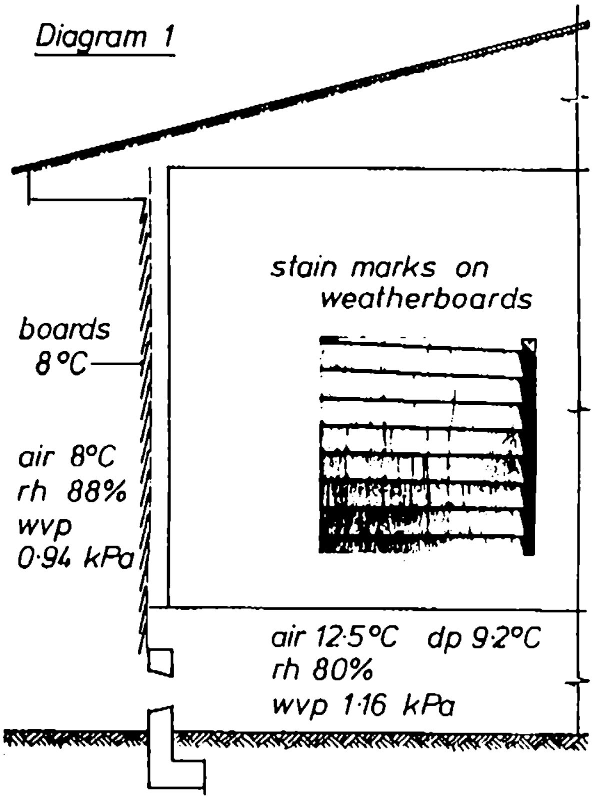
1.1.3. Table 3

Ground Moisture Sources

Porous claddings (2.16; 2.17)	2
Poor building practices (2.18 to 2.24)	7
Occupant activities (2.25 to 2.27)	3
Total	12

2. DETAILS OF CASE HISTORIES

2.1 House at Taupo - Maori and Island Affairs Department - Winter - 1969 - Refer Diagram 1.



Complaint:

Brown stains oozing from laps of weather boards - worst on coldest wall.

Investigation:

(a) Crawl space air 4.5°C warmer than outside
(b) Moisture content of crawl space air over 20% higher than outside.
(c) Weatherboard temperature below dew point temperature of crawl space air during warmest part of day.
(d) Restricted crawl space ventilation due to continious concrete perimeter foundations.

Cure:

Vapour Barrier over ground in crawl space.

Note:

(a) House in geothermal area
(b) Similar houses built previously in same area had no problems due to unrestricted ventilation of crawl space.

2.2 Cook Hospital - Gisborne - Winter 1964 - Refer Diagram 1

Complaint:

Severely stained weather boards on coldest wall.

Investigation:

Ward temperature maintained at 23°C
Crawl space temperature 18°C
Outside temperature noon 9°C
Breather type building paper behind weatherboards saturated and foil vapour barrier on inside face of studs was correctly installed.

Cure:

Vapour barrier over ground in crawl space

Note:

Site was high on a hill and before vapour barrier was installed it was ascertained that ground moisture varied with rainfall.

2.3 House at Royal Oak - 1981 - Refer Diagram 1.

Note:

Coldest wall faced a wet ground slope and moisture seeped under concrete foundations.

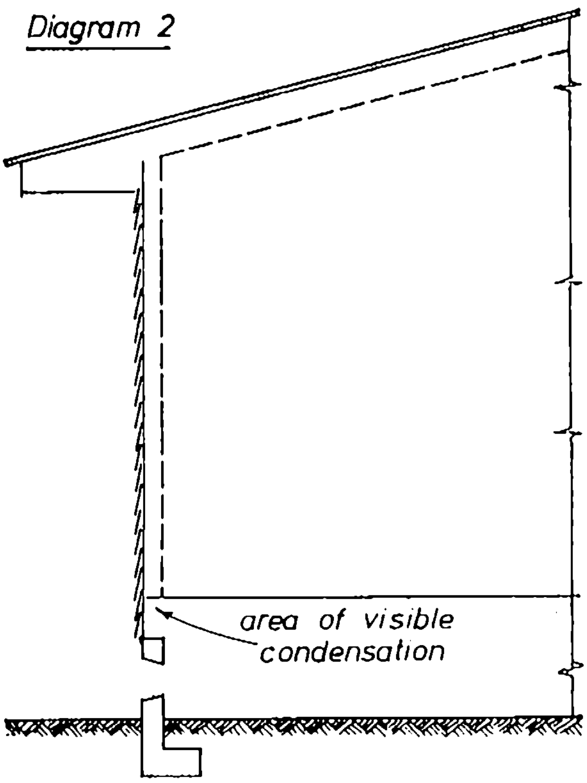
2.4 House at Mt. Eden - 1983 - Refer Diagram 1.

Note:

(a) Besides a wet slope feeding moisture under foundations, this older house had had a brick chimney removed, leaving an air cavity connecting crawl space with roof space, causing a spread of dampness through whole structure.

(b) Vapour barrier on ground had bonus affect of noticeably improving the health of a young family.

2.5 Timber Millers House - Rotorua - 1975 - Refer Diagram 2.



Complaint:

Visible moisture on surface of bottom wall plates.

Investigation:

Crawl space/basement with bare ground. On a fine day the moisture content of the basement air was over 30% higher than that of the outside air.

Cure:

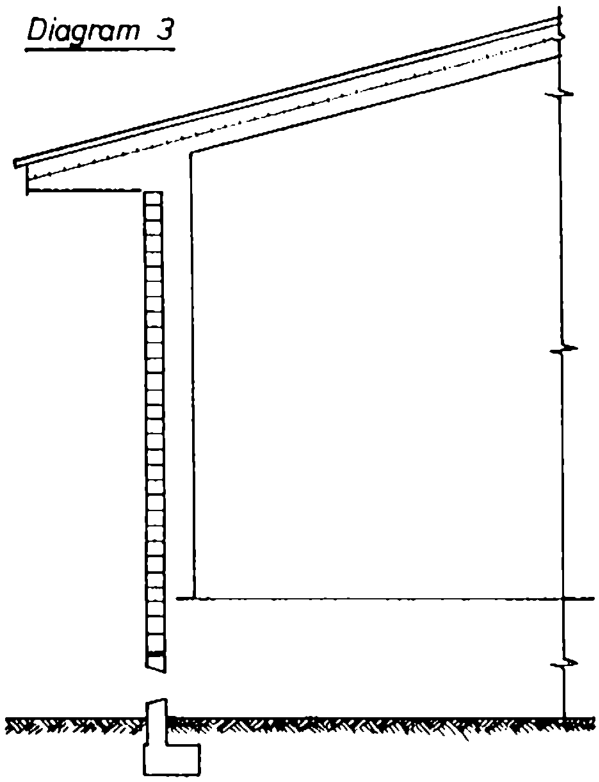
Vapour barrier on ground

Note:

(a) A bonus effect was the immediate elimination of severe condensation which had been forming on the inside of all windows.

(b) An unusual feature of this house was the lining of major rooms with strip timber which eased the infiltration of water vapour.

2.6 Riverside House - Hamilton - Refer Diagram 3.



Complaint:

Moisture stains on ceiling.

Investigation:

Damp site with air cavity behind brick veneer leading directly to small roof space under steel roof.

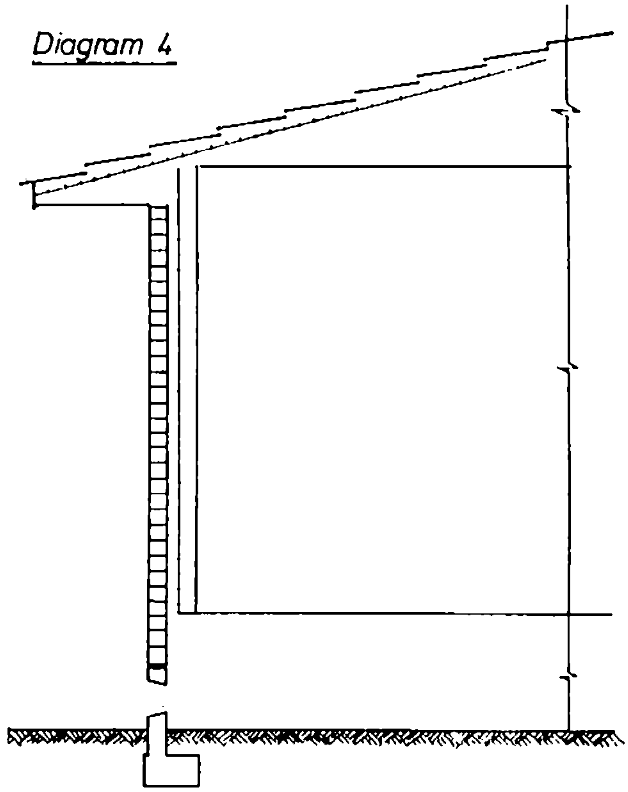
Dry joints or weep holes in bottom and top courses of bricks had been omitted.

Cure:

(a) Vapour barrier on ground
(b) Silicone treatment to brick surfaces to minimise moisture absorption.
(c) Ventilated ridging installed to assist drying out of roof space.

2.7 Large house in Kohimaramara - 1965 - wet clay sub soil - large areas of concrete paving all around house to minimise rain water soakage. Refer Diagram 4.

Diagram 4



Complaint:

(a) Corrosion of nails in strip timber flooring
(b) A section of flooring was "bouncey".

Investigation:

Masses of white mould growths on timbers under floors - visible moisture on bottom plates of exterior walls - moisture content of flooring excessive and swelling had caused lifting of joist off beares.

Cure:

Vapour barrier on ground.

Note:

Crawl space ventilation very restricted due to small numbers of foundation vents for a floor area of 200 square metres.

2.8
2.9 These two cases involved Spanish styled bungalows with concrete plastered walls on timber framework.

A cavity connects the crawl space to the roof space under a steel roof.

Severe condensation under the roofs had occured after storm water drainage had ceased to function, eventually causing excessive dampness in crawl spaces.

2.10 Papatoetoe house - An extra room with continuous foundations had been added on, but built over a disused and forgotten soak hole - dampness in roof space per brick veneer cavity.

2.11 Eastern Beach House - Plumber had forgotten to connect bath waste pipe - This resulted in damp roof space per wall cavity.

2.12 Paeroa House - A temporarily wet building site resulted in a rustic weatherboard bowing right out of position on cold wall.

A vapour barrier over the wet ground, plus small vents in timber sheathing to help drying out overcame this problem.

2.13
2.14
2.15 These cases in the late 1960's involved problems in roof spaces after the installation and operation of oil burning space heaters.

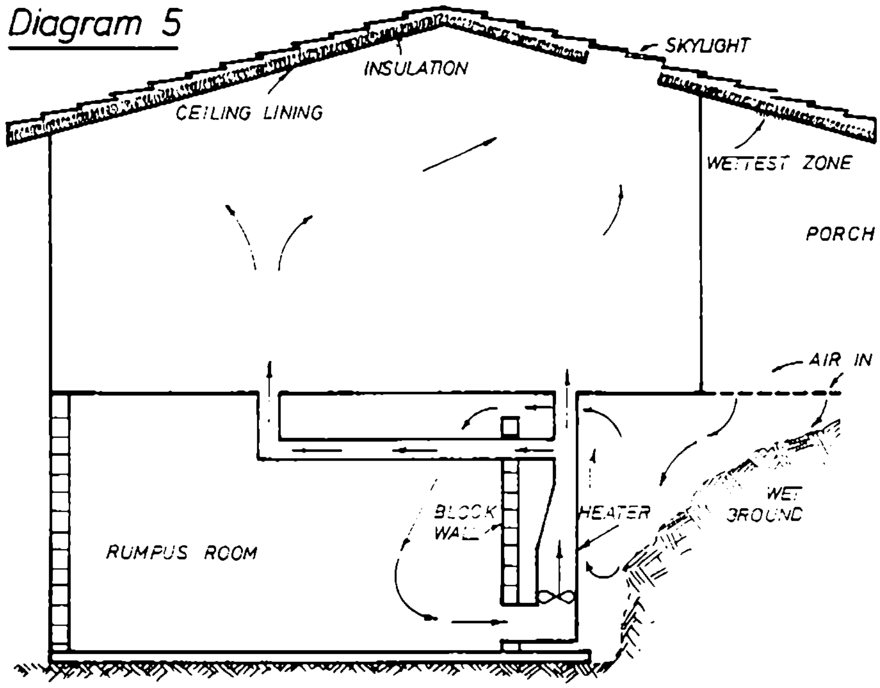
In two cases - Uninsulated hot air ducts caused increased evaporation of moisture from wet ground in the crawl spaces and ended up with damp roof spaces per wall cavity. Releif was result of vapour barrier placed on ground.

The other case is depicted in Diagram 5., where heated moist air was "pumped" into the structure and the ceiling/ roof insulation got wet.

Removal of roof and wet insulation - Fixing a vapour barrier over the ceiling with new insulation on top was one part of the cure.

A change of air source to the heater and covering wet ground were also recommended.

Diagram 5



2.16 2.17 Two cases of asbestos cement roofing with high moisture absorption.

When sun shines on wet roof water vapour is directed to cooler areas where it condenses.

One case was cured by a special surface treatment of the roof, while the other had the roof lifted and a vapour barriered insulation system installed with a roof underlay to minimise vapour movement.

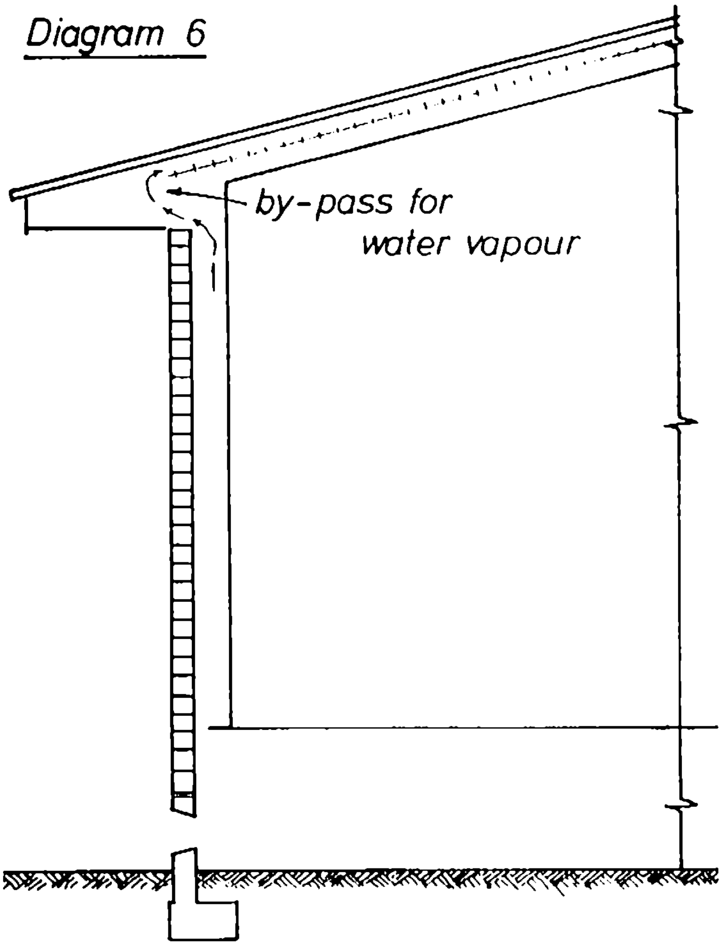
2.18 2.19 2.20 Before a minimum standard for thermal insulation became mandatory for residential buildings in 1978, it was common to use a reflective insulation membrane between roof and ceiling linings.

This membrane was placed in a weather lap format from eaves up to the ridge.

Some builders thinking it not necessary to insulate a roof line that overhung at the eaves, started the first run of foil in line with the outside wall.

This created a by-pass for water vapour and condenstion became a nuisance. Refer Diagram 6.

Diagram 6

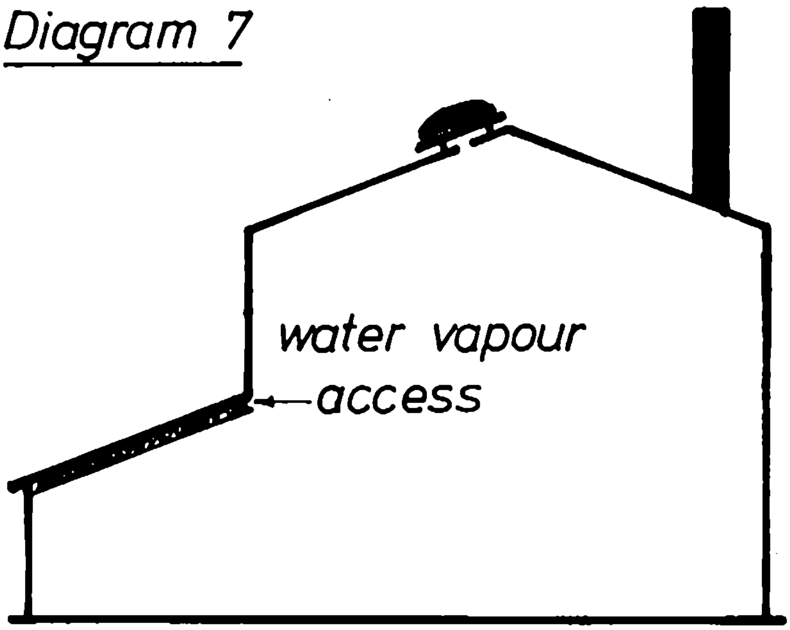


2.21 Sometimes a designer overlooks a potential moisture control problem.

A lean-to with an insulated roof was adjoining a paper manufacturing area.

Lack of design detail regarding the edge of the roof insulation allowed water vapour from the high humidity area to enter the fibreglass layer and saturate it in a matter of days. Refer Diagram 7.

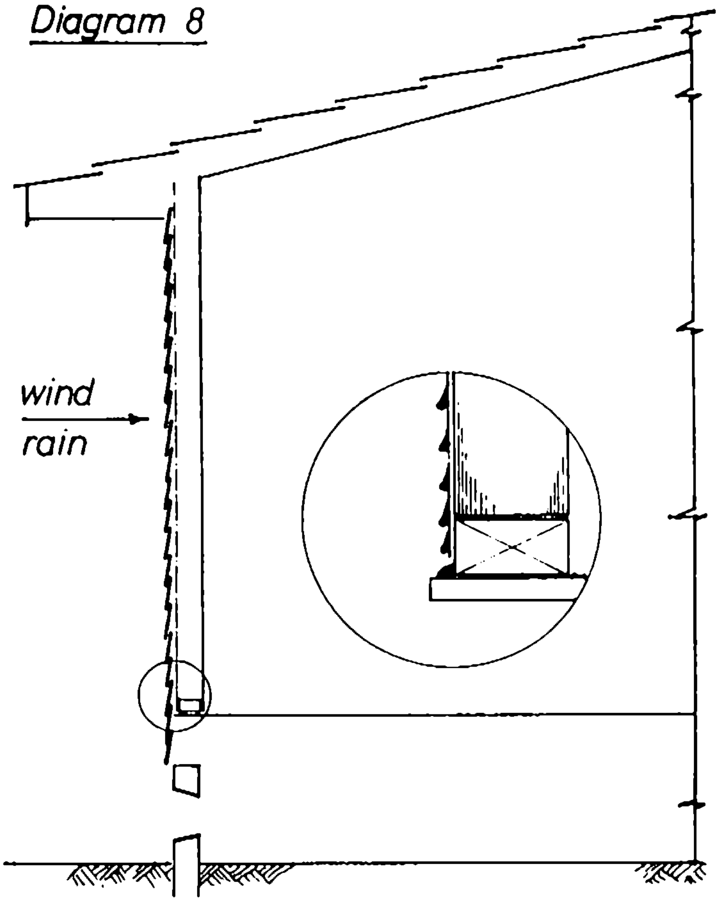
Diagram 7



2.22 A new house on an exposed site in Porirua suffered from water flowing across the floor during high wind and rain.

An investigation by the Building Research Association discovered that the building paper had not been placed as far down as the floor level and the flooring sheets protruded to form a ledge to catch wind blown water. (Refer Diagram 8).

Diagram 8



2.23 A well known Tauranga builder added a bedroom to his existing house which did not suffer from ground moisture problems.

The timber floor of the new room collapsed in one year because he had forgotten to put vents in the perimeter foundation wall.

2.24 An amateur added a room to his house in Avondale. Besides no underfloor ventilation, the site was very wet due to a subterranean flow from higher ground.

Walls and ceilings developed an ugly black mould.

2.25
2.26
2.27 One of six similar pensioner flats in Hastings had internal dampness problems due to occupant not understanding about window ventilation.

A change of ownership of a Timaru house proved that there was no building fault that had caused serious internal dampness and mould.

A Mt. Albert house had an exhaust fan directly over the cooking stove. The fan was not ducted to the outside and mouldy ceilings all over the dwelling resulted.

3. CONCLUSIONS:

3.1 Dry building sites in New Zealand are likely to contain not less than 250kg moisture per cubic metre.

Restricted ventilation causes this ground moisture to raise the water vapour pressure in the under-floor air space, which then becomes a ready source of water vapour to migrate to zones of lower water vapour pressure near cold cavity surfaces.

A ground cover vapour barrier should be specified whenever under floor ventilation is restricted.

3.2 Moisture absorbent claddings should be isolated from building cavities by a waterproof membrane. A ventilated air gap between the cladding and membrane is desirable, so as to avoid a rise of water vapour pressure in the gap.

3.3 Relevant sectors of the industry should contribute to the continuing education of builders regarding the placing and fixing of moisture control materials.

3.4 Likewise, it should be the responsibility of the industry as a whole to inform and educate home dwellers on the importance of interior ventilation in cold weather conditions and how to clear steam laden atmospheres without feeding them into building cavities or air spaces.

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PAPER 9

AIR LEAKAGE TESTS ON POLYETHYLENE MEMBRANE INSTALLED IN A WOOD FRAME WALL

C-Y. SHAW

Division of Building Research
National Research Council of Canada
Ottawa
Ontario
K1A 0R6
Canada

AIR LEAKAGE TESTS ON POLYETHYLENE MEMBRANE INSTALLED IN A WOOD FRAME WALL

by

C.Y. Shaw

ABSTRACT

This report presents the results of air leakage tests on polyethylene membranes installed in a frame wall. The results would be useful in evaluating the methods commonly used for installing such a component.

INTRODUCTION

A polyethylene membrane has been used extensively for improving airtightness and reducing problems of condensation in houses. There are no standards for the installation of such a component. The common practice is to install the polyethylene membrane in such a way that it envelops the house except for window and door openings. At a joint, the two sheets of polyethylene are overlapped, with the joint located over a solid wood backing, usually a stud. Staples are used to hold the polyethylene sheets together and in place. At windows and doors, a rough opening is made in the polyethylene and the edges are stapled to the surrounding wood frame.

Since the installer usually makes no attempt to seal the joints, a gap exists between the staples, especially when the polyethylene sheet is wrinkled. To reduce air leakage through the gaps, in some installations accoustic sealants and duct tape have been used to hold the sheets together. Also a 'spline system' is being investigated by CMHC for this purpose.

The Canada Mortgage and Housing Corporation asked the Division of Building Research to conduct air leakage tests on polyethylene membranes installed by these methods. The objective of the tests was to obtain the strength and air leakage characteristics of the joint between two sheets of polyethylene, as would occur in a wood frame wall, and between the polyethylene and the wood frame, as would occur around a window. The results would be useful in developing a standard test method for evaluating polyethylene membranes installed in a wood frame wall.

TEST APPARATUS

The test chamber was constructed with standard 38 by 89 mm wood studs. The test wall was 2.9 m wide by 2.3 m high. Pressure taps were installed at the interfaces of various wall components for measuring the pressure differences across the drywall, the polyethylene membrane and the wall assembly (Fig. 1). The pressures were measured using an electronic micromanometer with a resolution of 1 Pa and an accuracy within 1% of the measured value. The air flow rates were measured using a laminar flow element with an accuracy within 1% of the measured flow rate. The test chamber and the experimental set-up are shown in Fig. 1.

To measure the air leakage rate of the test chamber, the test wall was covered with a gypsum board sandwiched between two full sheets of polyethylene. Both the gypsum board and the polyethylene sheets were taped separately to the wood frame enclosing the test wall. The air leakage rate of the test chamber was measured several times before and during the experiment under both pressurization and depressurization conditions. The mean value of these measurements was used as the air leakage rate of the test chamber (Fig. 2). The net air leakage rate through the polyethylene membrane is

$$Q_{poly} = Q_m - Q_{ch} \tag{1}$$

where:

Q_{poly} = air leakage rate through polyethylene membrane, L/s,
Q_m = measured overall air leakage rate, L/s,
Q_{ch} = air leakage rate of test chamber, L/s.

RESULTS

The tests, conducted as shown in Table 1, were similar to those suggested by CMHC. For all tests, the polyethylene sheet was stapled to the studs at 305 mm centres. An accelerated weathering test was also conducted by the Building Materials Section of DBR on the sample of polyethylene used, to ensure that the material was in good condition.

Each air leakage test was conducted under both depressurization and pressurization conditions. A brief summary of the test results is also given in Table 1. The net air leakage rates through the polyethylene membrane were expressed as litres per second per unit length of crack (L/(s.m)). For the joint between two sheets of polyethylene, the length of crack was the length of the joint (2.3 m). For the window, it was the perimeter of the window frame (5.2 m). These air leakage rates were then plotted against the pressure difference across both the polyethylene sheet and the wall. These pressure differences are defined by the equation:

$$\Delta P_{wall} = \Delta P_{poly} + \Delta P_{sdg} \tag{2}$$

where:

ΔP_{wall} = pressure difference across wall, Pa,
ΔP_{poly} = pressure difference across polyethylene sheet, Pa,
ΔP_{sdg} = pressure difference across sheathing and siding, Pa.

<u>One full sheet of polyethylene, stapled to studs at 305 mm centres</u>

Test 1a: 4 mil, stapled, depressurization

The objective of the test was to measure the air leakage rate through a polyethylene membrane with no joint. The air leakage rate was too small to measure, even though numerous holes were punched in the polyethylene sheet by the staples. As shown in Fig. 3, depressurization helped to seal the holes by pressing the polyethylene sheet tightly against the wood frame. No permanent tear in the polyethylene sheet around the holes was observed at a pressure difference across the polyethylene of 781 Pa, the maximum pressure differential that could be obtained for this test.

Test 1b: as Test 1a, pressurization

Unlike conditions in the previous test, pressurization helped to expose the holes by pushing the polyethylene sheet away from the wood frame (Fig. 4a). Figure 4b shows the measured air leakage rates through the holes. Permanent tearing at the staples was observed when the pressure difference across the polyethylene reached 55 Pa, but the change in the leakage opening was too small to affect the air leakage characteristic.

Two sheets of polyethylene, overlapped and stapled

Test 2a: 4 mil, 40 mm overlap, depressurization

The air leakage rate increased with the pressure difference across the polyethylene (Fig. 5). After the pressure difference reached 140 Pa, it started to decrease as the air leakage rate continued to increase. The change occurred when the polyethylene was ripped at the staples. The maximum pressure difference that could be applied to the polyethylene membrane without tearing it was about 140 Pa.

Test 2b: as Test 2a, pressurization

Figure 6 shows that the air leakage rate increased continuously with the pressure differential. The maximum pressure difference across the polyethylene reached under pressurization conditions was about 14 Pa, because the gap between the staples was fully open when the polyethylene was pushed away from the wood frame under pressurization

Test 3: 6 mil, 40 mm overlap

Tests 2a and 2b were repeated with 6 mil polyethylene sheets. Figure 7 shows the air leakage characteristic of the 6 mil polyethylene under depressurization conditions. A comparison of the results between Test 3 (6 mil) and Test 2 (4 mil), indicates that the air leakage characteristic of the two polyethylene sheets was similar. The maximum pressure differential the 6 mil polyethylene could resist was about 160 Pa. The pressurization test led to a similar conclusion. All subsequent tests were conducted on 4 mil polyethylene sheets only.

Test 4: as Test 2a, gypsum board, depressurization

The objective of the test was to determine the effect of gypsum board on the air leakage characteristic of the polyethylene membrane. The air leakage through the polyethylene-gypsum board combination was too small to measure for pressure differences across the polyethylene up to 865 Pa. As Fig. 8 shows, the polyethylene sheet was under stress but was held firmly on the stud. This suggests that the gypsum board helped to hold the polyethylene sheets together and in place. A pressurization test was not conducted.

Test 5: as Test 2a, reinforced at staples, depressurization

Test 2a indicated that the weakest point of the polyethylene was at the staples. To overcome this problem, a piece of duct tape was placed on the polyethylene before it was stapled to the wood frame. The measured air leakage rates (Fig. 9a) increased continuously with the pressure differential for a pressure difference as high as 700 Pa. This kind of treatment for improving the strength of polyethylene locally works well to prevent it from tearing around the holes (Fig.9b).

A pressurization test was also conducted. The pressure difference across the polyethylene was too small to measure because pressurization helped to open the gaps between the staples.

Test 6a: 4 mil, 400 mm overlap, depressurization

This configuration was similar to that of Test 2a except that the two sheets of polyethylene were overlapped by 400 mm. The wider overlap permitted the joint to be stapled to two studs, instead of one as in the case of Test 2a. Figure 10a shows the measured air leakage rates. The air leakage characteristics were similar to those in Test 2a, but the air leakage rate through the 400 mm joint was smaller than that through the 40 mm one. Permanent tearing appeared at the holes, but the polyethylene sheets were held together and in place firmly by the two columns of staples (Fig. 10b).

Test 6b: as Test 6a, pressurization

The air leakage characteristic, as shown in Fig. 11, was different from that for a 40 mm joint (Fig. 6), because the flow resistance in the 400 mm joint was greater than that in the 40 mm one. Consequently, the air leakage rate through the wider joint was smaller than that through the narrower one.

Test 7a: 4 mil, spline method, depressurization

The spline method was developed to eliminate the air leakage through the joint between two sheets of polyethylene. Figure 12a shows that the measured air leakage rates were much greater than that for a full sheet of polyethylene with no joints (Test 1a). There was no air leakage through the joint, but some air leakage was found at locations where two joints met (e.g., corners, see Fig. 12b).

Test 7b: as Test 7a, pressurization

Figure 13 shows the measured air leakage rates. Again, the air leakage of this installation was greater than that of a full sheet of polyethylene for the same pressure differential (Test 1b).

Test 8: 4 mil, 40 mm overlap, taped

Figure 14a shows the measured air leakage rates under the depressurization condition. The tape worked well under depressurization, but did not reduce the air leakage to zero as expected. Under pressurization, however, the tape failed to hold the polyethylene sheets together (Fig. 14b).

Test 9: 4 mil, 40 mm overlap, caulked and covered with gypsum board

The test could only be conducted when the joint was covered by gypsum board because the non-drying caulking component failed to hold the two sheets of polyethylene together under pressure. Figures 15 and 16a show the measured air leakage rates under depressurization and pressurization conditions, respectively. Surprisingly, the air leakage rate through the caulked joint was greater than that through the uncaulked one (Test 4). The contacting surface between the polyethylene and the caulking component was not smooth (Fig. 16b). This suggests that instead of sealing the joint, in some cases the use of caulking component can produce the opposite result by preventing the gypsum board from pressing the polyethylene sheets tightly against the wood frame.

<u>Window frame</u>

Test 10: 4 mil, stapled

Figure 17a shows the air leakage characteristic for the window frame under depressurization conditions. The pressure difference across the polyethylene was not detectable at low air leakage rates. When the air leakage rate reached about 0.42 L/(s.m), there was an abrupt change in the air leakage characteristic. As shown in Fig. 17b, the polyethylene was stapled to both the window frame and the wall frame around it. At low air leakage rates, the polyethylene sheet was loosely covering the frames. This permitted the air to move freely through the gap between the polyethylene and the frames. When the leakage rate reached 0.42 L/(s.m), the polyethylene was pulled tightly against the wall frame. As a result, the flow resistance in the gaps was significantly increased which, in turn, caused a decrease in the air leakage rate.

A pressurization test was also conducted on the window. The pressure difference across the polyethylene was not detectable because the gap between the staples was fully open under pressurization.

Test 11: as Test 10, gypsum board

In this test, the polyethylene sheet stapled to the wall frame was covered by gypsum board, but that stapled to the window frame remained uncovered (Fig. 18a). Figure 18b shows the air leakage characteristic for the window under depressurization conditions. Unlike results from the previous test, the pressure difference across the polyethylene at low air leakage rates was measurable, because the gaps between the polyethylene and the wall frame were closed when the polyethylene sheet was covered with gypsum board. Similar to the previous test, an abrupt change in the air leakage characteristic was observed, when the edges of the polyethylene sheet were pulled towards the wall.

The results of a pressurization test (Fig. 19) however, did not indicate a similar change in the air leakage characteristic. This is because the amount of pressurization imposed was too small to cause such a change.

SUMMARY

The results could be summarized as follows:

1. A 6 mil polyethylene membrane was stiffer than a 4 mil membrane and had a greater air leakage rate through the joint.
2. The best method for installing a wall joint was to have the two sheets of polyethylene overlapped by about 400 mm, with the edges stapled to two vertical studs.
3. The spline system was too difficult to apply, especially at the corners.
4. Taping and caulking the joint did not produce an air-tight joint.
5. New technique is needed to fasten the edges of the polyethylene sheet to the window frame and hold the edges in place.

ACKNOWLEDGMENTS

This work was undertaken by the Division of Building Research under a request of the Canada Mortgage and Housing Corporation. The author wishes to acknowledge the cooperative effort of both organizations in supporting this project. The author also wishes to thank R.L. Quirouette, K.R. Solvason, R.P. Bowen and W.C. Brown for designing the test chamber and for their continuous interest in this project; G.F. Poirier for constructing the test chamber and M.O. Pelletier for conducting the tests and taking the photographs.

TABLE 1 Test Conditions and Results

Test No.	Test Conditions		Air Leakage Rates, L/(s.m) ΔP_{poly} = 50 Pa	ΔP_{poly}[2] = 100 Pa	Remarks
1a	One full sheet, 4 mil, stapled	S[1]	0.0	0.0	Air leakage too small to measure
1b	as Test 1[3]	P[1]	0.2	2.5[4]	Fig. 4b
2a	Two sheets, 4 mil, 40 mm overlap	S	0.15	0.3	Fig. 5
2b	as Test 2a	P	1.8[4]	2.4[4]	Fig. 6
3	Two sheets, 6 mil, 40 mm overlap	S	0.44	0.47	Fig. 7
4	as Test 2a, gypsum board	S	0.0	0.0	Air leakage too small to measure
5	as Test 2a, reinforced at staples	S	0.2	0.21	Fig. 9a
6a	Two sheets, 4 mil, 400 mm overlap	S	0.014	0.02	Fig. 10a
6b	as Test 6a	P	1.1	-	Fig. 11
7a	Two sheets, 4 mil, spline method	S	0.13	0.2	Fig. 12a
7b	as Test 7a	P	0.32	4.0	Fig. 13
8	Two sheets, 4 mil, 40 mm overlap, taped	S	0.05	0.07	Fig. 14a
9a	Two sheets, 4 mil, 40 mm overlap, caulked, gypsum board	S	0.04	0.06	Fig. 15
9b	as Test 9a	P	0.07	-	Fig. 16a
10	Window test, 4 mil, stapled	S	Fig. 17a		ΔP_{poly} too small to measure
11a	as Test 10, gypsum board	S	Fig. 18b		Air leakage characteristic changed
11b	as Test 11a	P	Fig. 19		

[1]S, depressurization (suction) test; P, pressurization test.
[2]ΔP_{poly}, pressure difference across polyethylene sheet.
[3]To facilitate comparison, value listed is net air leakage rate through polyethylene membrane divided by height of test wall.
[4]Extrapolated.

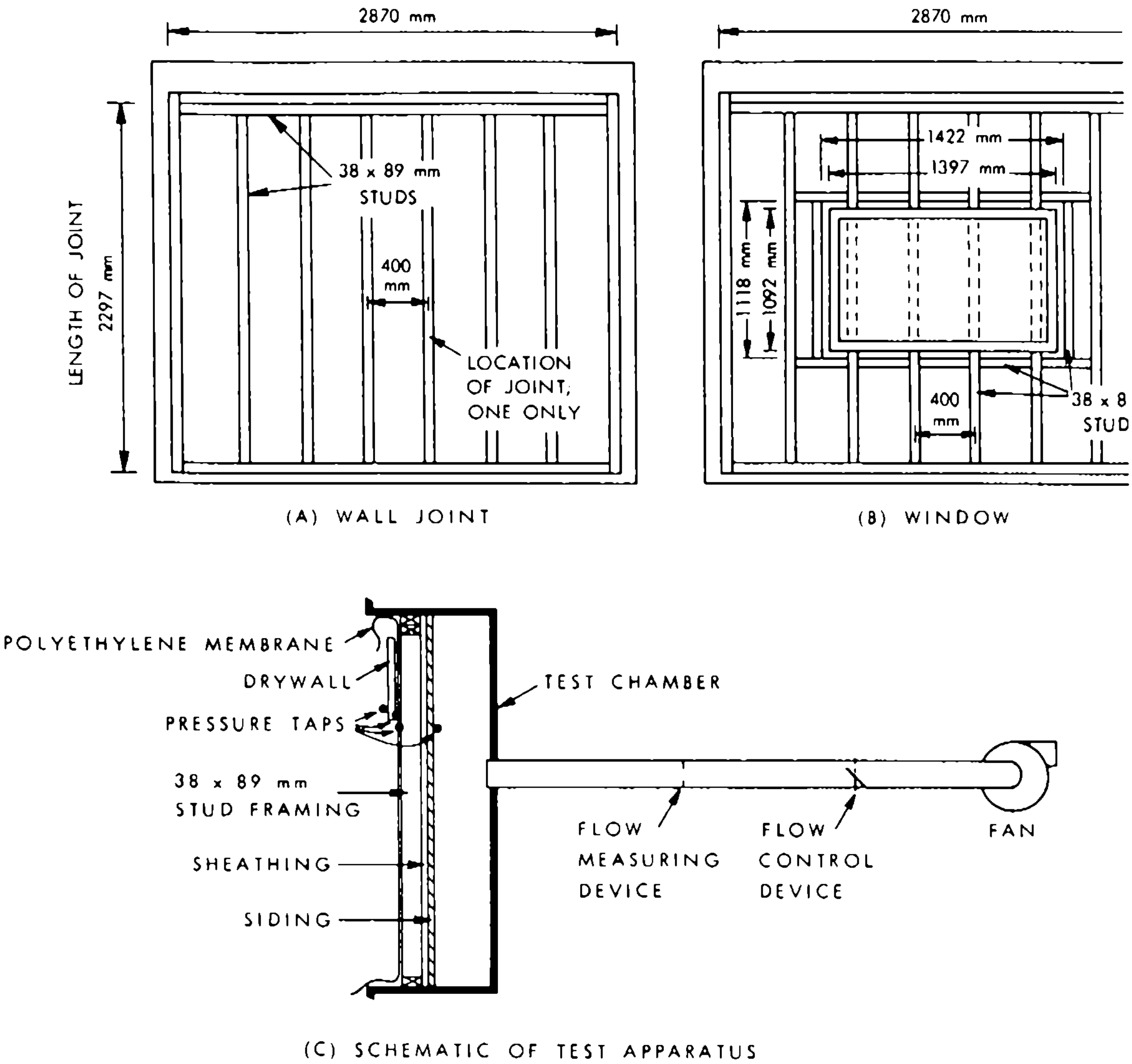

FIGURE 1

TEST CHAMBER AND EXPERIMENTAL SET-UP

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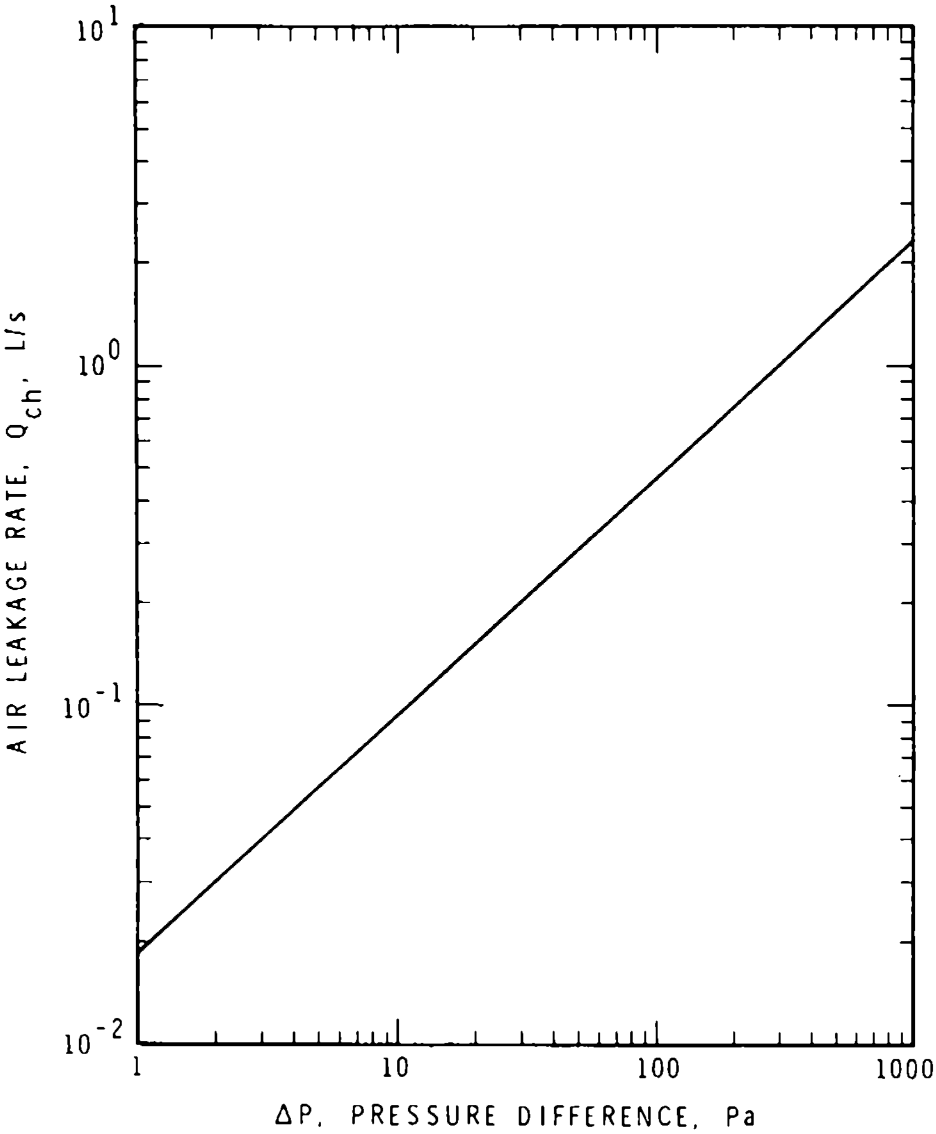

FIGURE 2

AIR LEAKAGE RATE OF TEST CHAMBER

BR 6621-2

FIGURE 3

DEPRESSURIZATION TEST

FIGURE 4a

PRESSURIZATION TEST

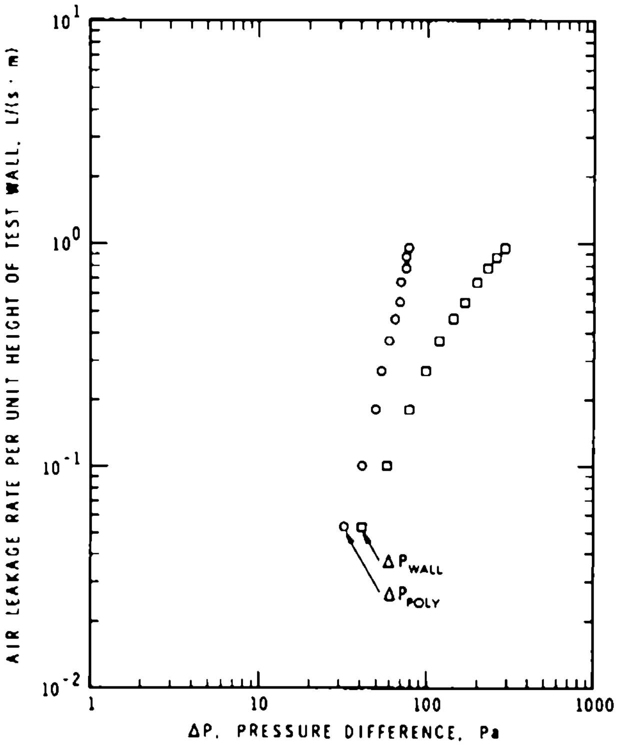

FIGURE 4b

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 1b, PRESSURIZATION, 4 mil, FULL SHEET STAPLED

BR 6621-3

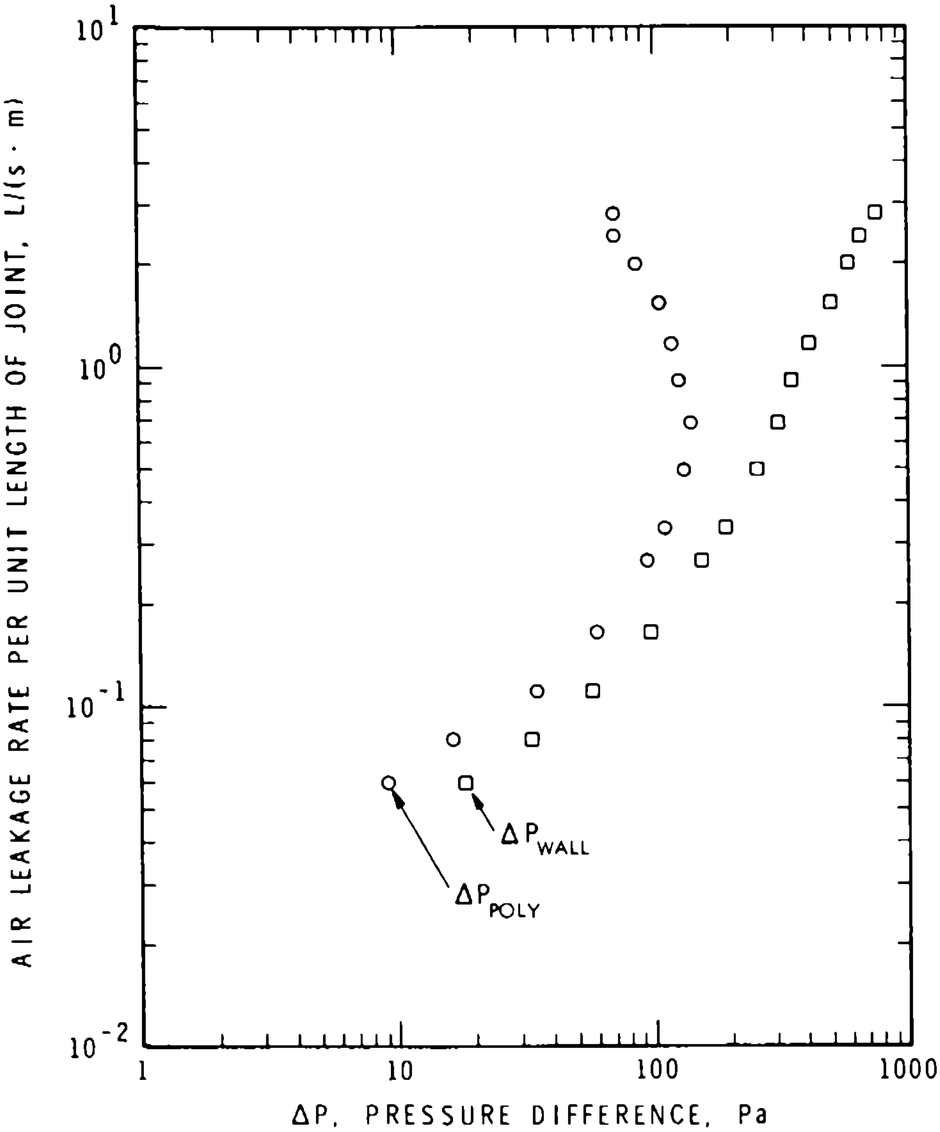

FIGURE 5

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE. TEST 2a, DEPRESSURIZATION, 4 mil, 40 mm OVERLAP

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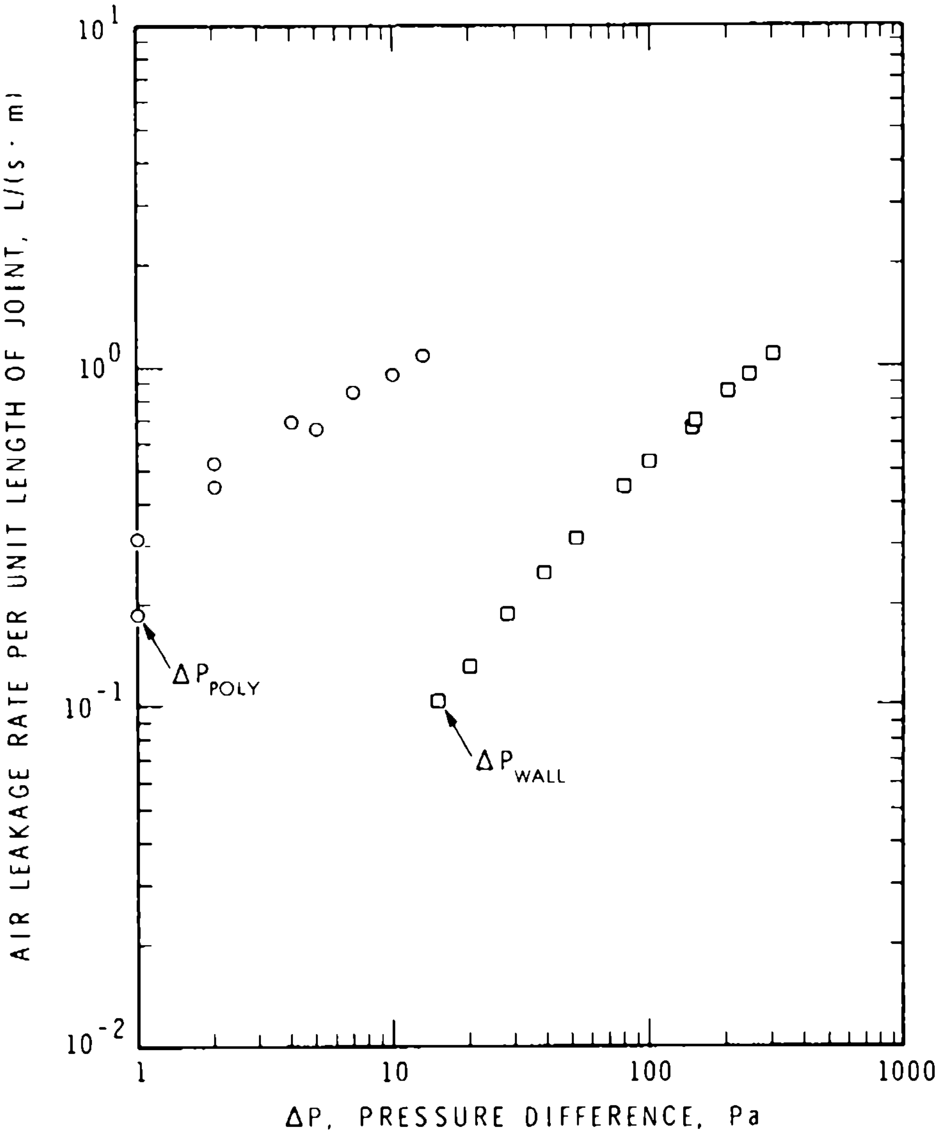

FIGURE 6

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 2b, PRESSURIZATION, 4 mil, 40 mm OVERLAP

BR 6621-5

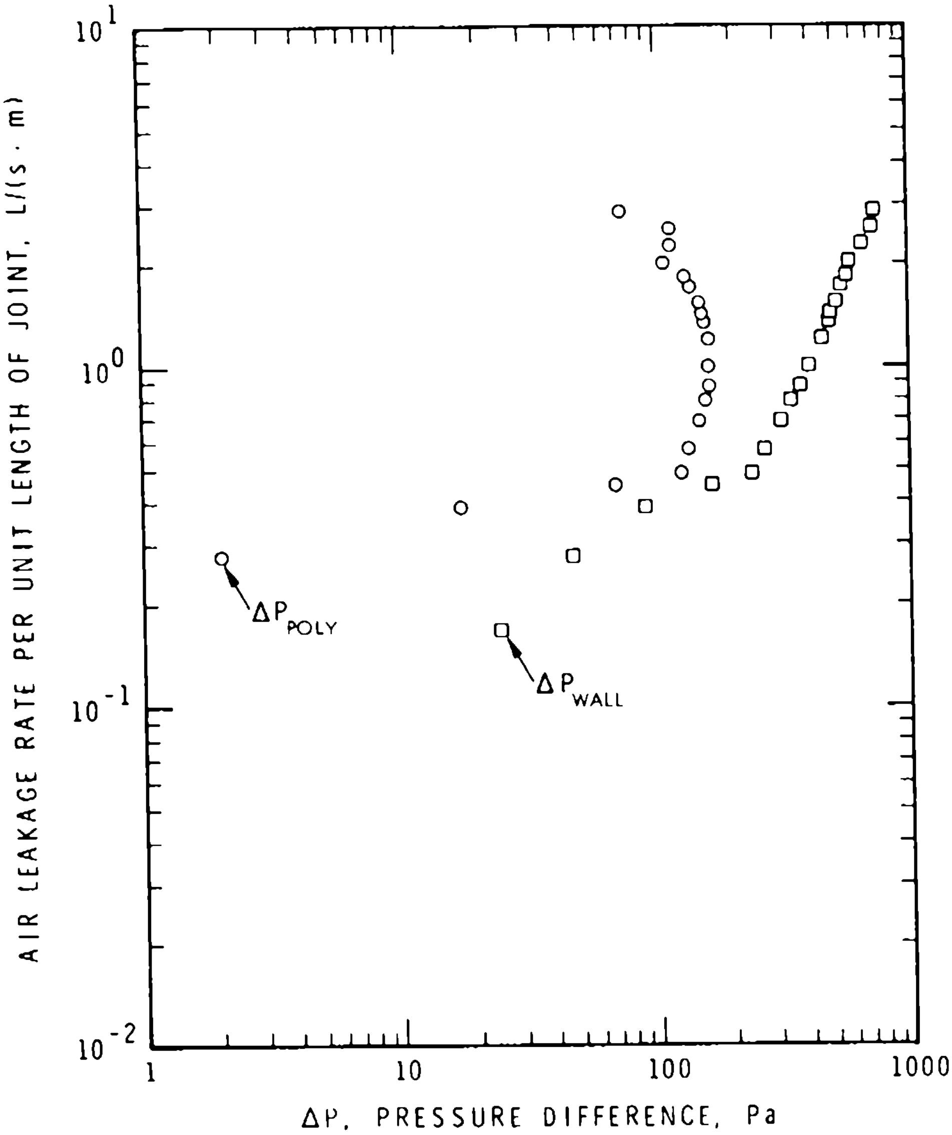

FIGURE 7

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 3, DEPRESSURIZATION, 6 mil, 40 mm OVERLAP

BR 6621-6

FIGURE 8

CONDITION OF POLYETHYLENE AFTER GYPSUM BOARDS REMOVED (ΔP_{POLY} = 865 Pa)

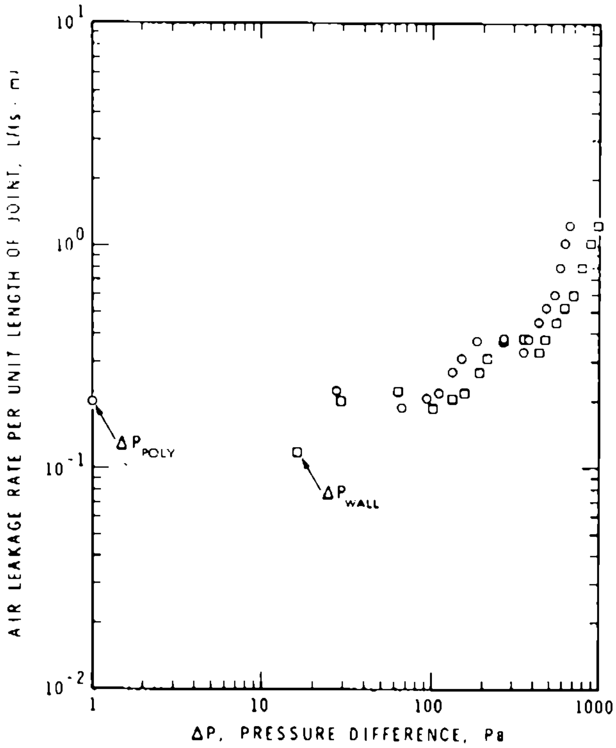

FIGURE 9a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 5, DEPRESSURIZATION, 4 mil, 40 mm OVERLAP,
REINFORCED AT STAPLES (JOINT ONLY)

BR 6621-7

FIGURE 9b

REINFORCED POLYETHYLENE UNDER DEPRESSURIZATION

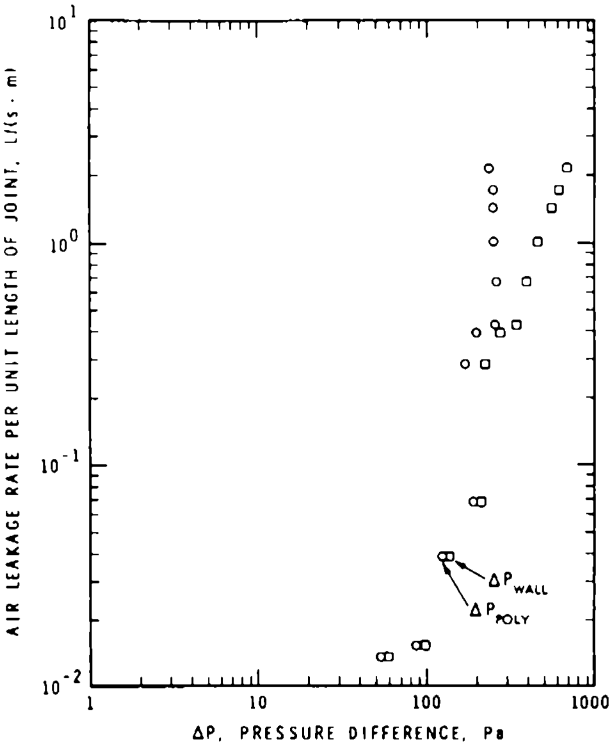

FIGURE 10 a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE. TEST 6a, DEPRESSURIZATION, 4 mil, 400 mm OVERLAP

BR 6621-8

FIGURE 10b

CONDITION OF 400 mm WIDE JOINT UNDER DEPRESSURIZATION

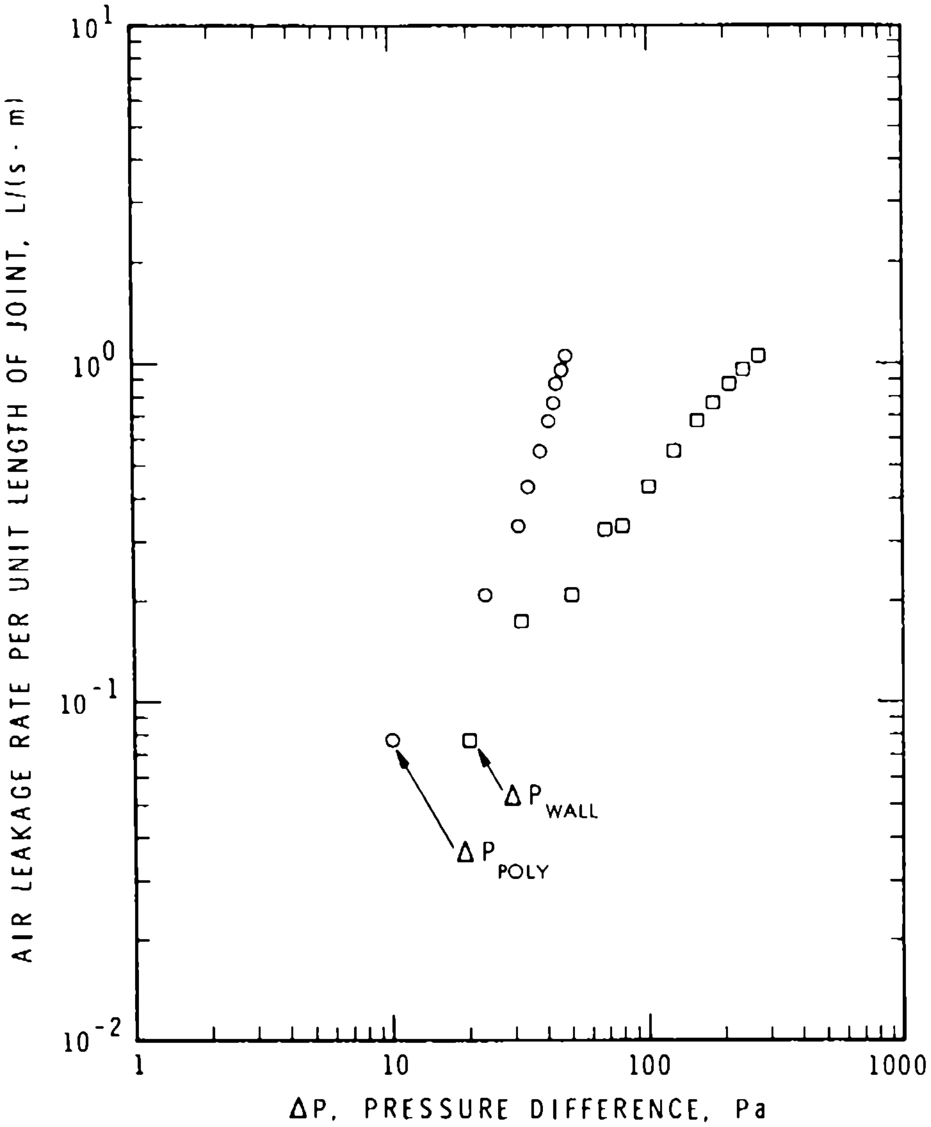

FIGURE 11

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 6b, PRESSURIZATION, 4 mil, 400 mm OVERLAP

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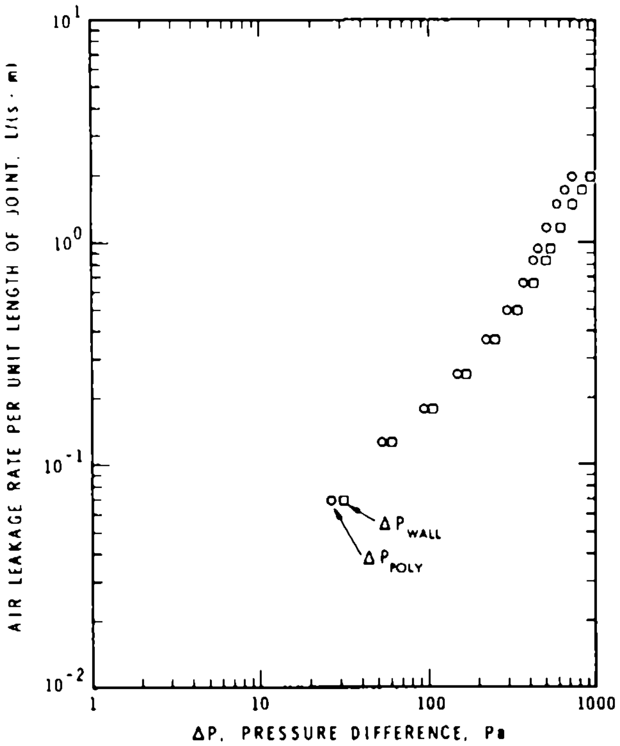

FIGURE 12a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 7a, DEPRESSURIZATION, 4 mil, SPLINE METHOD

BR 4671-10

FIGURE 12b

SOAP BUBBLE TEST SHOWING THE AIR LEAKAGE SOURCE, SPLINE METHOD

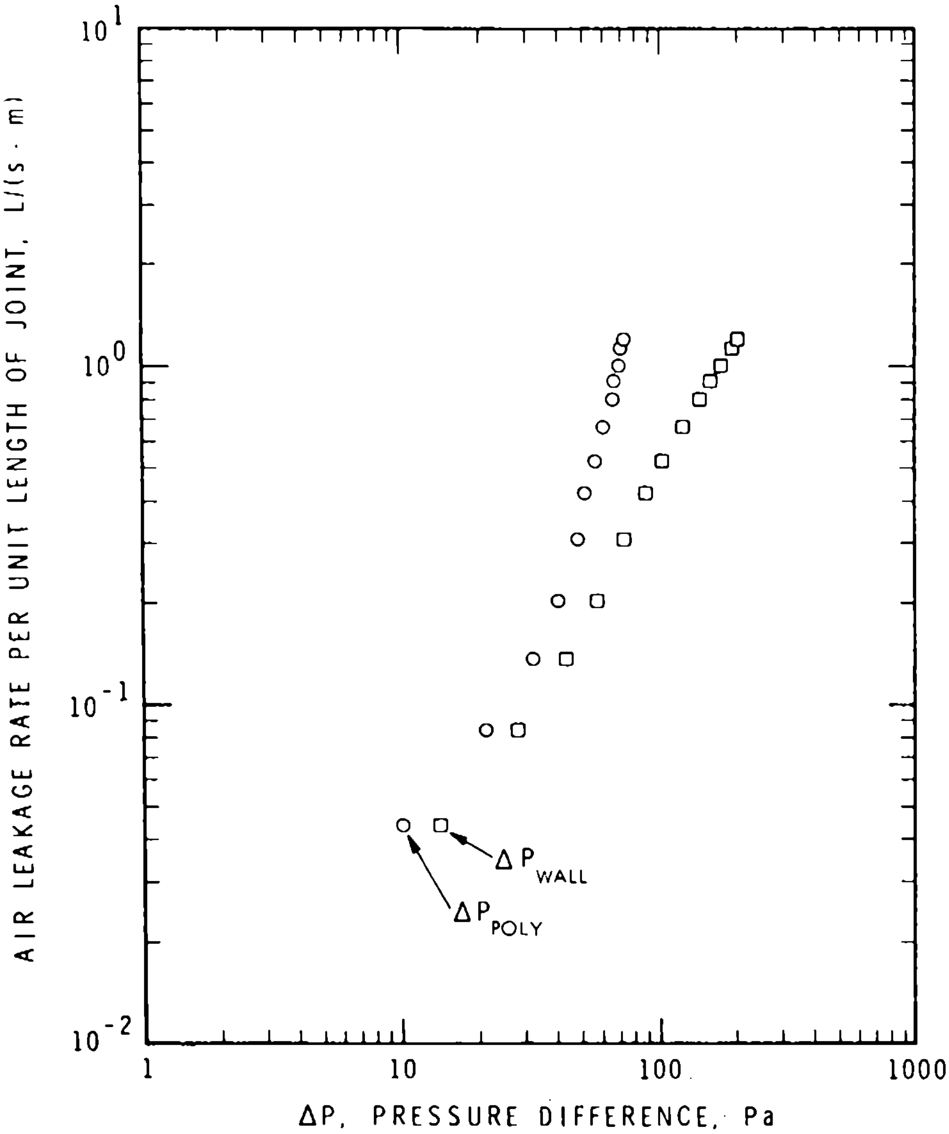

FIGURE 13

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 7b, PRESSURIZATION, 4 mil, SPLINE METHOD

BR 6621-11

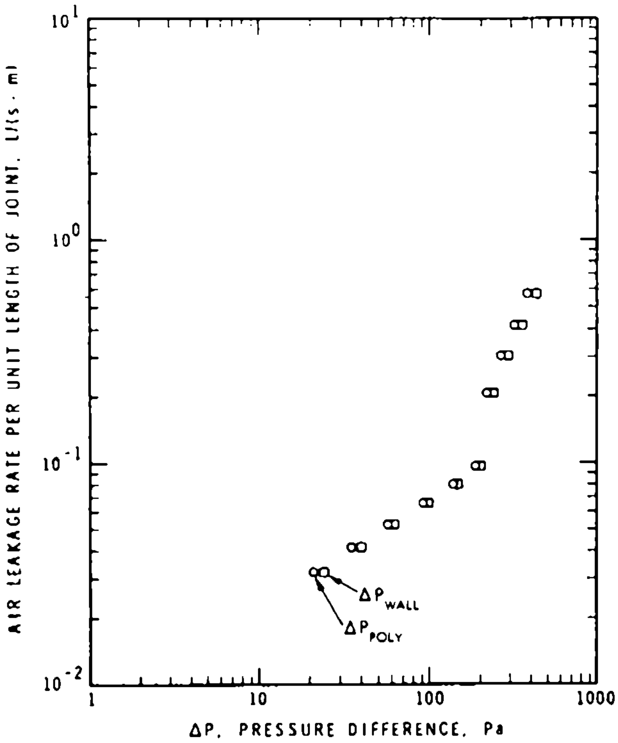

FIGURE 14a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE
TEST 8, DEPRESSURIZATION, 4 mil, 40 mm OVERLAP
(TAPED JOINT)

BR 6621-12

FIGURE 14b

CONDITION OF TAPED JOINT UNDER PRESSURIZATION

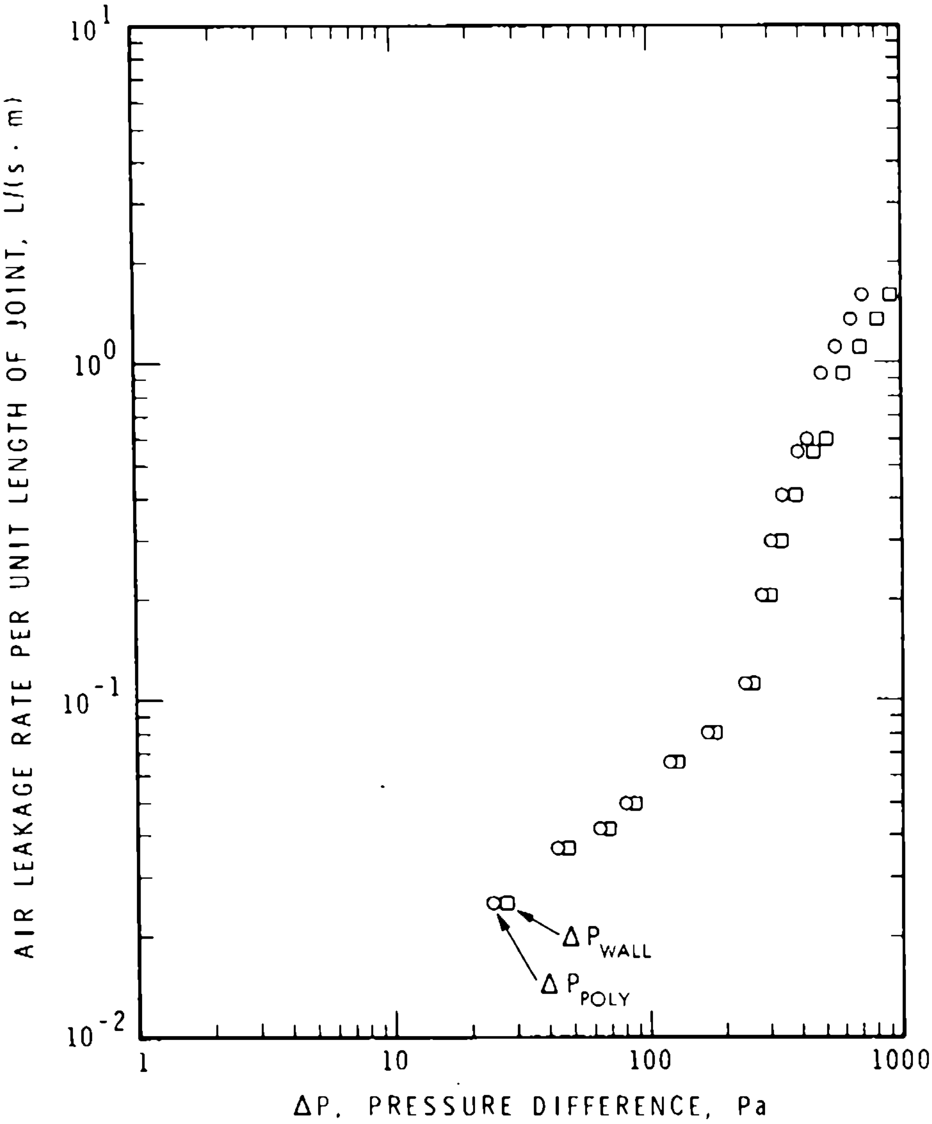

FIGURE 15

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE. TEST 9a, DEPRESSURIZATION, 4 mil, 40 mm OVERLAP (CAULKED JOINT), COVERED WITH GYPSUM BOARD

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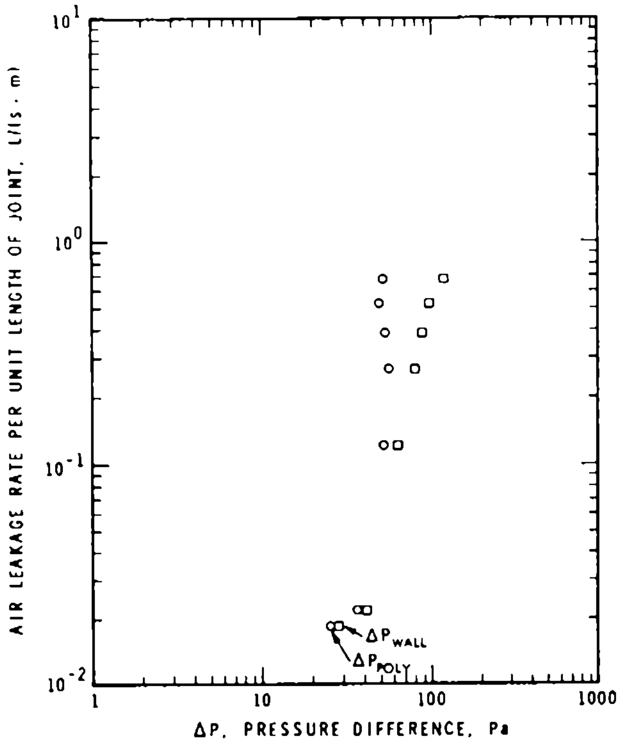

FIGURE 16 a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 9b, PRESSURIZATION, 4 mil, 40 mm OVERLAP
(CAULKED JOINT), COVERED WITH GYPSUM BOARD

BR 6621-14

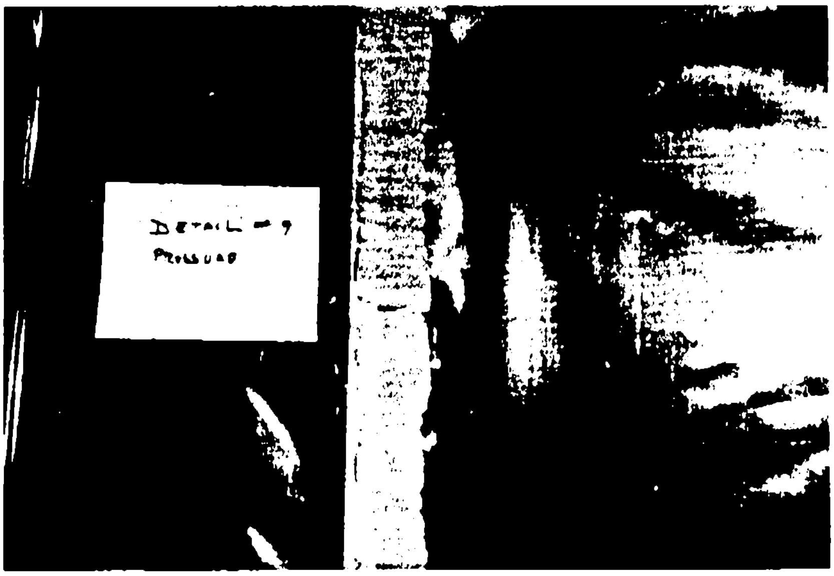

FIGURE 16b

CONDITION OF CAULKED JOINT AFTER
GYPSUM BOARDS REMOVED

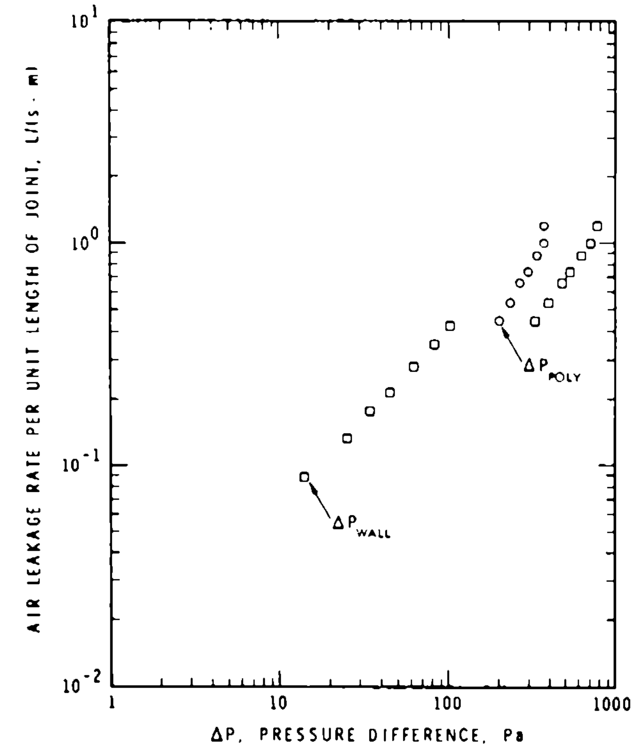

FIGURE 17a

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 10, DEPRESSURIZATION, WINDOW TEST,
STAPLES ON STUD AND FRAME

BR 6621-15

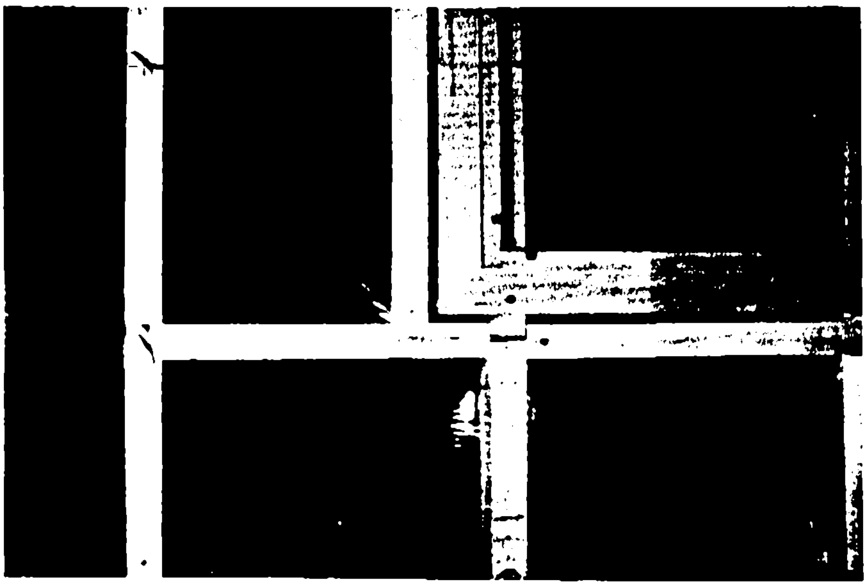

FIGURE 17b

CONDITION OF POLYETHYLENE AROUND WINDOW UNDER DEPRESSURIZATION

FIGURE 18a

INSTALLATION OF GYPSUM BOARD AROUND WINDOW

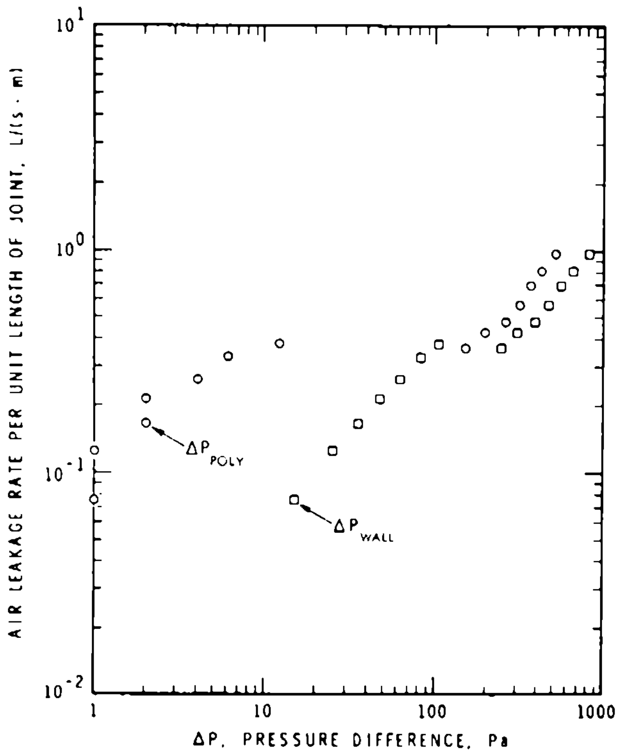

FIGURE 18b

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 11a, DEPRESSURIZATION, WINDOW TEST,
WINDOW PERIMETER COVERED WITH GYPSUM BOARD

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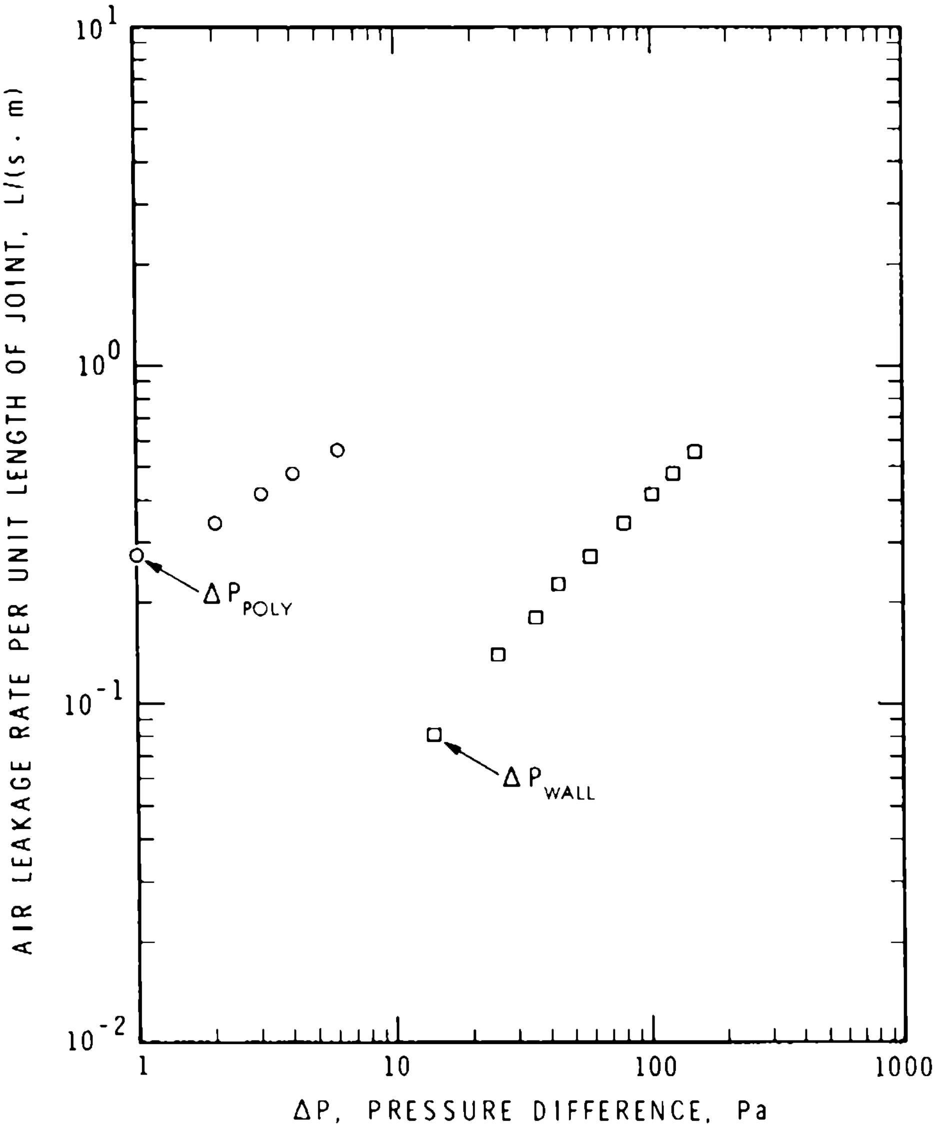


FIGURE 19

AIR LEAKAGE RATE VS PRESSURE DIFFERENCE.
TEST 11b, PRESSURIZATION, WINDOW TEST,
WINDOW PERIMETER COVERED WITH GYPSUM BOARD

BR 6621 17

AIR INFILTRATION AND VENTILATION CENTRE
MOISTURE WORKSHOP 1987

Building Research Association of New Zealand (BRANZ)
23rd March 1987

PAPER 10

VENTILATION TO REDUCE INDOOR CONDENSATION

ROBERT C. BISHOP

Building Research Association of New Zealand
Private Bag
Porirua
New Zealand

SYNOPSIS

Condensation causing mould and mildew is a common problem in New Zealand buildings. A reasonably balanced combination of air exchange and heating will prevent condensation. The relationships between these are presented graphically, showing the combinations which will prevent condensation under given ambient conditions. Finally, the amounts of natural ventilation available with various window openings and windspeeds are presented, as a means to achieve the required ventilation rate.

INTRODUCTION

Condensation, mould, and mildew growth arise when building occupants release moisture into the air (in particular from cooking and washing) which raises indoor relative humidity. These problems are longstanding in New Zealand, often causing significant damage to room surfaces.

Indoor humidity can usually be reduced by air exchange with outdoors. But as houses built in New Zealand since the 1960's are more airtight than older ones (typical infiltration rates are on the order of ½ air change per hour)[1] there are now increasing chances of harmful levels of moisture in houses.

These conditions imply that air exchange is often necessary in modern houses to reduce the concentrations of moisture, to avoid adverse effects. Under some conditions, infiltration is enough to avoid these effects, but the potential for ventilation must be considered to ensure this.

Correctly visualising the relationships between heating and air exchange in reducing condensation, and understanding the potential for natural ventilation by means of opening windows should help both designers and homeowners avoid humidity problems.

REQUIREMENTS FOR CONDENSATION

Moisture is generated in buildings from human respiration, as well as from cooking and washing, as outlined below[2,3] in Table 1. This moisture usually takes the form of water vapour in air, which serves to raise the indoor absolute humidity. Condensation occurs when air of a given humidity cools to its dewpoint.

TABLE 1 - SOURCES AND AMOUNTS OF MOISTURE GENERATION IN HOUSES

Source	Amount of moisture generated	
	Average (kg/day)	Peak (g/sec)
Clothes drying, unvented	12.0	1.50
Clothes washing	2.0	0.15
Cooking, unvented	2.2	0.30
Showers, each	0.2	1.50
Dishwashing	0.5	0.25
Human metabolism, at rest	0.1	0.004
Human metabolism, hard work	0.3	0.01

Thus, a requirement for surface condensation is that a surface be at or below the dew point temperature of the room air. Given a knowledge of this dewpoint temperature, the condensation risk can easily be determined by the "temperature index"[4] of the surfaces, and the indoor and outdoor temperatures.

The temperature index is defined as a ratio of thermal resistances: of the outside-air to inside-surface divided by that of the outside-air to inside-air. This ratio is between zero and one, approaching one when the surface is well insulated (low condensation risk), and approaching zero when the surface is poorly insulated (high condensation risk).

Thus $T_{surface} = T_{out} + (\text{Temperature Index}) \times (T_{in} - T_{out})$

where $\text{Temperature Index} = \dfrac{R\ (\text{surface to outside air})}{R\ (\text{indoor air to outside air})}$

Temperature indices were calculated for various building components, using their "handbook" values for thermal resistances.

The surface thermal resistances used in this calculation were varied to span the range of values for different conditions and yield a more general result than simply using the "handbook" values throughout.

Thus, three thermal resistances were used for both the inside and outside surfaces, including handbook values of 0.12 and 0.03, respectively.[5] Also typical high and low values of 0.18 and 0.09 (inside) and 0.10 and 0.01 (outside)[6] were included in the set of calculations. The inside surface temperature index was calculated for all nine possible combinations, and the mean and standard deviation of these results computed and reported in Table 2.

TABLE 2 - CALCULATED TEMPERATURE INDICES FOR BUILDING SURFACES

6 mm thick Single glazing	.26 ± .16
R - 1.5 insulated wall	.92 ± .02
R - 1.5 insulated wall at corner	.78 ± .05
R - 0.9 uninsulated cavity wall	.88 ± .03
R - 0.9 insulated wall at corner	.71 ± .06

The assumptions built into the temperature index calculation at the corners are that the indoor air film there has a thermal resistance value of R = 0.36, three times that of a normal indoor vertical surface, corresponding to a dead air pocket about 1 cm thick.[7]

The importance of this is that the temperature indices of room surfaces determine the conditions under which condensation will occur in a room, and the lower indices common to corners mean that condensation occurs there before it does on plane walls.

CONDENSATION CONDITIONS IN BUILDINGS

The relationship between the amounts of heating and air exchange needed to prevent condensation on room surfaces were calculated as follows:

For a given indoor moisture release rate, air change rate, and outdoor air temperature (assuming saturation humidity), the steady state indoor absolute humidity is calculated, using the formula:

$$W\ in\ (kg/kg) = W\ sat\ (T\ out) + \frac{\text{moisture release rate (kg/day)}}{24 * p * V * ACH \quad (kg/day)}$$

where:

W in	-	indoor absolute humidity (kg/kg)
W out	-	outdoor saturation absolute humidity (kg/kg)
p	-	air density (kg/cubic meter)
V	-	House volume (cubic meters/air change)
ACH	-	air change rate (air changes/hour)

This absolute humidity is converted to a dew point temperature, which is the temperature that the building surfaces must be kept warmer than to prevent condensation. Then knowing the temperature indices for each surface, the minimum room air temperature to prevent condensation is calculated from:

$$T\ room = T\ out + \frac{(T\ surface - T\ out)}{(Temperature\ Index)}$$

Then the heat requirement is found directly from the indoor and outdoor air temperatures and the building heat loss coefficient.

This calculation was performed for two houses, one insulated to New Zealand standard 4218P (a typical new house) and a totally uninsulated house (a typical "old" house). The moisture release rate chosen was 8 kg/day (typical for a family with washing and cooking but no unvented clothes drying), and the outside air temperature was 5°C (typical of New Zealand winter weather).

The house modelled was a single-storey, 10m by 10 m house with a 2.4 m ceiling height and 20 sq. m of windows. For the insulated house, thermal resistances used were R-1.9 for the roof, R-1.5 for the walls, R-1.3 for the timber floor, and R-0.17 for the window. For the uninsulated house these quantities were R-0.8 for the roof, R-0.9 for the walls, R-0.9 for the timber floor, and again, R-0.17 for the window.

Figure 1 shows the amounts of air exchange and heating energy needed to just prevent condensation on single-glazed window and other surfaces for the insulated house. The amount of heating needed to prevent condensation is shown on the vertical axis, as a function of the given air exchange rate, as shown on the horizontal axis. The curves on the figures represent the threshold of condensation for surfaces at the temperature indices shown. The shaded area on the graphs represent the conditions where condensation would occur on the wall surface, below the lowest curve marked "T.I. = 0.92 (Wall)". Condensation would occur below the higher curves, for surfaces at their temperature indices, though the areas below these curves are not shaded.

When the conditions in the house lie above the temperature index line describing the indoor heating and air exchange conditions, there should be no condensation on that surface. When the conditions in the house lie on or below this line, there is the potential for condensation. The diagonal lines stretching upwards to the right are lines of constant indoor air temperature, which occur at the heating and air exchange rates shown on the axes.

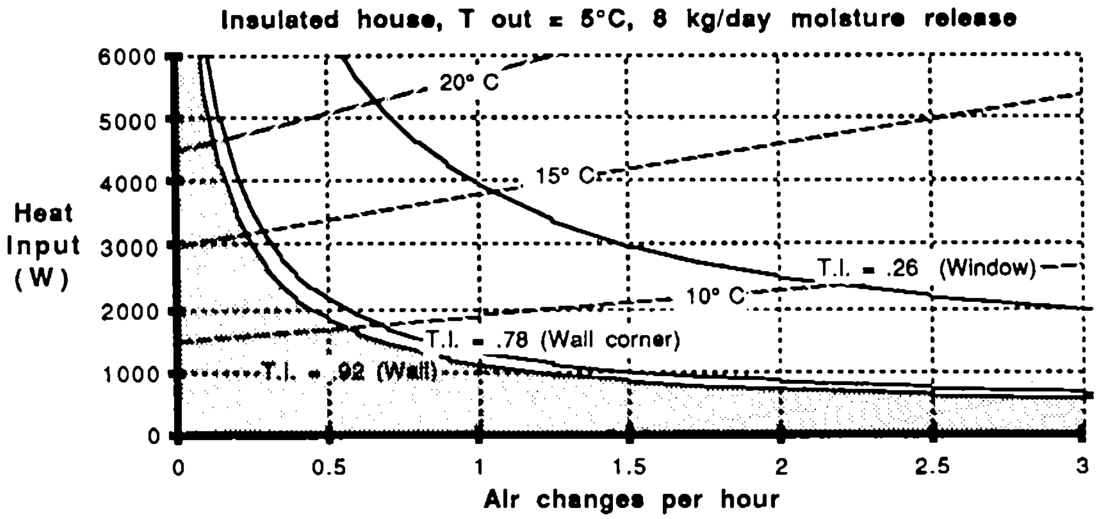


Figure 1 - Requirements to Avoid Condensation - Insulated House

Figure 2 repeats this for the uninsulated house, showing the amounts of air exchange and heating energy needed to just prevent condensation on single-glazed window and other surfaces there. The same patterns emerge, but more heating and higher temperatures are needed to avoid condensation for the uninsulated case.

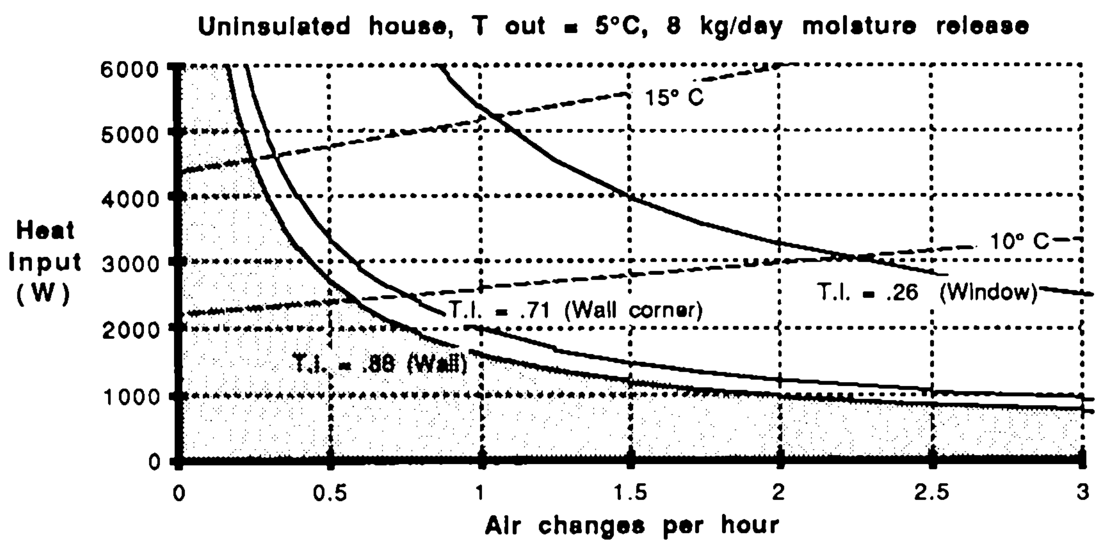


Figure 2 - Requirements to Avoid Condensation - Uninsulated House

The shape of these figures are their most important features. In the upper left of the graphs, condensation is controlled by air exchange. Under these conditions of moderate heating but very low air exchange, only small additional amounts of air exchange are needed to cross the lines and avoid condensation, but much additional heating would be needed to achieve the same result.

Likewise, in the lower right of the graphs, condensation is controlled by heating. At high air exchange but low heating rates, little additional heating is needed to cross the line and avoid condensation, but sometimes even unlimited amounts of extra air exchange will not achieve this.

For a bedroom at night, with moisture releases typical of the respiration of two occupants, the combinations of heating and air exchange needed to prevent condensation are shown in Figure 3. The two curves on this graph are for the temperature indices calculated for insulated walls and uninsulated corners as in Table 2. The outdoor conditions are the same as in Figures 1 and 2: 5°C at saturation humidity.

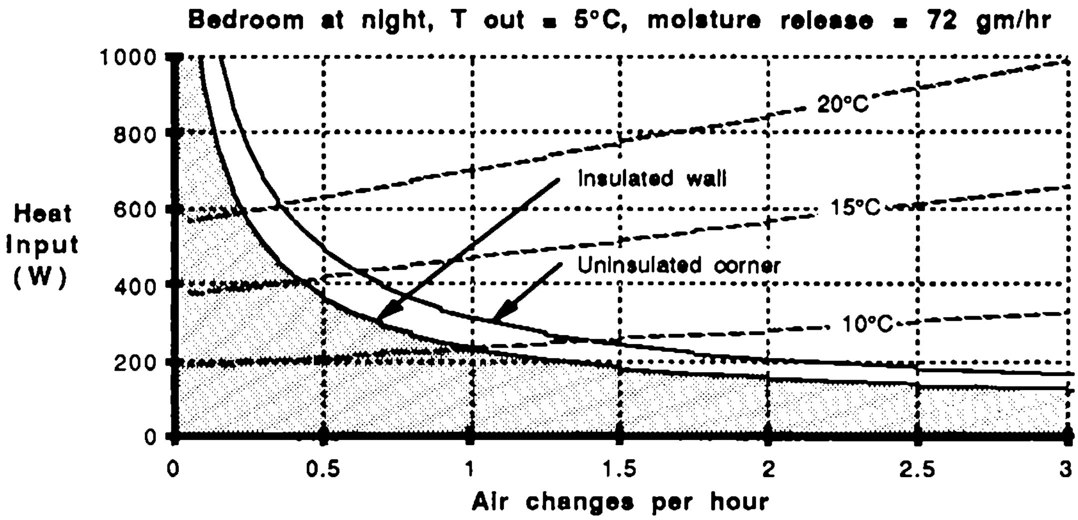


Figure 3 - Requirements to Avoid Condensation - Insulated Bedroom

This figure is notable in that it displays the same pattern as seen in Figures 1 and 2, but additionally shows the results of having different insulation levels as different temperature indices. As can be seen, with increasing insulation levels, the more resistant the wall is to condensation, as its interior surface temperatures will be higher.

For a kitchen with indoor moisture release rates typical of cooking, the heating and air exchange combinations needed to prevent condensation are shown in Figure 4, with the same temperature indices as the previous figure. Note the much higher required heat inputs, and consequent high temperatures for this case. It can be seen that there are almost always conditions where condensation will occur in kitchens, and that the amounts of air exchange, insulation, and heating needed to reduce the impact of this are greater, but similar in pattern to that required in other rooms.

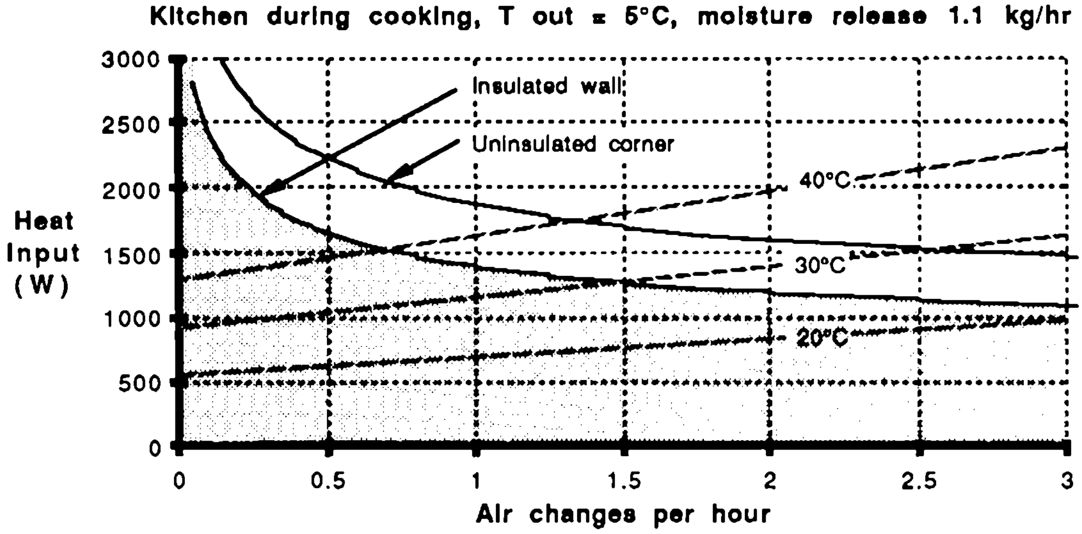


Figure 4 - Requirements to Avoid Condensation - Insulated Kitchen

The effect of variations in outdoor temperature on the whole-house heating and air exchange conditions needed to prevent wall surface condensation are shown in Figure 5. As is seen, at lower outdoor temperatures and similar air exchange rates, more heating is needed to prevent condensation. This is because the effect of colder wall surfaces outweighs the effect of the drier, colder outside air being exchanged.

The effect of variations in moisture release rate in the building are shown in Figure 6. They range from half to double the assumed "base case" moisture release rate of 8 kg/day. As expected, with higher rates of moisture release, more heating and air exchange are needed to prevent

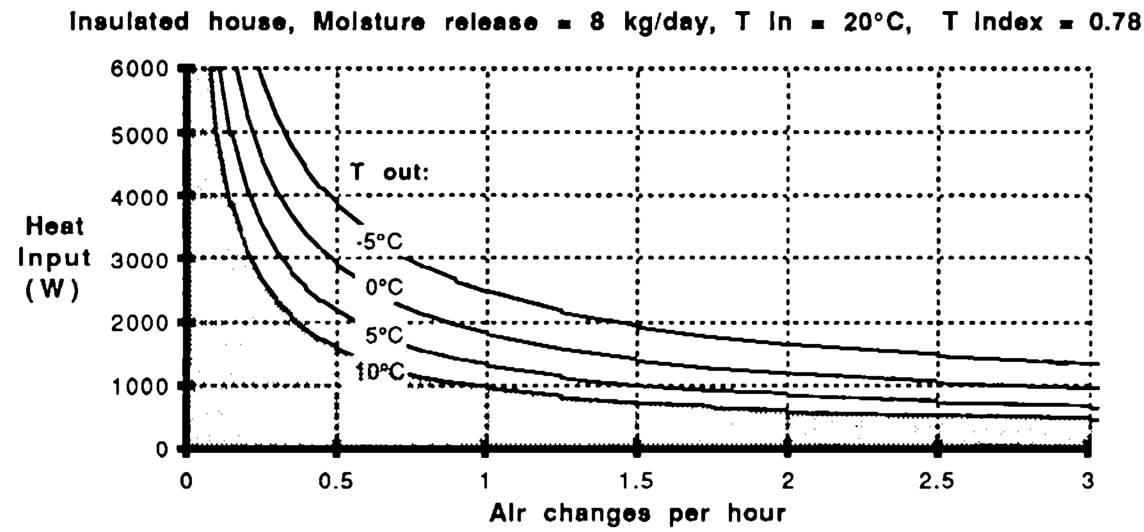


Figure 5 - Effects of Variations in Outdoor Temperature

condensation in room corners. Also note that the variation in the heating/air exchange lines due to these moisture release rate changes is similar in magnitude to those due to variations in outdoor temperature or surface temperature index.

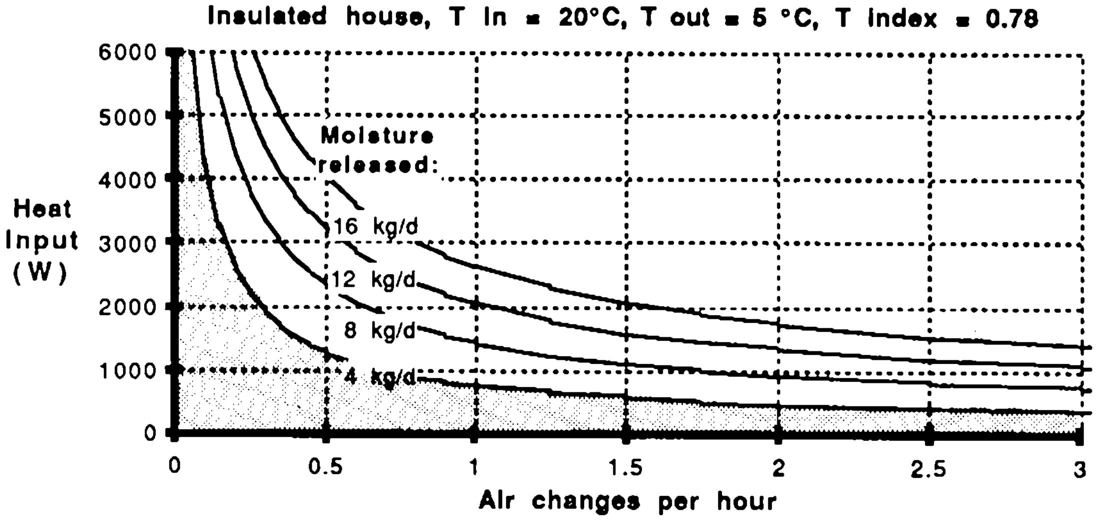


Figure 6 - Effects of Variations in Moisture Release Rate

These analyses generally follow an early BRANZ paper entitled "The Theory of Mould and Mildew"[3] which was published in 1972. It calculated the air exchange rates needed to avoid this 90% relative humidity level at building surfaces for various conditions of water vapour generation, and heating and insulation level.

Simplifications included in the analyses presented here include neglecting the fact that moisture damage begins before condensation occurs, and assuming a "ventilation efficiency" of 100%. Also, moisture transfer by mechanisms other than air exchange was neglected.

One of the most prevalent types of moisture damage is mould. Mould grows before condensation occurs due to the hygroscopic effects of most building materials, whereby they absorb moisture directly out of the air (and potentially feed mould and mildew) as a function of relative humidity, typically between 70% and 90% relative humidity.[8]

"Ventilation efficiency" is an empirical coefficient describing the effectiveness of pollutant removal by the ventilation air.[8] This coefficient is equal to unity when the ventilation air dilutes the pollutant concentration at the same rate as it dilutes the air in the space. However, for source ventilation of specific pollutants, the ventilation efficiency can be much higher than one, as when the pollutant is ventilated directly out of the building, and carried off much more quickly than the air of the whole building changes. And for whole-house air exchange the ventilation efficiency is often much lower than one, as the ventilation air dilutes a concentrated pollutant less effectively than it changes the air of the whole space.

For ventilation efficiencies lower than unity, higher air exchange rates than shown in the preceding figures would be required to prevent condensation; for more efficient ventilation, a lower total flow rate would be needed. And to reduce indoor relative humidity rates below the 100% assumed on the curves in the figures, proportionally more air exchange would be required.

THE NEED FOR VENTILATION

Air infiltration is the uncontrolled leakage of air into a building. It reduces the levels of water vapour in the air to approach equilibrium with the outside air. Historically, infiltration combined with the practice of "airing out the house" by opening windows kept the water vapour and pollutant concentrations at a low enough level to usually avoid problems. However, as the airtightness in buildings continues to improve, infiltration is often drastically reduced.

The driving forces of air infiltration theoretically include both wind and temperature difference (thermal buoyancy or stack effect), but practically, the temperature difference has a minimal effect on infiltration rates. In New Zealand, with low indoor/outdoor temperature differences and building heights, stack effect only accounts for a small fraction of typical infiltration rates.

Figure 7 shows the percentage of wind induced driving force produced by thermal (stack) temperature differences given for varying wind velocities. Typical average wind speeds encountered in New Zealand are in the 5 to 10 m/sec range, so the stack effect usually provides a force about 1/10 that of the wind.

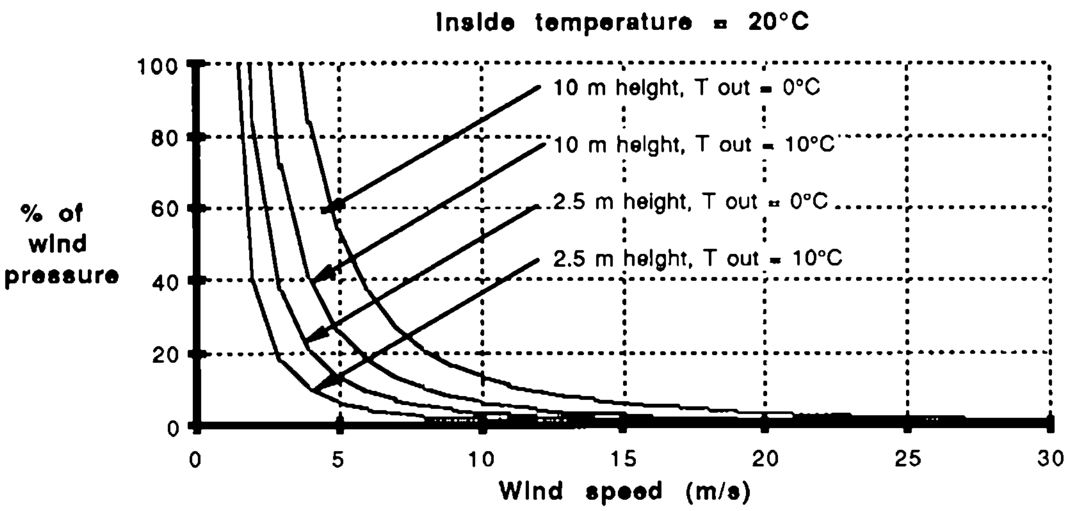
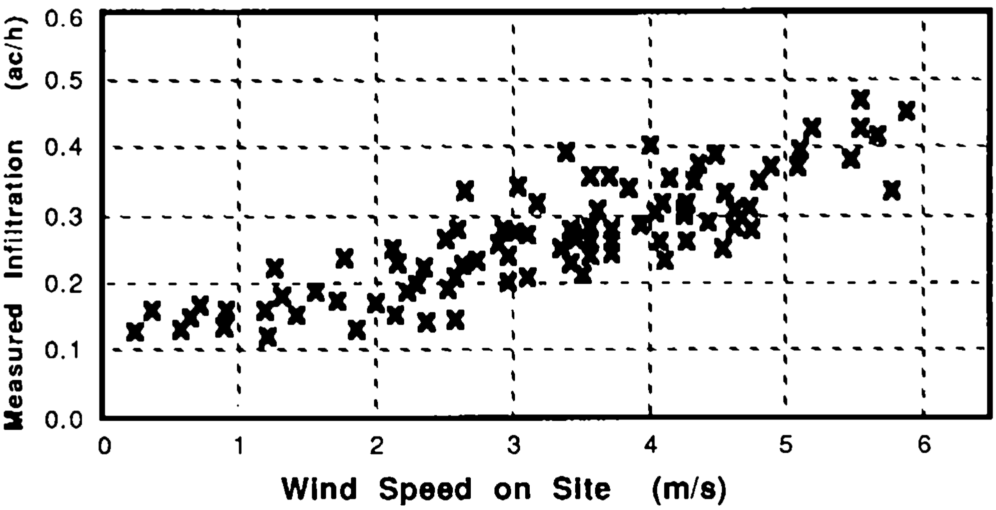


Figure 7 - Thermal (Stack) Pressure as Percent of Wind Pressure

The importance of this is that the colder temperatures experienced in winter do not in general lead to increases in the infiltration rate, although the rate of natural ventilation is much reduced then (due to people keeping their windows closed to conserve heat).

Figure 8 shows the results of measurements made in a typical Lower Hutt house,[10] where infiltration rates were continually monitored with tracer gas and correlated with wind speeds and temperature differences. Note that although there is a good correlation between wind speed and infiltration rate, there is not with temperature. Also note that the house was more airtight than the national average, with measured infiltration rates of typically 0.25 ACH or less.



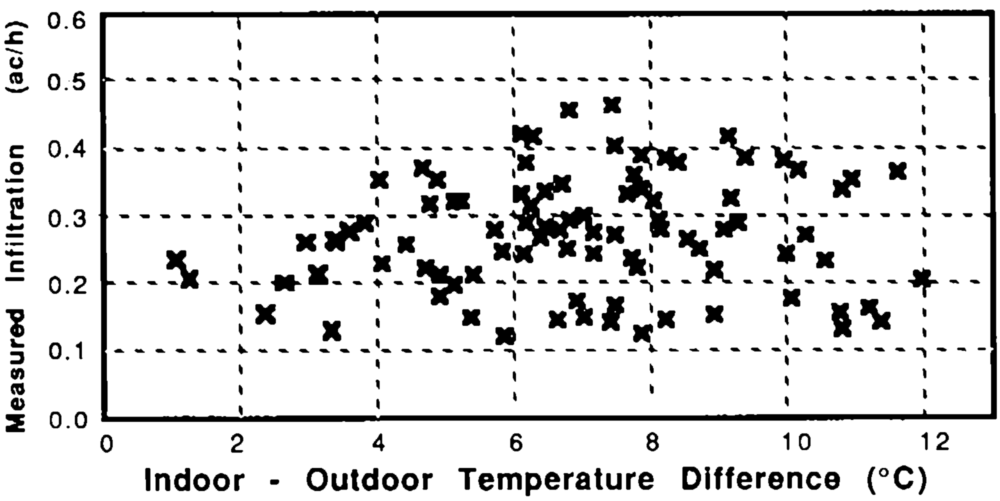


Figure 8 - Measured Infiltration Rates and Correlations

Based on this data, infiltration in New Zealand houses can adequately be treated as a function of wind speed only. The problem with this is that sufficient wind is not always present to drive infiltration when moisture must be ventilated.

NATURAL VENTILATION POTENTIAL

Because there is a need for ventilation, and since most New Zealand buildings do not have purpose-built ventilation systems, an obvious solution is to include provisions for natural ventilation, by manual opening of windows. As the leakage areas are so much larger when doors and windows are opened than the natural ones occurring in the fabric of a building, the amounts of air flow are consequently much higher than for infiltration.

But, as excess ventilation causes extra heating loads, as well as reducing comfort due to cold drafts, it is necessary to be able to estimate how far windows should be opened to provide sufficient ventilation.

Thus, Figure 9 has been calculated from standard aerodynamics to show the amount of ventilation achievable by opening one meter wide windows on the up-and down-wind sides of a house to the same amount. It assumes a 100 sq. meter house with infiltration leakage sites similar to the house in Figure 8, minimal internal flow resistance in the house, shielding coefficients of +1.0 on the upwind face of the building and -1.0 on the downwind face, and wind speeds as experienced at ceiling level.

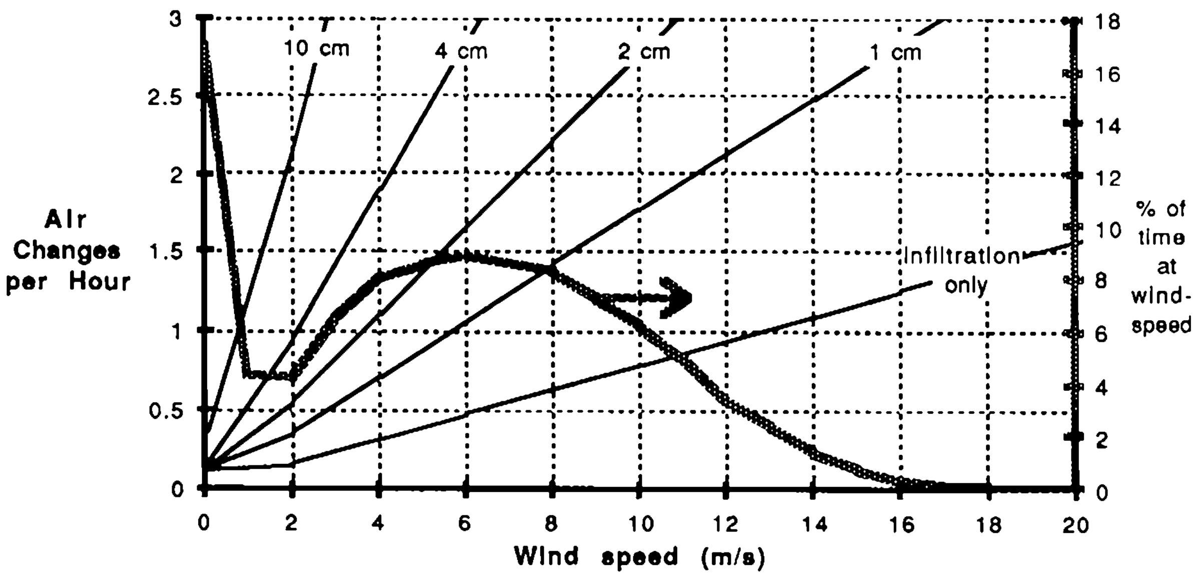


Figure 9 - Potential Natural Ventilation Rates and Windspeed Distribution

As can be seen from Figure 9, high natural ventilation rates can be achieved at relatively narrow window openings, even at quite moderate wind speeds. The distribution of windspeeds measured in Wellington are also included on this figure, with the vertical axis on the right side of the graph indicating the percentage of time the wind is measured at each speed.[11]

The purpose of this graph is to "calibrate the intuition" of homeowners and designers, to offer guidance, in conjunction with the previous figures showing the requirements for air exchange.

A final technique for moisture and pollutant control is that of mechanical ventilation, most common in commercial buildings (especially kitchens). Exhaust fans in kitchens above stoves are common fixtures, used to remove the excess moisture and fumes of cooking. In some of the more modern, low energy houses in cold climates throughout the world, where they are built very airtight, whole-house mechanical ventilation is provided, often with heat recovery. It is notable, though, that for mechanical ventilation to work effectively, the building must be quite tight to infiltration to begin with, or the mechanical ventilation system will be "swamped" by the infiltration under certain conditions.[12]

CONCLUSIONS

Condensation has been shown to be alleviated by a combination of air exchange and heating. Neither will solve the problem alone.

For very low heating rates, as in the case for many New Zealand houses, simply increasing the air exchange rate does not reduce the indoor relative humidity enough to avoid condensation. Some heating is required for this, often quite a small amount.

Likewise, on very still nights, when air change rates are very low, simply adding heating will not reduce condensation. Some form of added ventilation is needed to accomplish this.

A favoured technique to achieve this is natural ventilation, by opening windows on two sides of the house, and encouraging a slight draught or breeze through it. A method is included in the text to approximate the amount of ventilation that can be achieved by this technique at various window openings, depending on outside windspeed.

Ventilation is an important contributor to reducing condensation and indoor air pollution. With a better understanding of the mechanisms and driving forces of infiltration and natural ventilation, New Zealand designers should be able to accommodate this need by placing windows where they can catch prevailing winds, and not trying to provide "high and low" ventilator combinations.

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DISCUSSION

Paper 2: 'Seasonal storage of moisture in roof sheathing'
M. Sherman (USA)

M. Cunningham (New Zealand): Did you collect a data set that lasted for a full year ?

M. Sherman (USA): *Not in one data set but I have covered all seasons over a range of experiments.*

H. Trethowen (New Zealand): Attic moisture - We have observed very large vertical temperature AND relative humidity gradients in attic spaces, during daytime (from sunshine). Have you ?

M. Sherman (USA): *We did not observe humidity gradients. We believe that in open attics the various components will come into thermal equilibrium over the course of a day and that gradients will have only a small effect on the net transfer in/out of the timber.*

J. Brunsell (Norway): How did you measure the ratio of the moisture coming from the indoor air and from the outdoor air ?

M. Sherman (USA): *The outdoor air conditions were known from weather data, the indoor air was measured. Leakage areas for the walls, ceiling etc were assumed and the LBL infiltration model used to estimate the indoor air flows into the attic.*

W. F. de Gids (Netherlands): Can you give any figures of attic space ventilation rates ? This is especially important because you said it was a single zone model.

M. Sherman (USA): *The attic spaces we investigated were well ventilated. Daytime inside-outside temperature differences were quite large and significant winds were common. All of these combine to cause quite high air exchange rates most of the time.*

K. L. Biggs (Australia): Were the roofs lined ? If not, air change rates can be very high, 10-60 or more ach, depending on wind speed.

M. Sherman (USA): *The roofs were open frame and, as you indicate, quite leaky. I expect that there were high air change rates under windy conditions.*

Paper 3: 'Air flow resistances in timber frame walls'
M. Bassett (New Zealand)

H. Bruhns (Australia)
I was surprised by the very high air flow through the building paper. Is that due to defects in insulation or the porosity of the paper ?

M. Bassett (New Zealand)
New Zealand building paper is rather more porous than lining materials. For instance but we expect that, as for wall linings, the major air leaks will occur at joints. The air flow resistance at this point in the wall will therefore range from close to zero for poorly applied traditional building paper to very high (highest R in the wall) for some view materials, i.e. spun-bonded olefin papers, which come in full stud height sheets. There is potential here for making a very big change to air flow resistances in walls of New Zealand domestic buildings and we have to consider what effect this will have on air flows that can, for instance, dry out wet framing timber.

M. Sherman (USA)
The building papers used in New Zealand are quite hygroscopic but relatively leaky. The current spun-bonded poly-olefin papers used in the better houses in the U.S. are the reverse. 1) What is the New Zealand experience with the new products ? 2) In light of all of the other moisture storage possibilities , is the moisture storage of the paper significant in the protection of the structure ?

M. Bassett (New Zealand)
Spun-bonded poly-olefin papers are relatively new to New Zealand houses and have been little used so far. Moisture absorbancy is a parameter specified in the New Zealand standard on building papers which is probably important in storing overnight condensation where it can dry out when the sun comes up next day. Rain leaks can similarly be absorbed for later drying. I am not aware of measurements that support this role of building papers.

M. Cunningham (New Zealand)
Do you see moisture problems with new building systems, i.e. those with new building papers and cladding materials with low moisture storage capacities ?

M. Bassett (New Zealand)
Not sure.

M. Sherman (USA)
Comment - This is not a problem in the USA and perhaps may not be in New Zealand.

M Cunningham (New Zealand)
Comment - Could well be in New Zealand. Our standard requires building paper to have moisture retention properties, to allow overnight condensation to be held and then re-evaporated in the morning. This may be lost.

R. Clarke (Australia)	Other comments on building paper invite my comments on Australian practice - especially in the context of problems that may arise with alternative products which are not hygroscopic and are good vapour barriers. The problem is foreseen that excess moisture remains inside the wall. Reflector foil is used in Australia but manufacturers advise against its use under weatherboards unless a micro-punctured (breather) foil is used. Otherwise moisture is trapped behind weatherboards, unable to adsorb into either stud space (timbers, etc.) or paper itself. Severe board cupping otherwise readily occurs. Early onset on weatherboard decay has also been observed in my personal experience.
<u>Paper 4</u>:	'The use of equivalent electrical circuits to describe the moisture behaviour of structures' M. J. Cunningham (New Zealand)
R. Bishop (New Zealand)	Can you justify lumping the moisture content of the wood all together ? Might it not take a finite time for the moisture to migrate from the centre to the surface of the wood ?
M. Cunningham (New Zealand)	*Yes, the lumping is an assumption. It is justified by the long time constants involved in drying. For shorter time period modelling this would need to be examined more closely. The behaviour would be similar for all softwoods.*
M. Sherman (USA)	Your assumption of linearity (i.e. constant "K") can cause significant error when the temperature varies seasonally. The time constant for the wood can easily vary by a factor of 5 between summer and winter. Would not it be better to use a few different time constants over the year ?
M. Cunningham (New Zealand)	*The technique's main thrust is to aim at concepts that will have at least approximate validity to allow faster progress to be made through improved intuition. There is no attempt at this stage to model accurately as in e.g. Sherman's work.* *The effect in question is far less in practise than might initially be expected. Swings in mean framing temperature will be somewhere between external temperature swings and internal swings. In New Zealand this would work out on a monthly mean basis for timber temperatures as say midsummer 20°c, midwinter 10°c. This in turn reflects to K values for Pinus Radiata as 20 and 10Pa/(kg/m³) respectively, in terms of a swing about a mean this is 15±5, i.e. a 33% swing in the K value about its mean.*

This affects the equation solutions in the following way:

1. *Sinusoidal Driving Forces - Numerical modelling using a variable K gives about a 20% difference in amplitude swings for sinusoidal driving forces over values predicted using a mean value of K.*

2. *Transient Decay - (e.g. drying of construction moisture). Drying takes place obviously most substantially over one time constants which will be of the order of one month for timbers and construction details considered. A mean value of K for conditions over this time period can be used, as it will not change much in size over this time period.*

<u>Paper 6</u>: 'Short presentation of the airborne moisture problems and research activities within this field in Norway' J. Brunsell (Norway)

R. Bishop (New Zealand): Why are the battens between cladding and wind barrier oriented horizontally, and does that interfere with the ventilation of that cavity ?

J. Brunsell (Norway): *The battens are oriented perpendicular to the chosen cladding direction. The claddings are typically board on board (i.e. - very wide battens on the boards) so there are vertical channels. The important thing is to separate the building paper (wind barrier) from the cladding, to allow them both to dry out. The cavity is more important than the ventilation openings.*

W. F. de Gids (Netherlands): Is there any attempt to require a minimum air tightness in Norway ? If not how do you handle situations with an N_{50} in the range of 0.5 or even lower ?

J. Brunsell (Norway): *There is no required minimum level of the N_{50} value for Norwegian buildings. We are measuring the tightness with the inlets and outlets closed, so even if we get a completely tight house we can get ventilation through inlets and outlets. The problems occur when people close the inlets under normal conditions, usually because of draught.*

K. L. Biggs (Australia): What buildings do you intend to pressurize with the large fan system shown on your slides (30,000 m^3/h) ?

J. Brunsell (Norway): *We intend to pressurize more residential buildings, e.g. office buildings, school buildings etc.*

T. Baumgartner (Switzerland)
Why is the building ventilation system not used to make the pressurization test ?

J. Brunsell (Norway)
We do, but we want to find the accuracy of using the ventilation systems compared to the "correct" measurements with our own fan.

Paper 7: 'The control of condensation within buildings in the U.K.'
A. Wilson (U.K.)

H. Trethowen (New Zealand)

1. Why does the Glaser method rather than Keiper's method make it easier to include for air leakages, and for initial drying, etc. ?
2. Evidence (from many countries) is that the greater part of moisture transfer in and out of building cavities, is carried by moving air streams through cracks in joints, which commonly predominates over moisture flow through bulk material.

A. Wilson (U.K.)

1. *The reason why we have kept with the Glaser method is that it uses the same philosophy already used and goes a few steps further in predicting condensation. The building industry tends to move fairly cautiously.*
2. *Work in the U.K. at BRE both at PRL and the Scottish Laboratory have found similar causes. As yet a full understanding of the air flow method is not available.*

K. L. Biggs (Australia)
Contrary to the emphasis on airborne moisture transfer by Harry Trethowen, the draft BS5250 seems still to focus on vapour diffusion processes.

A. Wilson (U.K.)
I agree with the comment. In the U.K. the standards and building recommendations tend to lag behind the research being carried out. Work in the U.K. has shown that airborne moisture transfer is very important, methods for modelling its effect have yet to be fully developed.

R. Bishop (New Zealand)
This is an important point. If air motion carries the water, NOT vapour diffusion, should we not ignore vapour diffusion calculations and vapour barriers and focus on the real problem ? How do other researchers feel about this ?

J. Brunsell (Norway)
Yes it is air motion.

W. F. de Gids (Netherlands)
I feel that in roofs vapour barrier can be justified.

J. Kronvall (Sweden)
Early polythenes degraded badly with UV, but later formulations were much more stable. Sweden has a standard for durability of polythene.

M. Cunningham (New Zealand) In timber framed construction as distinct from masonry construction the problem of moisture performance is two-dimensional not one-dimensional, as flow takes place from the framing to the cavity, and then from the cavity to outside, as well as through the linings directly in and out of timber.

Paper 9: 'Air leakage tests on polythene membrane installed in a wood frame wall.
C-Y. Shaw (Canada)

M. Bassett (New Zealand) I note that you have measured air leakage rates through joints in air barriers at very high pressures (700Pa). I presume this is in recognition of the need to support wind loads. Is there evidence that air barriers have failed under wind pressure - evidence for instance coming from airtightness tests of houses that show houses have become less airtight that they were when first completed ?

C-Y. Shaw (Canada) *There is no evidence that vapour barriers have failed under wind pressure. High ΔP was used to see how well vapour barriers can support wind loads.*

P. Charlesworth (U.K.) What is width of vapour barrier sheets ? Would complete wrap-around sheets eliminate problems through joints in barrier ?

C-Y. Shaw (Canada) *The width of vapour barrier sheets is about 3 m. It is not always possible to cover a house with a continuous sheet of vapour barrier.*

Paper 10: 'Ventilation to reduce indoor condensation'
R. C. Bishop (New Zealand)

M. Down (Australia)

1. What would be the position on the graph in Figure 3 for insulated bedrooms at the "window curve" ?
2. What would be the effect on any of the "window curves" at curtains or other 'night' insulation ?

R. Bishop (New Zealand) *Curves are for a very general case - exact position of window curve is less important that the "pattern". From the pattern of previous graphs note about where the window curve would be.*

Insulating the windows with curtains, etc. would reduce their temperature indices and move the curves up and right. In practice, curtains might reduce the moisture flow to those surfaces and so reduce the condensation potential overall.

Section 2 :

Review and bibliography

REVIEW

1. INTRODUCTION

Moisture is a widespread problem affecting buildings in many climatic zones. The most noticeable ways in which this difficulty manifests itself are mould growth on walls and furnishings, and surface condensation. Moisture is generated in buildings as part of the metabolic process of occupants and as a consequence of normal day-to-day activities such as cooking and washing. It is variously estimated that, for normal houshold activities, between approximately 7 and 14 Kg of moisture may be generated within the home each day[1,2]. In addition, this total can be considerably increased by the use of unvented oil heaters and gas cookers and by indoor clothes drying. If not adequately controlled, the capacity of the air within the building to accommodate water vapour will eventually be exceeded, at which point condensation will occur. This problem is most likely to be apparent in the immediate vicinity of cold surfaces such as single-glazed windows, thermal bridges and areas of poor thermal insulation. A potentially much more serious problem is for moisture-laden warm air to pass through adventitious openings in the envelope of the building and to condense, on cooling and dilution, within the building fabric. This form of condensation is most serious, although less common, and can result in severe structural damage.

In addition to the moisture input generated by activities taking place within the building, the possibility of condensation occurring is very much related to both internal air temperature and the rate of air removal by ventilation, together with the previous history of the building, e.g. the state of dryness of materials, and hygroscopy. Since these factors have a direct impact on space heating needs, the control of moisture is of the utmost significance in building energy conservation design. In fact, airborne moisture into or out of structure cavities is often now seen as the predominant issue.

The objective of this technical note is to outline some of the principles behind air driven aspects of moisture in buildings and to review a selection of relevant literature taken from the Air Infiltration and Ventilation Centre's bibliographic database, AIRBASE.

2. BACKGROUND

Water vapour is always present as a constituent of the atmosphere. The amount present may vary considerably and is primarily dependent on geographic location and on variations in climatic parameters. The moisture content of air may be expressed in absolute terms either in the form of mass per unit mass of dry air (specific humidity) or as a partial pressure (vapour pressure). The amount of moisture that may be held within the atmosphere in vapour form increases as a function of both atmospheric pressure and air temperature. For a given atmospheric pressure, the percentage ratio between the actual vapour pressure of air at a given temperature and the maximum possible (saturated) vapour pressure at the same temperature is defined as the relative humidity. Should the moisture content of air increase, or the temperature of moist air reduce to the point where a relative humidity of 100% is attained (dew point temperature), then condensation will occur.

As cold air has a much lower capacity for holding moisture in vapour form than warm air (Figure 1), condensation is more likely to occur at depressed room temperatures. For a similar reason, climatic differences also impart important regional differences to the problem.

Atmospheric air in extremely cold climates, for example, has a much lower water content for a given relative humidity than does air in much milder climatic regions. This is illustrated in Figure 2, where the average moisture content of outside air throughout the winter months for locations in Canada, New Zealand and the United Kingdom is illustrated. This shows that the average mid-winter water content of the atmosphere in Southern England is approximately 3.5 times greater than that in Ottawa, Canada, while in New Zealand the water content can exceed the Canadian value by a factor of almost 5. However, both England and New Zealand are associated with much less severe temperatures outdoors and therefore condensation risk may not be markedly higher. For a given rate of moisture generation within a building, a higher rate of ventilation may be necessary to dilute moisture in some regions than in others. British Standard 5925[3] provides useful guidelines and nomograms to calculate the ventilation rates necessary to prevent excessive indoor humidity levels in dwellings at 17°C.

3. MINIMISING MOISTURE RISKS

It is unlikely to be possible to control the risk of condensation by concentrating effort solely on any single contributory factor. It is more probable that a balanced approach to the problem involving a combination of measures will yield more successful results. Primary remedies should include a reduction in the generation of moisture, ensuring the thermal integrity of the building and providing adequate ventilation. The use of dehumidification may also be of some importance[4]. From the design aspect, the hygroscopic properties of wall coverings or of the building itself may also influence the likelihood of condensation formation.

The control of moisture generation is largely in the hands of the occupant. It is clear that the designer's task in anticipating the requirements of the occupant is formidable and it is questionable that an energy efficient approach could be achieved if it became necessary in every case to accommodate the worst possible scenarios of occupant abuse. Education and perhaps statutory limitations on the availability of unvented appliances may prove to be a more successful route.

The thermal integrity of the building covers not only the need to maintain a sufficiently high temperature to avoid condensation but also the need to ensure that there are no cold spots which may depress temperatures sufficiently to cause severe localised problems. Undoubtedly some compromise is necessary since space heating is costly and therefore may not prove an attractive option to the occupier. The solution primarily rests with good building design and construction.

The BRANZ report "Theory of condensation and mildew" (1972) provides an interesting summary as follows:

> "It has been suggested that a simple diagnostic rule can be formed for wet, temperate climates, that if there is wintertime mildew or condensation, and the indoor-outdoor temperature difference is:
>
> less than 6-7°C, then there is not enough <u>heating</u>
> more than 6-7°C, then there is not enough <u>ventilation</u>
>
> and if it is difficult to maintain this minimum, then there is not enough <u>insulation</u>."

Ventilation approach also needs to be planned with care. To avoid the risk of condensation, moist air needs to be extracted from the building before problems arise. More importantly, generated moisture should be extracted at source by the appropriate use of vents and exhaust terminals. Provision also needs to be made for adequate ventilation.

In mild climates, air infiltration coupled with window opening tends to provide the main source of fresh air, particularly in dwellings. Specific problems associated with this approach include wide variations in air change rates and haphazard air flow patterns. The latter problem, most especially, can give rise to moisture problems, although overall ventilation rates may be regarded as sufficient. In countries subjected to severe climatic conditions, buildings are necessarily much tighter and ventilation needs are increasingly being met by mechanical means. In such areas, this approach has proved extremely popular, since nowadays it almost always provides for heat recovery with the result that the additional capital cost of mechanical ventilation can often be quickly recovered. As a further advantage, mechanical ventilation can be used to achieve an optimum air distribution pattern for improved moisture control. However, in milder regions, the potential for cost effective heat recovery is extremely limited and thus this solution to the moisture problem is unlikely to be introduced to any significant extent in the foreseeable future. It is therefore essential to re-examine current ventilation approaches and to develop solutions that are both appropriate and acceptable to the requirements of the occupant.

4. CALCULATION TECHNIQUES IN DESIGN

Recent advances in both experimental techniques and mathematical modelling approaches have resulted in a considerable improvement in the understanding of air distribution and air renewal in buildings. By combining the results of many measurements, it has become possible to verify the performance of numerical models and to develop very powerful predictive methods. It is these methods, in conjunction with experimental support, that should now be focussed on the problem of moisture control. In particular, air flow models can be expected to give basic predictions on weather-related air flow and air change patterns. Thus they offer an inexpensive method for assessing design ideas at an early stage of development. From such work, the necessary guidelines for ventilation control of moisture may evolve. At a more complex level, combined dynamic heat loss and ventilation models, which may be used to predict condensation directly, are also becoming available[5]. While it can be expected that such models will remain exclusively in the research sector for some time to come, their application may still be expected to make an important contribution to the understanding and prevention of moisture problems.

4. REVIEW OF LITERATURE

The moisture level in buildings is important for two reasons:

1. The comfort of the occupants.
2. The preservation of the building fabric.

Brundrett[6] outlines moisture criteria for both people and the building itself. Schaffer[7] regards a relative humidity of 30% (plus or minus 5) sufficient for both healthy and comfortable conditions in cold climates. A review of the relevant health literature by Sterling et al[8] gives a range between 40% and 60% at normal room temperature to minimise risks to human health. Cornish and Sanders[9] recommend that it should be kept under 70% to prevent mould growth. Burberry[10] suggests that the increasing problems of condensation reflect both a change in life style of the occupants and changes in building design and construction.

Air leakage through the building envelope traditionally has been regarded as an acceptable means of ventilation, although it is a major cause of condensation problems according to Handegord[11]. He discusses the influence of air leakage openings and their location on the pattern of air flow through buildings and the resulting condensation.

However, if sufficient ventilation is provided, humidity can be reduced. Daler[12] calculates air flow rates for natural ventilation with closed windows, hopper windows and controlled ventilation. But in recent years, houses have been constructed or renovated to make them tighter.

Minogue[13] defines three categories of energy conservation in housing that may have a direct impact on the likely incidence of either surface or interstitial condensation in temperate climates:

(a) reduction of heating levels, i.e. reduced average temperature.

(b) reduction in air infiltration, i.e. reduced average rates of air change.

(c) increase in insulation, i.e. increased average U values of the fabric external elements.

Often older houses are not renovated to a sufficiently high standard with the result that tenants on low incomes are not able to maintain sufficiently high temperatures to avoid condensation and mould growth (Finbow[14]). Korsgaard and Lundqvist[15] compared the humidity levels in 24 pairs of renovated and unrenovated dwellings. The actual humidity levels in the living and bedrooms of the renovated dwellings were significantly higher than in the unrenovated ones. Hjalmarsson and Elfgren[16] have also investigated the problems that moisture can cause in airtight houses. However, Nylund[17] questions the common assumption that tight houses cause mould.

Predicting temperatures and humidities is a complex task. Lifestyles and incomes vary so that heat and moisture inputs differ in different houses, and within a house the problems change from room to room. It is not possible to take account of all the situations that might occur but Loudon[18] has derived information for the more important aspects of the problem for different types of house. He has calculated the effect of ventilation on temperature and relative humidity for a whole house uniformly heated, with moisture from household activities uniformly distributed through the house and also for a kitchen and an unheated bedroom. Assuming an outside temperature of 0°C and a relative humidity of 90%, the calculations indicate that a certain initial minimum amount of heat and ventilation are needed to avoid the danger of mould.

Milbank[19] shows how the fabric heat loss of the house and the rate of moisture generation define a minimum heat requirement to limit mould growth.

Gertis and Erhorn[20] noted that the areas most likely to be at risk from condensation and mould inside a building were, in particular, corners of outside walls and along the ceiling angle. Lubke[21] presents a procedure for determining the minimum airflow required to prevent condensation on the inner surface of corners formed by two-dimensional external walls.

The Nordic Committee on Building Regulations[22] recommends that buildings shall be constructed in such a way or provided at least with such basic ventilation, that harmful condensation on elements of structure is prevented.

In colder regions, the relative humidity in houses is much lower. A survey in Canada by Kent et al[23] of the National Research Council indicated that the indoor humidity ratio is a function of outside conditions but is influenced by the seasonal ventilation habits of the occupants and the moisture storage of hygroscopic materials in the house. In winter, the relative humidity level indoors is between 25% and 30% on average, even in areas having low temperatures, and approaches the maximum humidity attainable without condensation on double-glazed windows.

Kronvall[24] gives data for moisture rates in different climatic zones and considers different approaches to ventilation in different climates. He concludes with a set of general recommendations for ventilation for moisture control in dwellings in different climates.

4.1 Roofs and Attics

By markedly reducing loss of heat from the living areas, increased insulation results in the roof space being colder. However, it does not reduce the migration of water vapour into the roof space from the living area. Oughton[25] notes that, with roof spaces that have been thermally insulated, the relative humidity levels tend to increase and the risk of condensation may, consequently, be greater. The type of damage that condensation can cause in insulated domestic roofs is described in a paper from the UK Building Research Establishment[26]. However, a survey of houses in Utah, Alabama, Ohio and Maryland USA by Johnson[27], while showing that the average absolute humidities in winter in attics for homes with ceiling insulation were some 19% higher than for homes without insulation, also suggested that if attics were well ventilated there would be no consequential difference.

Flat roofs of cold roof deck design may become prone to condensation if the efficiency of the ventilation is impaired by the use or installation of cavity barriers[28].

Moisture enters the roof largely by air flow and not by diffusion through the ceiling. In order for a vapour barrier to be effective, Dutt[29] suggests that it should aim to block flow. He suggests a continuous sheet of, for example, polyethylene film or aluminium foil.

The ingress of moisture is particularly important in roofs containing wood-based materials which are susceptible to moisture degrade, and McIntyre[30] recommends that the most vulnerable materials - flaxboard and strawboard - should not be used unless an unusually high degree of protection from moisture can be assured. But results of an experimental study by Cleary[31] show that the roof sheathing is in dynamic equilibrium with moisture in the roof space air and that several hundred kilograms of water can be stored in the attic wood before any ill-effects are noted. He has also demonstrated the existence of daily and seasonal cycles of roof space moisture parameters[32].

Cornish and Hendry[33] discuss the basic design principles for avoiding condensation in addition to different types of roof such as sheeted roofs, pitched roofs, flat roofs and roofs incorporating a pressurized roof space.

Several models have been formulated to predict moisture in roof spaces. Hens and Vaes[34] developed a three-step stationary convection and diffusion model. Burch and Luna[35] have developed a model for predicting the heat and moisture transfer into residential attic spaces which can be utilized to predict required attic ventilation rates for preventing condensation. Burch et al[36] later improved upon this model to include water vapour absorption at wood surfaces. The Greater London Council[37-39] detailed several techniques for predicting the risk of condensation in both walls and roofs.

Increasing the roof ventilation appeared to be as effective as other solutions such as pressurization of the roof space or an exhaust in the living space, in a study performed by Tamura et al[40].

A major study of the effect of ventilation strategy on timber flat roofs of cold deck construction on combatting condensation and moisture accumulation has been undertaken by Korsgaard et al[41] in Denmark. They found that the optimum form of roof ventilation was edge-to-edge ventilation and suggested that the use of vents be avoided.

An article in the Architects' Journal[42] discusses interstitial condensation in roofs, and a further section considers difficulties, and ways of preventing condensation. Causes are seen as the high vapour resistance in built up felt and polymetric membrane roofing, and the difficulties of ventilating the spaces between joists of a typical domestic-scale cold-deck flat roof, as well as extra insulation at ceiling level. Discusses the failure of sheeted industrial roofs.

Falconer[43] discusses problems of condensation in cavity roofs of industrial buildings, including ventilation air itself as a moisture source, and recommends remedies for condensation.

Johnson[44] discusses the involuntary introduction of condensation problems as a result of failure to understand the principles appropriate to a particular roof. He distinguishes between surface and interstitial condensation. Approaches to various types of roof are described, including warm and cold deck roofs and lean-to roofs.

4.2 Crawl Spaces

Where there is high relative air humidity in crawl spaces, moisture may migrate into the living areas of the dwelling. Oldengarm[45] reviews the phenomena that may play a role in this:

(a) Infiltration of crawl space air through air leakages in the ground floor construction.

(b) Infiltration of crawl space air through air leakages between the crawl space and the air cavity of the facade construction.

(c) Vapour diffusion or capillary transport through the ground floor construction. An increased moisture transport may occur at cold surface areas where condensation takes place.

(d) Capillary transport through the foundation and floor connections.

4.3 Kitchens and Bathrooms

Shair et al[46] suggest that an air change rate of 8 ach provides reasonable control of the moisture content of bathroom air during and after a shower. Daler[47] gives figures for both kitchens and bathrooms.

Humphries[48] sees kitchens as the main problem areas for moisture production, especially when flueless heaters are used, generating a high vapour content.

Edwards and Irwin[49] conducted an experiment to ascertain the effectiveness of a passive ventilation system installed in the kitchen and bathroom of a house of timber framed construction, in comparison with the use of mechanical extraction, window head ventilators and window opening as alternative means of ventilation. Rates of moisture extraction were calculated and the effects on condensation risks assessed.

4.4 Bedrooms

An investigation into the ventilation of bedrooms by the Greater London Council[50] found that even a small amount of ventilation can be effective in combating condensation. The pressure of water vapour in a poorly heated bedroom will often be lower than that in the warmer parts of the house. Thus convection will drive water vapour from the warmer rooms to the colder ones and is one of the reasons why condensation problems are so often found in bedrooms.

Loudon[51] calculated that for an unheated bedroom, the relative humidity does not fall below 70% whatever the ventilation rate, and that a certain initial minimum amount of heat and/or insulation was necessary.

Ventilation must be planned to avoid excess humidity in buildings and particularly to combat condensation in bedrooms[52].

Erhorn[53] found use of natural ventilation to be most frequent in bedrooms.

4.5 Humidifiers and Dehumidifiers

While humidification of some houses in winter might be desirable from the comfort and health viewpoint, Shelton[54] advises that it should be kept to a minimum consistent with adequate comfort.

In cases where quantities of moisture are produced, some form of ventilation extract or vent may be necessary. In buildings using mechanical ventilation with heat exchangers, the type of heat exchanger can influence the moisture removal capabilities of the system. Hoagland[55] found rotary heat exchangers to have advantages over stationary systems. Brundrett and Barker[56] suggest the use of a heat pump dehumidifier. Brundrett and Blundell[57] describe the experimental verification of an advanced heat pump dehumidifier. Brundrett and Galbraith[58] assessed the performance of three types of electric dehumidifier in 30 dwellings in Scotland. Their performance was found to be satisfactory. Over 80% of the householders liked the dehumidifiers, the one unsatisfactory feature being noise. Hansen[59] summarises the conditions for use of dehumidifiers. Dehumidifiers are normally designed for optimum efficiency at 27°C air temperature and 60% relative humidity. At normal room temperatures and humidity levels below 50%, their efficiency drops markedly. In cold climates, relative humidities above 40% or so can cause serious condensation, so humidifiers are not particularly practical.

BRE field trials[60] of some available remedies for condensation and mould led to a new understanding of the factors involved in the occurrence of condensation and the ways in which they interact. Remedies tested included extract fans under tenant or humidistat control and domestic dehumidifiers to control moisture.

An account of humidity control and the effectiveness of dehumidifiers, which are found to be more effective in well heated spaces, is given[61]; they are sometimes found to be too noisy, and emptying them of condensation can be a disincentive. Describes also the use of single glazing as a simple dehumidifier with gutters collecting the condensation.

4.6 Building Materials

Claesson[62] describes the physical processes involved in energy and moisture flow through porous building materials, such as concrete or brick. Kohonen[63] uses simulation to analyse the thermal and moisture conditions in multi-layer building constructions. This method makes it possible to study transient phenomena because boundary conditions vary as functions of time and because moisture transfer processes are relatively slow due to the moisture capacity of the materials in the construction.

The Centre Scientifique Technique de la Construction[64] have studied the moisture present in building construction on completion of the building work. This moisture is due to water absorbed by the material while waiting to be installed, water necessary for the installation and atmospheric water absorbed during the construction process. In addition, the building materials will be affected by condensation from the air and by the hygroscopicity of the materials.

Tenwolde[65] investigates the effect of air leakage on moisture accumulation. The location of condensation may change with changing air leakage rates. He uses a computer method to gain a better understanding of the effects of air leakage on moisture accumulation.

4.7 Walls and Cavities

Timber frame housing originated in North America, Scandinavia and Central Europe. While Tsongas et al[66] demonstrated that the addition of wall insulation without a vapour barrier does not cause moisture damage in homes with wood siding in climates similar to that of Western Oregon, USA, this may not hold true for other climates.

In New Zealand, Cunningham[67,68] has developed an analytical model describing the moisture behaviour of a building cavity containing hygroscopic material. He has extended this[69] to take account of evaporating surfaces within the cavity, e.g. soil, and secondly, in deriving solutions for varying climatic conditions (even if condensation never occurs within the cavity) cavity-relative humidity may be high enough for long enough to obtain quite high moisture content of hygroscopic material, leading to corrosion of metal, mould and rot.

Recent theoretical work at the Building Research Association of New Zealand[70] has offered a general model of moisture behaviour in structures. This model includes for the effects of cavity air leakage, for the hygroscopic behaviour of timber, for the effects of condensation and various geometric factors.

In the UK, Hardy[71] discusses the risks of interstitial condensation due to both climate and the standard of workmanship. Problems in walls are found in association with all materials. A number of cases of water and frost damage in masonry and non-loadbearing walls have been experienced by Wilson and Garden[72] in Canada, where condensation due to exfiltration of air was the primary source of moisture.

In reference (73) condensation processes are considered, including conditions for surface and interstitial condensation in walls, and it is stressed that insulation in the wrong place can exacerbate the problem by making parts of the building fabric colder.

4.8 Vapour Barriers

Roloff[74] has developed a method based on a model to determine a direct relationship between any period of condensation and requisite vapour barriers.

Dutt[75] suggests that there is some misunderstanding of the nature of vapour barriers. He argues that vapour flux by diffusion is negligible and presents evidence of condensation in attics equipped with traditional vapour barriers. Burch and Luna[76] agree that the effectiveness of a vapour barrier is reduced by air leakage into the attic.

The effectiveness of a vapour barrier depends almost entirely on how carefully it is installed. The Canada Mortgage and Housing Corporation[77] give instructions to builders for installing vapour barriers to meet the required standards.

Johnson[78] distinguishes between a vapour control layer and a vapour barrier in relation to cold and warm deck roofs, and explains how condensation risks can be reduced.

4.9 Models

Loudon[79] developed one of the earlier models predicting moisture and ventilation interactions. Brundrett and Galbraith[80] used it many years later in their study on the use of dehumidifiers and found that it worked well.

Kusuda[81] and Miller[82] have both produced and validated models of indoor humidities. Kusuda's calculation for room moisture balance takes into account the surface condensation evaporation and absorption/desorption coefficients. Miller includes infiltration characteristics of the structure, summer humidity ratio hours, thermostat set point and equipment energy efficiency ratio. Lubke[83] presented a procedure for the determination of the specific minimum air flow required in a particular building to prevent condensation on the inner surface of corners formed by two-dimensional external walls.

Cunningham[84-86] also has developed a model of moisture concentrations in building cavities, starting with non-condensing cavities, then condensing cavities and allowing for evaporating surfaces within the cavity. The Greater London Council[87-89] also issued guidelines on modelling condensation in building structures. Burch[90] included the adsorption of water vapour at wood surfaces in his model of attic condensation, and Cleary[91] worked along similar lines.

Kohonen[92] formulated a numerical algorithm and a computer program for the analysis of thermal and moisture conditions in multilayer constructions. Tenwolde[93] also concentrated on multilayered constructions in modelling steady-state one-dimensional water vapour movement.

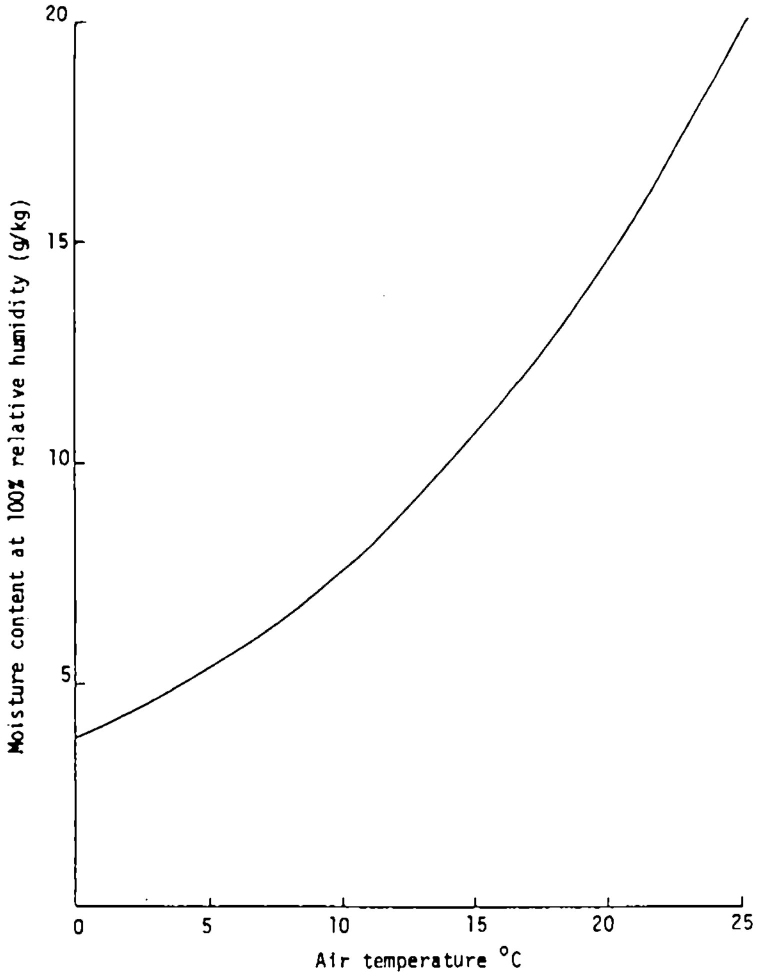

FIGURE 1: Moisture content of saturated air

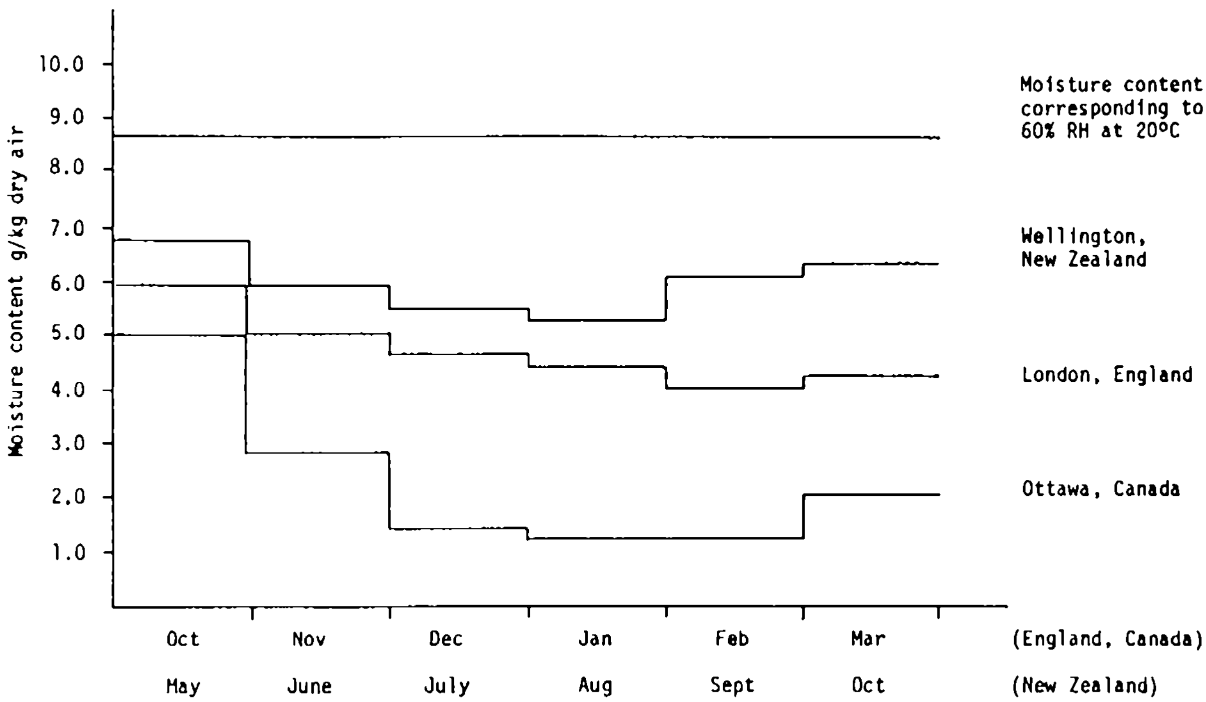

FIGURE 2: Monthly average moisture content of outdoor air

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Presents calculations of mean temperatures and relative humidities , shown graphically for three typical housing types assuming different heat and moisture inputs:
1) whole house uniformly heated with moisture from household activities uniformly distributed;
2) kitchen at constant temperature with high moisture emission rate;
3) unheated bedroom with two occupants assumed to be in thermal equilibrium with a room below at 15 c.
Concludes that there is a certain critical amount of heat needed to give a relative humidity of less than 70% and thus avoid the danger of mould growth . Also finds there is a minimum amount of ventilation needed, but this minimum amount is shown to be much the same as is required for hygienic purposes i.e. 0.5 to 1.0 air changes per hour for the house as a whole.
KEYWORDS
moisture, condensation, ventilation, house

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KEYWORDS
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ABSTRACT

Describes trials undertaken by BRE and ECRC at Inverclyde to test small domestic electric dehumidifiers in council houses. Assesses 3 types of machine, selected to give a range of extraction rates from 1-4 kg per day. These were supplied free of charge and the running costs reimbursed. Shows that the equipment did lower the moisture levels in the houses satisfactorily. Preliminary analysis of results show that the early BRE model predicting moisture and ventilation interactions work well.
KEYWORDS
dehumidifier, condensation, modelling, house,

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KEYWORDS
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ABSTRACT
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KEYWORDS
moisture, house, wood frame, review,

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ABSTRACT
The determination of an acceptable range of humidity is complicated by the conflicting effects of an increase or decrease in humidity levels on the speed of chemical interactions and growth of biological organisms and pathogens that may affect human health and comfort. Ideally, ventilative characteristics of offices and dwellings should strive for levels of humidity that not only are perceived as comfortable but also minimize the growth of organisms and the

speed of chemical processes that will cause discomfort and illness once they are present in sufficient quantity. A review of the relevant health literature suggests that the optimal conditions to minimize risks to human health occur in the narrow range between 40% and 60% relative humidity at normal room temperatures. Although this range is much narrower than the current ASHRAE standard, reducing the range of acceptable humidity would help alleviate many of the health and comfort problems in buildings, especially those that appear to plague modern, sealed office structures.
KEYWORDS
health, human comfort, humidity, office, residential building

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KEYWORDS
humidity, condensation, insulation, natural ventilation, heating, flat,

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KEYWORDS
condensation, moisture,

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ABSTRACT
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location of condensation in relation to these patterns, as well as methods of controlling moisture entry and removal of accumulated moisture. Advocates development of construction details, techniques and standards to ensure airtightness in buildings and building components, as the primary acheiving energy conservation through improved building performance and extended service life.
KEYWORDS
condensation, air flow, air leakage, wind, stack effect,

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ABSTRACT
Ventilation requirements for the reduction of humidity. Required air change rates for hygiene and moisture removal for various rooms are given. Air flow rates are calculated for natural ventilation with closed windows, hopper windows and controlled ventilation. Ventilation by window opening is discussed. Gives examples of the transfer of moisture within a building, and the main reasons for ventilation, with particular emphasis on moisture removal. Lists danger of condensation on various building elements, causes and remedies. Advises on ventilation measures.
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air change rate, natural ventilation, ventilation needs, air movement, humidity, condensation, air flow, residential building, kitchen, bedroom

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KEYWORDS
condensation, air change rate, residential building, energy conservation, insulation

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KEYWORDS
heating, condensation, insulation,

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KEYWORDS
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KEYWORDS
tight house, condensation,

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KEYWORDS
condensation, mould, residential building, insulation, heating, air conditioning, heat loss

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KEYWORDS
natural ventilation, humidity, moisture, condensation, insulation, air change rate, window

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which combine to determine whether a building will have moisture problems. Presents a procedure for the straightforward determination of the specific minimum air flow required in a particular building to prevent condensation on the inner surface of corners formed by two dimensional external walls. Determines the base air flow and the supplementary air flow for four models of representative apartments. Concludes that for adequate ventilation of dwellings it is necessary to have a set value of the leakiness of the building envelope.
KEYWORDS
moisture, condensation, ventilation needs, air infiltration, flat, air leakage, humidity, modelling

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KEYWORDS
indoor climate, ventilation needs, pollutant, radon, air quality, thermal comfort, buildings

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KEYWORDS
humidity, house, occupancy effects,

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ABSTRACT
One of the most important reasons for ventilation of dwellings is moisture control. Ventilation strategies differ. The article deals with 1) Ventilation as a measure for moisture control in dwellings: comfort aspects, durability aspects, air humidity and ventilation: 2) Principles for risk analyses;

surface phenomena, moisture conditions within buildings components; 3) Ventilation requirements in different climates; climatic data for different climatic zones, principles for moisture- ventilation analysis, and analyses of the examples. The conclusion offers some general recommendations for ventilation for moisture control in dwellings in different climates.
KEYWORDS
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KEYWORDS
condensation, roof space,

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KEYWORDS
roof space, condensation, insulation,

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Moisture Migration in Buildings, ASTM STP 779, M.Lieff and H.R.Trechsel Eds, ASTM 1982 p.234-240 DATE 01:01:1982 in English AIC 863
ABSTRACT
Studies moisture conditions in homes in 2 studies. In one study, 17 homes in 4 states were probed in mid-March 1977, and all moisture content levels were found to be within the acceptable range of equilibrium moisture contents. In another study, collects data for 16 homes in north-central Utah, Southern Alabama, Northern Ohio and central Maryland. Makes measurements in each home for approx 1 week in the summer and 1 week in the winter. All homes have

well-ventilated attics. Calculations show the average absolute humidities in winter in attics for homes with a ceiling vapour barrier are 19% higher than for attics without a ceiling vapour barrier. More extensive measurements probably would show no consequential difference in relative humidity in well ventilated attics with homes having a ceiling vapour barrier or those without.
KEYWORDS
moisture, attic, vapour barrier,

28.
Building Research Establishment
NO 235 Cavity barriers and ventilation in flat and low-pitched roofs.
BIBINF
B.R.E. digest no.218 4p. 2 figs. ISBN 0-11-724146-6 DATE 01:01:1978 in English AIC 1369
ABSTRACT
Reviews the requirement in building regulations for cavity barriers in roofs. States need for providing ventilation in the cavities of certain forms of roof construction,particularly those with a continuous waterproof vapour barrier to avoid moisture build-up. Examines how adequate air movement can be provided in both new and existing flat roof voids, designed with or having installed cavity barriers.
KEYWORDS
roof, vapour barrier, ventilation, moisture, cavity barrier.

29.
Dutt G.S.
NO 300 Condensation in attics : are vapor barriers really the answer ?.
BIBINF
Princeton University, Center for energy and environmental studies DATE 01:05:1979 in English. AIC 65.
= Energy and Buildings vol.2 no.4 Dec 1979 p251-258.
ABSTRACT
Calculations of water vapour flow through walls and ceilings are frequently based on the permeability of building materials and implicitly assume that most of the vapour transport takes place by diffusion. Finds that this model is generally invalid since for normal construction practices in U.S. wood frame houses, vapour transport is almost entirely by air movement. "Kraft" paper "vapour barriers" frequently attached to batt insulation do not effectively hinder air or moisture flow into attics.
An effective vapour barrier should aim to block air flow and in new housing, a continuous sheet placed between the ceiling and frame of the attic floor should effectively hinder air and moisture flow. Recommends that in existing housing adequate opening for ventilation with outside air to the attic should be provided to prevent moisture buildup and condensation.
KEYWORDS
vapour barrier, attic, condensation, water vapour, moisture,

30.
McIntyre I.S.
NO 377 Moisture in a timber-based flat roof of cold deck construction
BIBINF
Building Research Establishment Information Paper. 1p 35/79 DATE 01:11:1979 in English AIC 152
ABSTRACT
Reports tests made to examine moisture problems in a flat roof of cold deck construction. Tests simulated the effect of normal, wet and very wet conditions below the roof with no ventilation of the roof. Found that without ventilation there is a substantial risk of moisture degrade and condensation problems. Roof was then ventilated at five air changes per hour and this was found to be effective in solving moisture problems. Suggests this as a minimum

ventilation rate and that where it is difficult to provide ventilation in a flat roof, a warm deck design should be considered.
KEYWORDS
roof, moisture, condensation, ventilation.

31.
Cleary P.
NO 1520 Moisture control by attic ventilation - an in-situ study.
BIBINF
Technical paper submitted for ASHRAE 1985 Annual Conference, Honolulu, Hawaii, 23-26 June 1985. LBL-18062, EEB-epb-84-6, Applied Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, 1984. 22pp, 10 tabs, 19 refs. DATE 00:07:1984 in English AIC 977
ABSTRACT
Moisture enters an attic both from the house and from the ventilation air. It has been assumed that when the roof sheathing temperature cools below the attic air dew point, condensation occurs on the roof sheathing. If this were true, then increased attic insulation levels would require increased attic ventilation rates. Results from an experimental study are presented which show that in fact the roof sheathing is in dynamic equilibrium with moisture in the attic air, and that several hundred pounds of water can be stored in the attic wood without ill effects. A model of this process is presented and used to predict hour by hour and seasonal moisture levels. Applications of the model are discussed.
KEYWORDS
attic, roof, insulation, natural ventilation, wood, moisture, theoretical modelling.

32.
Cleary P, Sherman M.
NO 1750 Seasonal storage of moisture in roof sheathing.
BIBINF
Paper presented at the International Symposium on Moisture and Humidity-1985, Washington, DC, April 15-18, 1985. Berkeley,USA: Applied Science Division, Lawrence Berkeley Laboratory, University of California, 1984. LBL-17774. EEB-epb-85-01. 17p. 7 figs, 15 refs. DATE 00:12:1984 in English AIC 1126
ABSTRACT
Recent work has demonstrated the existence of daily and seasonal cycles in attic moisture parameters. Over the course of a day, the attic air humidity may vary by a factor of three, and during the course of a winter there is storage of perhaps 45 kg of water in the roof sheathing and roofing trusses. On a daily basis the moisture flow is quite significant, of the order of 2 kg per hour: this is far greater than the moisture generation rate in a house, which is typically 0.45 kg per hour. The daily cycles suggest that as the roof sheathing is warmed by incident solar radiation, water is driven off and removed by the ventilation air. A simple method to predict the seasonal variation of wood moisture content has been developed by considering the hour-by-hour transport of water into and out of the wood surfaces of the attic. To validate the model, hour-by-hour measurements of wood resistance, attic and outside dew-point and meteorological variables were made over a four-month period on an unoccupied house in Oroville, California. The roof sheathing moisture content was found to vary from approximately 14% in December to 7% in early April. Measurements are compared with predictions. The model can form a part of a methodology to test ventilation strategies to ensure that well insulated attics do not have moisture problems. Further research is needed to predict attic ventilation rates and the flow of air from the living space to the attic. This model may not apply to more harsh climates, nor to moist cooling climates.
KEYWORDS
roof, roof space, natural ventilation, moisture, humidity

33.
Cornish J.P. Hendry I.W.L.
NO 451 Avoidance of condensation in roofs.
BIBINF
Building Research Establishment, current paper 1/75. 6p 4 figs, 3 refs.
= Proceedings Conference, "Roofs and roofing" 9-13 Sept. 1974. DATE 11:09:1974 in English AIC 1371
ABSTRACT
Sets out in general terms the design principles for avoiding condensation in roofs, pitched and flat. Recommends providing a rain shield permeable to water vapour, a vapour barrier on the warm side of the structure and in roofs with air spaces to ventilate the air space or blow dry air into the roof space. Discusses application of these to particular types of roofs.
KEYWORDS
roof, condensation, vapour barrier,

34.
Hens H, Vaes F.
NO 1726 The influence of air leakage on the condensation behaviour of lightweight roofs.
BIBINF
Air Infiltration Review, November 1984, Vol 6, No 1, p8-10. 3 figs, 1 tab, 3 refs. DATE 00:11:1984 in English AIC 1079
ABSTRACT
The theoretical background, admittance measurements and experimental work on interstitial condensation in lightweight roofs caused by air leakages is discussed. Describes a theoretical model of condensation behaviour taking into account moisture transfer by air flow as well as diffusion. Gives the air flow admittance for various roofing materials, ceiling systems and different roof-sections. Experimental results agreed well with the theoretical model.
KEYWORDS
condensation, moisture, roof, air leakage

35.
Burch D.M. Luna D.E.
NO 466 A mathematical model for predicting attic ventilation rates required for preventing condensation on roof sheathing
BIBINF
ASHRAE transactions vol 86 no 1. 10 figs, 3 tabs, 14 refs. DATE 01:01:1980 in English. AIC 175
ABSTRACT
Presents mathematical model for predicting the heat transfer and moisture-transfer processes in residential attic spaces. Uses model to predict attic ventilation rates required for preventing condensation or frost accumulation on the underside of roof sheathing. Gives attic ventilation charts covering a wide range of outdoor temperatures, ceiling thermal resistances and ceiling air penetration rates. Finds that the addition of a ceiling vapour barrier reduced the required attic ventilation rate by 36%, but the effectiveness of a vapour barrier was reduced by air leakage into the attic. Using measured data of Hinrichs, attic ventilation rates predicted by the mathematical model are converted into net free ventilation areas for soffit venting.
KEYWORDS
attic, vapour barrier, condensation, ventilation needs.

36.
Burch D.M. Lemay M.R. Rian B.J. Parker E.J.
NO 1397 Experimental validation of an attic condensation model.
BIBINF
Preprint ASHRAE 1984 Annual Meeting Kansas City USA 17-20 June 1984 17pp. 10

figs. 6 tabs. 4 refs. DATE 17:06:1984 in English AIC 901
ABSTRACT
A small test house having a pitched roof/ventilated attic was installed in a high bay environmental chamber. The test house and its attic were extensively instrumented for measuring heat and moisture transfer. The test house was exposed to a series of steady and diurnal outdoor climatic conditions. Tests were conducted with and without ventilation into the attic. A mathematical model was developed that included the adsorption of water vapour at wood surfaces in the attic. This closely predicted the attic dew-point temperatures for both the steady and dynamic outdoor cycle tests. The model showed that wood surfaces of the attic at a moisture content of 12.5% adsorped water vapour and maintained the wood surface dew-point temperature below the roof sheathing temperature, thereby preventing condensation. The wood surfaces of the attic would continue to adsorb water vapour until they attained moisture equilibrium with the attic air, after which condensation would occur.
KEYWORDS
attic, heat loss, moisture, modelling, condensation,

37.
Greater London Council
NO 1728 Interstitial condensation. Assessment of risk.
BIBINF
GLC Bulletin 141, Item 9 (Committee date 2/84). Building Technical File, April 1984, No 5, p33-36. 8 figs, 2 tabs. DATE 00:04:1984 in English AIC 1081
ABSTRACT
Sets out the mathematical techniques for determining 1 the most likely position of the condensation plane, 2 the limiting humidity at a given room temperature, below which condensation will not accumulate within the structure, 3 the rate at which condensate is likely to accumulate at the plane if the relative humidity within the structure persistently exceeds the limiting humidity. The technique is a graphical one and assumes that the conditions chosen for the purpose of the analysis remain constant indefinitely, a condition known as "steady state". Warnings are given on the limitations of the steady state approach to the analysis of heat and vapour flow situations, and advice is given on the interpretation of the results. A few hints are given to those interested in writing a simple computer program to use the techniques described.
KEYWORDS
condensation, humidity, mathematical modelling

38.
Greater London Council
NO 1729 Condensation: prevention better than cure.
BIBINF
GLC Bulletin 142, Item 8 (Committee date 5/84). Building Technical File, July 1984, No 6, p33-42. 10 figs, 2 tabs. DATE 00:07:1984 in English AIC 1082
ABSTRACT
Describes in detail a computer-based technique for predicting the risk of condensation occurring in building structures. The technique not only indicates the position at which condensation is likely to occur, but also puts a figure on the risk of decay in timber within the structure. In the case of ventilated roofs or walls it gives the minimum sizes for ventilation openings.
KEYWORDS
mathematical modelling, condensation, ventilation needs, roof space, wall, wood frame

39.
Greater London Council
NO 1730 Condensation prevention: loft ventilation - a discussion paper.
BIBINF
GLC Bulletin 144, Item 4 (Committee date 10/84). Building Technical File,

January 1985, No 8, p25-29. 5 figs, 2 tabs, 10 refs. DATE 00:01:1985 in English AIC 1083

ABSTRACT

This is the third item in a series on methods for predicting condensation risks within structures. It answers criticisms made of the method described in NO 1729, on the basis that the method does not give the same answers, nor does it take account of the effect of the occurrence of condensation on the vapour pressure gradient within the structure, as does the graphical method described in NO 1728. The present item explains how the original equations may be altered to produce the same answers as the graphical method, and goes on to discuss the practicalities of the ventilation of roof spaces, with particular reference to the current and anticipated future requirements for the insulation of roofs, and draws conclusions relating to the inclusion of vapour-resistive layers and the position of the insulant.

KEYWORDS

condensation, ventilation needs, mathematical modelling, roof space

40.
Tamura, G. T.; Kuester, G. H.; Handegord, G. O.;
NO 2059 Condensation Problems in Flat Wood-Frame Roofs; LOCATION - North America;

BIBINF

RESEARCH.LOC = Ottawa, Canada; TYPE = REPORT; DATE 01:09:1974; REPORT.NO = NRCC 14589; PUBLISHER.NAME = National Research Council Canada; PUBLISHER.CITY = Ottawa, Canada; AIC 323 in English

ABSTRACT

Flat wood-frame house roofs with insulation applied between joists are susceptible to condensation problems in cold climates. Investigation of difficulties experienced in a wood-frame row housing project in Eastern Canada showed that many interrelated factors contribute to the occurrence of problems and demonstrated that control of air leakage through the ceiling is the one primary requirement for successful performance.;

KEYWORDS

- CONDENSATION; AIR QUALITY AIR LEAKAGE, roof, CEILING

41.
Korsgaard V, Christensen G, Prebensen K et al
NO 1828 Ventilation of timber flat roofs.

BIBINF

Building Research & Practice, July/August 1985, Vol 13, No 4, p211-219. 13 figs, 4 refs. DATE 00:07:1985 in English AIC 1204

ABSTRACT

A major cooperative study of the effect of ventilation of timber flat (cold) roofs on combatting condensation and moisture accumulation has been undertaken in Denmark. Field measurements of moisture content in a number of test roofs over long periods and under different conditions are evaluated and conclusions drawn. They include the advice that, where moisture accumulation is a problem, it can be aggravated if roof vents are installed.

KEYWORDS

natural ventilation, ventilation strategy, roof, roof space, moisture, condensation, air tightness

42.
Anon
NO 2293 Construction risks and remedies - condensation. Part 1 - risks, Part 2 - remedies.

BIBINF

Archit J, 9 and 16 April 1986, Vol 183, Nos 15 and 16, 49-58, 69-81, 16 figs,4 tabs, 12 refs.
DATE 00:04:1986 in English AIC 1650

ABSTRACT
One of a series of articles focussing on problem areas in buildings. 1) Examines condensation risks in buildings. Treats condensation processes, water vapour input and movement, conditions for surface and interstitial condensation in walls and roofs. 2) Treats condensation avoidance in general, humidity control, controlling vapour flow, adding insulation, heating, mould. Illustrates numerous examples diagrammatically from various building types.
KEYWORDS
condensation, water vapour, surface condensation, interstitial condensation, wall, roof, humidity control, mould

43.
Falconer P
NO 2151 Metal industrial roofs moisture problems.
BIBINF
Architects' Journal, 7th May 1986. p53-55. DATE 07:05:1986 in English AIC 1535
ABSTRACT
Discusses problems of condensation in cavity roofs of industrial buildings, including ventilation air as a moisture source. Lists points to watch when foam filling the cavity.
KEYWORDS
roof, industrial building, condensation, moisture

44.
Johnson K.
NO 2186 High and dry
BIBINF
Building, 18 July 1986, p46-47, 1 fig, 2 refs DATE 18:07:1986 in English AIC 1593
ABSTRACT
Failure to understand the principles appropriate to a particular roof makes it all too easy to introduce condensation problems, often serious ones. A distinction between surface condensation and interstitial condensation is made. Before attempting work on any roof it is necessary to determine how the roof is designed to work. If the principles are wrong, the whole design should be checked and if necessary corrected. Approaches to various types of roof are described: cold or warm deck roofs with vapour control layers or vapour barriers, flat, pitched or lean-to roofs, giving suggestions for reduction of risk of condensation.
KEYWORDS
condensation, vapour barrier, roof

45.
Oldengarm J
NO 1793 Monitoring of ventilation and humidity in crawl spaces of dwellings.
BIBINF
6th AIC Conference "Ventilation Strategies and Measurement Techniques", Het Meerdal Park, Netherlands, 16-19 September 1985. Bracknell, UK: Air Infiltration Centre, 1985. p22.1-22.10. 13 figs, 1 ref. DATE 00:09:1985 in English AIC bk
ABSTRACT
Several physical phenomena which may contribute to moisture migration from the crawl space to the living spaces in houses are outlined. Results of two projects to monitor moisture migration are presented.
KEYWORDS
moisture, humidity, basement, air infiltration, natural ventilation, air change rate

46.
Shair F.H. Wolbrink D.W. Bowen L.O. Neelley C.E. Sampsel K.E.
NO 369 Influence of mechanical ventilation on moisture content of bathroom air.
BIBINF
ASHRAE jnl. vol21 no7 p54-60 9figs, 9refs. DATE 01:07:1979 in English AIC 148.
ABSTRACT
Reports experimental investigation of moisture content of bathroom air during and after a shower. Describes test apparatus and procedure. Gives graphs of dry and wet bulb temperature, relative humidity and absolute humidity for various mechanical ventilation rates as functions of time. Gives results of measurements of tracer-gas decay rates for various mechanical ventilation rates.
Presents theoretical model for calculations of moisture content in air in bathrooms and finds excellent agreement with experimental data. Concludes that without mechanical ventilation ASHRAE standard 62-73 for ventilation in bathrooms cannot be met. Suggests ventilation rate of eight air changes per hour to provide reasonable control of moisture content of bathroom air during and after shower.
KEYWORDS
moisture, mechanical ventilation, bathroom, humidity,

47.
Daler, op. cit., ref. 12.

48.
Humphreys W
NO 2189 Condensation : is the builder to blame?
BIBINF
Building Trades Journal, Vol 191, No 5645, 6 March 1986, p30-32, 4 figs DATE 06:03:1986 in English AIC 1596
ABSTRACT
The article discusses how far the builder is to blame for condensation and its subsequent problems of mould growth. The UK Building Regulations of 1985 for ventilation and condensation do not go far enough in discouraging inadequate forms of ventilation, which frequently go unused. Attempts to economise on energy use by not heating unused rooms also increase the risk of condensation. There is a moral responsibility on the part of the builder to go beyond the basic requirements by including additional or more suitable forms of ventilation. The production of excessive amounts of water vapour is seen as the crux of the problem in housing, frequently the result in using flueless heaters. The three requirements necessary to avoid or lessen condensation are adequate heat input, good thermal insulation and a reasonable rate of ventilation. The builder has some responsibility for control of design and for giving advice to occupants, particularly in the area of ventilation. Recommendations for the builder in the areas of design (heating, insulation, ventilation), and occupation are included.
KEYWORDS
condensation, water vapour, flue, kitchen

49.
Edwards R E, Irwin C
NO 2317 The use of passive ventilation systems for condensation control in dwellings and their effect upon energy consumption.
BIBINF
7th AIVC Conference,"Occupant interaction with ventilation systems", 29 September - 2 October 1986, Stratford on Avon, UK, Bracknell, AIVC, 1986, p16.1-16.14, 2 figs, 5 tabs, 5 refs.
DATE 00:09:1986 in English AIC bk, AIC 2047
ABSTRACT

Various means of condensation control are available. The use of a passive ventilation system to achieve this aim has several attractions, not the least of which is that the occupants of houses fitted with such a system need little, if any, knowledge of the principles involved, or instruction in its use, to derive maximum benefit. This paper describes a program of work which compares the performance of a passive ventilation system, installed in the kitchen and bathroom of a house of timber framed construction, in comparison with the use of mechanical extraction, window head ventilators, and opening of windows, as alternative means of ventilation. Particular emphasis is placed upon the influences of wind speed and wind direction. Using the ventilation rate measurements in conjunction with dry and wet bulb temperature data, rates of moisture extraction due to the four different means of ventilation are calculated, and the effects upon condensation risks are assessed in the light of predicted minimum ventilation rates required to avoid condensation. Comparison of predicted minimum and measured ventilation rates leads to the estimation of the effect of each type of ventilation upon space heating energy consumption.
KEYWORDS
condensation, passive ventilation, kitchen, bathroom, house, mechanical ventilation, window opening, wind speed, wind direction, ventilation rate

50.
Greater London Council
NO 680 Controlling condensation in dwellings - 1 - ventilation.
BIBINF
GLC Development and Materials Bulletin no.126 item 5 5p. DATE 01:03:1980 in English AIC 330
ABSTRACT
Discusses condensation within dwellings. Treats conditions conducive to reducing risk of condensation, factors which control concentration of water vapour in the air in a building and temperature of building fabric. Distinguishes between those under control of occupier and those controlled by design of building fabric. Considers in particular effect of ventilation on dewpoint of the air in bedrooms and humidity and temperature conditions in a bedroom during the day. Provides several case histories which illustrate relationship between ventilation and condensation.
KEYWORDS
condensation, residential building,

51.
Loudon, op. cit., ref. 1.

52.
Anon.
NO 1611 Ventilation with windows. Planning is the most important prerequisite.
Luften mit fenstern: die grundliche planung ist wichtigste voraussetzung.
BIBINF
Glas + Rahmen, September 1983, No 17, p915-920, 4 figs. DATE 00:09:1983 in German AIC 1017
ABSTRACT
It is necessary to design the ventilation system to avoid excess humidity in the apartments. Discusses the sources of moisture release in rooms, properties of air temperatures in relation to moisture absorption, condensation in bedrooms in particular, and moisture damage to building fabric. Advises on ventilation measures to control humidity.
KEYWORDS
natural ventilation, window, ventilation needs, humidity, condensation

53.
Erhorn E
NO 2312 Influence of the meteorological conditions on the inhabitants' behaviour in dwellings with mechanical ventilation.
BIBINF
7th AIVC Conference,"Occupant interaction with ventilation systems", 29 September - 2 October 1986, Stratford on Avon, UK, Bracknell, AIVC, 1986, p11.1-11.16, 10 figs, 2 tabs, 5 refs.
DATE 00:09:1986 in English AIC bk
ABSTRACT
Studies on occupants' ventilation behaviour were conducted in a demonstration building in Duisburg-Neumuhl (GDR). Analyses were based on values measured from January 1 - December 31, 1984 in 24 flats with identical ground plans, all of which were equipped with mechanical ventilation systems. Data on all opening positions of all openable window sashs and door leaves were continuously recorded, thus providing exact time data for all opening positions to be stored on data carriers. All available data had to pass two plausibility tests, which resulted in 70% of the main room data considered eligible for analysis. In evaluating the occupants' behaviour with regard to the different types of rooms, natural ventilation was found to be most frequent in bedrooms, followed, in decreasing frequency, by children's rooms and living rooms. When finally comparing the present results with studies on users' ventilation behaviour in flats with conventional window ventilation, it was found that in buildings with mechanical ventilation systems window ventilation duration is reduced to a quarter of the corresponding values recorded for buildings with traditional ventilation.
KEYWORDS
mechanical ventilation, occupant behaviour, flat, window, door, bedroom, wind speed, outdoor air, temperature, moisture

54.
Shelton J.W.
NO 34 The energy cost of humidification.
BIBINF
ASHRAE. j. January 1976, 18, (1), 52-55, 1 fig, 4 tabs, 4 refs. DATE 01:01:1976 in English AIC 1367
ABSTRACT
Points out that energy necessary to humidify air in a dwelling is usually far greater than consequent decreased sensible heat loss. Provides basic information necessary to calculate moisture deficit or surplus due to air exchange. Calculates rate of moisture addition or subtraction from air to house to maintain given humidity ratio. Determines under what circumstances humidification results in net savings of energy, describing factors affecting humidity in typical households. Concludes that net energy cost of humidification varies with each situation. Tabulates recommended maximum humidities as a function of outside temperature to avoid condensation problems.
KEYWORDS
humidity, residential building, energy losses

55.
Hoagland L C
NO 1798 Moisture removal characteristics of heat recovery ventilation systems utilizing a sensible rotary heat exchanger and comparison with stationary heat exchanger systems.
BIBINF
Moisture and Humidity 1985. Measurement and Control in Science and Industry. Proceedings of the 1985 International Symposium on Moisture and Humidity, Washington DC, April 15-18 1985. p965-972. 7 figs, 8 refs. DATE 00:04:1985 in English AIC 1172
ABSTRACT

Increased air tightness in new energy-efficient housing has led to serious problems with excessive indoor moisture in winter as well as with other trapped indoor air contaminants. Heat recovery ventilation systems are being used increasingly as an effective means to solve these indoor pollution problems by introducing fresh, drier outdoor air without the full penalty of the associated heating and cooling costs. Both stationary and rotary type heat exchangers are available for energy recovery. Stationary type heat exchangers with non-permeable membranes separating the exhaust air and fresh air streams typically reject all of the moisture contained in the exhaust air stream relative to the moisture content of outdoor air. Advocates of this type of heat exchange system claim that its moisture rejection capability offers an important advantage over the rotary type heat exchanger which only rejects part of this moisture at low outdoor temperatures. (Condensation deposited from the exhaust stream in the rotary heat exchanger is re-evaporated into the fresh air stream). The test and analytical results presented here for moisture rejection characteristics of rotary heat exchanger systems illustrate the following advantages for a rotary system designed to provide the recommended 1/2 air change per hour (ACH) mechanical ventilation in an average size home (1600 ft2) which has only 0.25 ACH natural ventilation. 1. Rotary exchanger system provides 12-16 litres per day moisture removal rate (required level for average family of 4) over a broad range of outdoor temperatures (down to -20 deg C and below) without developing indoor relative humidity levels that are either excessively high or uncomfortably low. 2. Due to their moisture transfer characteristics, rotary exchangers do not normally freeze up and require defrosting action as do stationary type heat exchangers. The absence of defrost cycles allows rotary heat exchangers to operate at considerably higher seasonal average heat recovery efficiency than stationary type exchangers.
KEYWORDS
moisture, heat exchanger

56.
Brundrett G.W. Barker R.
NO 80 Opportunities for energy conservation by heat pump dehumidifier and odour treatment.
BIBINF
E.C.R.C. Great Britain. DATE 01:01:1980 in english AIC 239
ABSTRACT
Discusses minimum ventilation necessary for occupied buildings and finds that occupiers minimum needs are based on dilution of body odours and that in Britain a high ventilation rate is necessary to reduce humidity. Describes two electrical solutions to the ventilation problem. The first is a combined ozone and ultra violet irradiation to oxidize the malodours. The second is the application of a heat pump dehumidifier to remove excess moisture in mild weather.
KEYWORDS
ventilation needs, heat pump, humidity, odour, ozone,

57.
Brundrett G.W. Blundell C.J.
NO 652 An advanced dehumidifer for Britain.
BIBINF
Heat.Vent.Eng. November 1980 vol.54 no.632 p.6-9 7 figs. 9 refs. DATE 01:11:1980 in English AIC 336
ABSTRACT
States condensation caused by high humidity is a major problem in British homes. Describes a conventional heat pump dehumidifier for removing moisture from the air. Describes the advanced dehumidifier developed by the Electricity Council Research Centre which is designed to work in cold damp conditions typical of British winters. Gives details of the design and reports that tests

of a prototype show that the design is more than twice as effective in terms of litres of water extracted per unit energy than conventional designs.
KEYWORDS
heat pump, dehumidifier, moisture, condensation,

58.
Brundrett and Galbraith, op. cit., ref. 4.

59.
Hansen A T.
NO 1467 Moisture problems in houses.
BIBINF
Canada National Research Council, Digest 231, 1984, 6pp, 3 figs, 8 refs, DATE 00:00:1984 in English, AIC 949
ABSTRACT
Examines the causes of condensation problems and ways of reducing or eliminating them. Deals with diffusion through the building envelope, mechanical dehumidification and ventilation. Considers condensation inside cavities and roof spaces
KEYWORDS
condensation, moisture, house, air infiltration, ventilation, roof, wall, roof space, mechanical ventilation, humidity, dehumidifier

60.
Anon
NO 2280 Testing acute condensation and mould growth remedies.
BIBINF
Building Trades Journal, 6 March 1986, Vol 191, No 5645. p36,38-39. 4 figs, 2 photos. DATE 06:03:1986 in English AIC 1590
ABSTRACT
A new Building Research Establishment audio-visual package, 'Remedies for condensation and mould in traditional housing' sets out the findings of field trials of some available remedies for condensation and mould, carried out in England and Scotland on estates which had a history of complaints of dampness. This research has led to a new understanding of the factors involved in the occurence of condensation and the ways in which they interact. Condensation is most likely to be a problem in the homes which use the least heating. In planning remedies for condensation and mould, the challenge is to find measures which will be effective even at low levels of energy usage. Remedies tested by BRE include improved wall insulation, by both cavity fill and external methods, extract fans under tenant or humidistat control, full and partial central heating, and domestic dehumidifiers. The effectiveness of fungicidal washes and paints was also tested. The results pointed to the effectiveness and cost of different remedies in varying situations, some of which worked very well, others having little effect.
KEYWORDS
condensation, insulation, fan

61.
Anon
NO 2134 Construction risks and remedies: Condensation. Part 2. The remedies.
BIBINF
Architects' journal, 16th April 1986, p69-81, 8 figs, 1 tab, 29 refs. DATE 16:04:1986 in English AIC 1519
ABSTRACT
Discusses methods of preventing condensation: dehumidification, ventilation, controlling vapour flow; insulation and heating. Particular attention is paid to interstitial condensation and condensation in roofs
KEYWORDS
Condensation, humidity, water vapour, dehumidification, ventilation strategy.

62.
Claesson J.
NO 195 Fundamentals of moisture and energy flow in capillary-porous building materials
BIBINF
Proc. Int. Seminar on Heat transfer in building, Dubrovnik August 29-September 2 1977, UNESCO, Yugoslavia Int. centre for heat mass transfer DATE 29:08:1977 in English. AIC 1368
ABSTRACT
Discusses basic physical features of combined energy and moisture flow in porous building material. Discusses mathematical and physical structure of these dynamic processes in terms of local thermodynamic equilibrium, flows induced by gradients in intensive state variables and conservation of energy, moisture and other components. Gives conditions for thermodynamic equilibrium, discusses peculiarities of pore-water tension, and problems concerning energy flow. Deals with the causes of hysteresis and the complications due to hysteresis.
KEYWORDS
moisture, wall

63.
Kohonen R.
NO 1426 Transient analysis of the thermal and moisture physical behaviour of building constructions
BIBINF
Building and Environment 1984, vol.19, no.1, 1-11, 8 figs, 8 refs. DATE 01:01:1984, in English, AIC 918.
ABSTRACT
For the transient analysis of the thermal and moisture oonditions in multilayer constructions a numerical algorithm and a computer program based on the Crank-Nicholson method and quasi linearisation are formulated. Temperature and moisture content are used as transport potentials. In energy balance equations and conditions, convention and accumulation of moisture, the diffusion flow of water vapour, the capillary and surface diffusion flow of liquid water and the viscous flow of humid air and water are considered. The boundary layer and interfacial balance equations are derived. The accuracy of the numerical algorithm is compared with an analytical solution for thermally semi-infinite body. The validity of the simulation method is verified by two experiments.
KEYWORDS
moisture, modelling, water, water vapour, boundary layer

64.
Belgium. Centre Scientifique et Technique de la Construction
NO 1483 Humidity problems in buildings
Problemes d'humidite dans les batiments
BIBINF
Technical information note 153, May-June 1984, 84pp, 28 figs, 23 tabs, 18 refs DATE 00:05:1984 in French AIC 1030
ABSTRACT
Treats the causes of deterioration in buildings, thermal bridges, the indoor climate, data for the design and execution of buildings and living conditions in rooms. Section headings are The formation of moulds, Humidity in buildings, The temperature factor, tau, as a criterion of the thermal quality of the structural elements, Conditions of occupation of buildings, Thermal bridges, Natural ventilation of buildings, Conclusions, Advice.
KEYWORDS
humidity, indoor climate, ventilation, natural ventilation, temperature, air tightness, moisture

65.
Tenwolde A.
NO 1697 Steady-state one-dimensional water vapor movement by diffusion and convection in a multilayered wall.
BIBINF
Preprint No 2879, ASHRAE Transactions, 1985, Vol 91, Pt 1. 20p. 11 figs, 9 refs. DATE 00:00:1985 in English AIC 1056
ABSTRACT
Current moisture analysis methods for walls ignore air leakage effects or are not directly applicable to multilayered walls. Mathematical equations were developed for water vapour flow, vapour pressures, and moisture accumulation under steady-state conditions with homogeneous one-dimensional airflow through a multilayered wall. A computer method was developed on the basis of these equations. With this method, a better qualitative understanding may be gained of the effects of air leakage on moisture accumulation. Sample analyses show that significant moisture accumulation should not be expected in nonhygroscopic cavity insulation, with or without air leakage. The location of condensation may change with changing air leakage rates. Diffusion vapour flow and temperatures are affected by air leakage. Consequently, diffusion and convection may not be treated as independent and additive. Doing so may lead to significant overestimates of moisture accumulation rates. Although the practical use of this method is limited, it is a step toward the development of more comprehensive and realistic methods of moisture analysis.
KEYWORDS
mathematical modelling, moisture, condensation, air leakage, wall

66.
Tsongas G.A. Odell F.G. Thompson J.C.
NO 461 A field study of moisture damage in walls insulated without a vapour barrier.
BIBINF
Proceedings ASHRAE/DOE Conference "Thermal performance of the exterior envelopes of buildings" 3-5 December 1979 Florida. DATE 04:12:1979 in English AIC 1372
ABSTRACT
Describes the results of a major study to find out whether or not wall insulation installed without a vapour barrier causes an increased risk of moisture damage within walls. The exterior walls of 96 homes in Portland, Oregon were opened. Presents results of field and laboratory tests which show the absence of indications of moisture damage. Gives data on shrinkage and settling of insulation and results of air leakage measurements by fan pressurization tests. Concludes that the addition of wall insulation without a vapour barrier does not cause moisture damage in existing homes.
KEYWORDS
vapour barrier, insulation, wall, moisture

67.
Cunningham M J.
NO 1578 A new analytical approach to the long term behaviour of moisture concentrations in building cavities - 1. Non-condensing cavity.
BIBINF
Building and Environment, 1983, Vol 18, No 3, pp109-116, 4 figs, 11 refs. DATE 00:00:1983 in English AIC 1004
ABSTRACT
This paper, the first of two, presents a conceptual model of moisture concentrations in a building cavity. The model is comprehensive and general considering air infiltration, vapour diffusion and material hygroscopicity under non-steady state conditions. The resulting linearised coupled differential equations are analytically solved to study the case of long term

cavity moisture behaviour. Dimensionless parameters and algebraic formulae are presented describing all important moisture performance parameters for a non-condensing cavity. Two primary time constants are identified, and a third, which governs the drying rate, derived. This allows the identification of three drying regimes based on cavity tightness. Some general design recommendations are given.
KEYWORDS
building components, roof, moisture, wood frame, mathematical modelling

68.
Cunningham M J.
NO 1579 A new analytical approach to the long term behaviour of moisture concentrations in building cavities - 2. Condensing cavity.
BIBINF
Building and Environment, 1983, Vol 18, No 3, pp117-124, 3 figs, 5 refs. DATE 00:00:1983 in English AIC 1005
ABSTRACT
A previous paper analysed a mathematical model of a non-condensing cavity. This paper extends the analysis of the first paper to analyse the seasonal moisture behaviour of a condensing building cavity. Climate statistics are used to calculate the duration of the winter wet-up period, and a rate of condensation formula is integrated to give total winter condensation. Although engineering design calculations cannot yet be attempted, some illustrative examples are given based on field data. The results give preliminary verification of the model analysed in both papers.
KEYWORDS
building components, roof, moisture, wood frame, condensation, mathematical modelling

69.
Cunningham M.J.
NO 1382 Further analytical studies of building cavity moisture concentrations.
BIBINF
Building and Environment vol.19 no.1 p.21-28 1984 6 figs. 1 tab. 15 refs. DATE 01:01:1984 in English AIC 886
ABSTRACT
The model of moisture concentrations in a building cavity containing hygroscopic material presented in earlier works is extended to allow for evaporating surfaces within the cavity (eg soil, water tanks) and fluctuating external climatic conditions. Linearized coupled differential equations are solved for three cases - 1. Steady state 2. Step function 3. Periodic climate driving forces. The third case gives formulae predicting the cavity moisture contents at any time of day or year, and shows that the steady state approximation is adequate for all but the tightest cavities. Field results give good agreement with model predictions.
KEYWORDS
modelling, moisture, cavity,

70.
Trethowan H A.
NO 1561 Current research in building moisture control.
BIBINF
Annual Conference, Institution of Professional Engineers of New Zealand, February 1983. Paper 30. 8pp, 5 refs. DATE 00:02:1983 in English AIC 953
ABSTRACT
Evidence of the importance of air infiltration in moisture control in building structures has been steadily accumulating. A general model of moisture behaviour in structures has been built up including for the effects of cavity air leakage, for the hygroscopic behaviour of timber, for the effects of

condensation and various geometric factors. Current projects include sorption properties of New Zealand building materials, combined heat/moisture transfer in cavities, ground evaporation, field studies on roof space condensation problems and laboratory tests on moisture behaviour and related heat flow behaviour in several roof types.
KEYWORDS
wood, building components, moisture, humidity, roof space, condensation, roof

71.
Hardy A.C.
NO 1415 Timber frame construction and interstitial condensation.
BIBINF
Proc.CIB Workshop on indoor air quality and energy conservation Helsinki June 1983 ESPOO Report B3 p.VI.1-VI.7 5 refs. DATE 01:06:1984 in English AIC bk, AIC 1829
ABSTRACT
States that the higher internal humidity and lower structural temperatures in UK timber frame houses, as compared to the US and central Europe increases the risk of interstitial condensation. Condensation risk has also increased in all countries because of energy conservation measures and changes in heating patterns, occupation density and moisture production. Gives recommendations for the prevention of interstitial condensation.
KEYWORDS
wood frame, house, condensation,

72.
Wilson A.G. Garden G.K.
NO 63 Moisture accumulation in walls due to air leakage.
BIBINF
Canada NRC, Divn. of Bldg. Res., NRC 9131, 9 pp, 4 photos, 2 diagrs, 2 tabs. D.B.R. technical paper no. 227 DATE 01:08:1965 in English AIC 1168
ABSTRACT
A number of cases of water and frost damage in masonry and non loadbearing walls have been examined. This damage could not have resulted from vapour diffusion or rain penetration and is primarily caused by condensation due to exfiltration of air. Air exfiltrates through the many cracks and joints and in this connection the result of chimney action and wind is explained in some detail, including the pattern and magnitude of building pressure differences that induce ex-filtration together with a discussion regarding the moisture that is transferred. Some examples of related building failures are described.
KEYWORDS
air infiltration, condensation, crack, joint, stack effect, wind, pressure difference, moisture

73.
Anon, op. cit., ref. 42.

74.
Roloff J
NO 696 On the relationship between ventilation and condensation protection of buildings.
Zur zusammenhang zwischen Luftung und Feuchtigkeitsschutz von Gebauden.
BIBINF
St. Gebaud April 1980 vol 34, no 4, p106-109 6 figs, 6 refs. DATE 01:04:1980 in German AIC 1374
ABSTRACT
Treats drawbacks of current methods used in East Germany of calculating vapour barriers used to protect building elements from condensation. Notes building materials for which moisture absorbed in winter is sufficient to cause condensation damage before it has diffused in summer. Develops method based on

calculation model of determining direct relation between any period of condensation and requisite vapour barriers. In addition amount of water accumulated during condensation period can also be determined. Notes part which ventilation plays even for apparently purely structural solutions.
KEYWORDS
vapour barrier, condensation, theoretical modelling

75.
Dutt, op. cit., ref. 27.

76.
Burch and Luna, op. cit., ref. 33.

77.
Sawers J W
NO 955 Condensation in the home: where, why and what to do.
BIBINF
CMHC/SCHL Report NHA 5319 03/85 1984 rev 29pp 40 figs. 2 tabs. DATE 00:00:1985 in English and French AIC 566
ABSTRACT
Defines types of condensation occurring in houses and describes practical ways for the householder to control surface and concealed condensation. Gives instructions to builders for installing air/vapour barriers to meet the required standards, and shows ways in which ventilation can control condensation.
KEYWORDS
condensation, vapour barrier, house,

78.
Johnson, op. cit., ref. 44.

79.
Loudon, op. cit., ref. 1.

80.
Brundrett and Galbraith, op. cit., ref. 4.

81.
Kusuda T.
NO 1192 Indoor humidity calculations.
BIBINF
Preprint Ashrae Transactions 1983 vol.89 pt.2A and B 12pp. 13 figs. 6 refs. DATE 01:01:1983 in English AIC 748
ABSTRACT
Compares measured hourly data on indoor humidity with data obtained by calculative values for NBS Houston test houses and for the high mass test building in an environmental chamber. Measured values are usually very different from the calculated values if no considerations are given to moisture absorption and desorption phenomena that take place at the interior surfaces. Introduces the Tsuchiya model that permits the evaluation of room surface moisture absorption capability. The model is based upon the detailed simulation calculation for room moisture balance that includes surface condensation evaporation and absorption/desorption coefficients. These coefficients are determined in such a manner that the measured room humidity levels coincide with the calculated values.
KEYWORDS
humidity, modelling,

82.
Miller J.D.

NO 1395 Development and validation of a moisture mass balance model for predicting residential cooling energy consumption.
BIBINF
Preprint ASHRAE 1984 Annual Meeting Kansas City USA 17-20 June 1984 18pp. 10 figs. 2 tabs. 9 refs. DATE 17:06:1984 in English AIC 899
ABSTRACT
To simulate time-dependent interior humidity, a moisture mass balance is applied to the control volume of the envelope of a residential structure. Moisture transport mechanisms incorporated include infiltration, cooling coil condensation, internal generation from occupants, sorption from hygroscopic building materials, reevaporation of condensate, and air-to-air heat exchangers. Presents equations and computer algorithms. Comparisons of model predictions and experimental data demonstrate acceptable accuracy. Gives details on the application of the model in generating a regression equation that calculates seasonal performance factors (SPF) for cooling equipment. Inputs to the equation are - infiltration characteristics of the structure, summer humidity ratio hours, thermostat set point and equipment EER. Presents a database of humidity ratio hours generated from TRY weather tapes. Plots of SPF show strong variation with summer humidity ratio hours.
KEYWORDS
modelling, prediction, energy consumption, humidity, air infiltration, moisture,

83.
Lubke, op. cit., ref. 20.

84.
Cunningham, op. cit., ref. 57.

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Cunningham, op. cit., ref. 58.

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Cunningham, op. cit., ref. 59.

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Greater London Council, op. cit., ref. 35.

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Greater London Council, op. cit., ref. 36.

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Greater London Council, op. cit., ref. 37.

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Burch, op. cit., ref. 34.

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Cleary, op. cit., ref. 29.

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Kohonen, op. cit., ref. 53.

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Tenwolde, op. cit., ref. 55.

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Air Infiltration and Ventilation Centre

Old Bracknell Lane West,
Bracknell, Berkshire,
Great Britain,
RG12 4AH.

Tel : National 0344 53123
International + 44 344 53123
Telex: 848288 (BSRIAC G)
ISBN 0 946075 31 1

Operating Agent for International Energy Agency, Oscar Faber Consulting Engineers, Upper Marlborough Road, St. Albans, Herts, Great Britain