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HUMIDITY IN ATTICS - SOURCES AND CONTROL METHODS

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ABSTRACT

Guidelines for the control of moisture in attics are in a state of flux. The 1981 ASHRAE Handbook of Fundamentals gives only "Past Practice", and notes that such practice might not be currently valid. Furthermore, in the past it was assumed that the attic was an inert structure on which moisture would either condense or pass through unaffected.

Results are presented which show that the attic is in a constant state of flux, absorbing and releasing moisture. A mathematical model for predicting the moisture content of attic wood members is presented. The model is used to predict hour-by-hour attic air humidity ratio, and seasonal wood moisture content. Results are compared with measured data.

The application of the model to the re-calculation of attic ventilation standards is discussed, both with respect to condensation and wood rot.

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INTRODUCTION

There is general agreement among experts in the field that attics should be ventilated to prevent condensation and wood decay. Rules of thumb exist for the area of vents needed for houses in various parts of the U.S., but these are not supported by hard data. For example, the Fundamentals Handbook of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in 1981 changed the status of attic ventilation rules from "Recommended Good Practice" to "Past Practice", noting:

> Prior to the advent of well insulated, tightly constructed housing, general recommendations concerning the use of vapor retarders and attic ventilation were made in earlier editions of the ASHRAE Handbook. The research and studies that formed the basis of these recommendations were based on representative post World War II single-family residential construction. Although these recommendations may no longer be precisely valid by virtue of modern construction practices, a summary follows as a point of reference. The other material in this chapter is more up to date. [1]

The rules of thumb have been used with success in existing construction. But modern energy conservation practices, such as the use of greatly increased attic insulation levels and the introduction of various forms of ceiling moisture and air barriers, have radically changed the conditions found in attics. The lower temperatures and higher humidity levels now found in attics may demand quite different strategies if moisture damage is to be prevented. There is a body of anecdotal evidence that indicates that moisture transport in well-insulated houses is not yet understood. For example, at the recent "Superinsulation Forum"[2] in Rochester, Minnesota, a full morning was devoted to discussions on the topic "Moisture Problems and Air Vapor Barrier Installation in Cold and Warm Climates".

The classic concept of attic ventilation is as follows. The roof is an inert weather shield for the ceiling. Outside air enters the attic, mixes with warm moist air entering the attic from the house, and comes into contact with the underside of the roof. If the temperature of this 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."[3]

It will be shown below that this picture is skewed. The roof sheathing is far from inert. Even a well-ventilated attic, with no signs of water anywhere, might absorb one hundred kilograms (220 pounds) of moisture over the course of a winter, and release it in the spring. In the early winter, moisture is absorbed directly from the air into the wood. The moisture content of the wood increases, and no condensation occurs. In the spring, the reverse flow takes place. Water vapour is driven off, and the wood moisture content decreases. Water problems can occur in three ways. Water might be delivered to the surface faster than it can be absorbed; if that happens, condensation will occur. Secondly, the wood might become saturated with water; free water will collect within the wood, and its structural properties will be degraded. Thirdly, in the spring the wood could warm up before it dries out, in which case fungus could attack the wood.

To predict ventilation strategies for avoidance of condensation, structural problems and conditions that lead to wood rot, a theory is needed which includes moisture storage and transport.

A study of moisture flows in attics was undertaken by Lawrence Berkeley Laboratory, and a theoretical model developed. This paper presents that model, and indicates the further research that will be needed if attic ventilation is to be placed on a sound footing. This paper does not give full technical details of the measurement techniques, which will be found in papers still in preparation.

EXPERIMENTAL PROCEDURE

The attic of a single-family unoccupied house in Oroville, California, was monitored over the six-month period December 1983 - May 1984. (See Figure 1.) Oroville is located in the northeast Sacramento valley, approximately 120 km (75 miles) northwest of Sacramento.

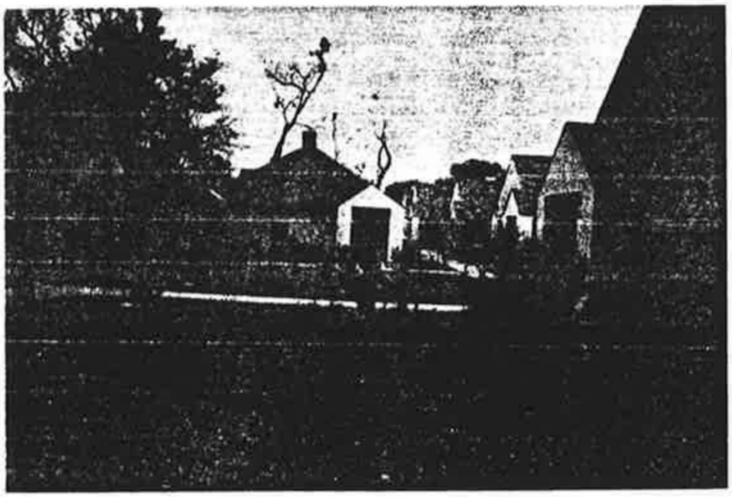

Figure 1. Winston Gardens, public housing for the elderly in Oroville, California

The winter is mild. Chico, about 30 miles away in the same climate-zone, has the following 30-year averages[4]: 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 a single-story, 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). It was built to the US Department of Housing and Urban Development's Minimum Property Standards (HUD MPS), and has RSI 3.3 (R-19) fiberglass batt insulation in the attic. Venting is by 1000 cm^2 (156 sq inches) of soffit vents along one side of the house, 1850 cm^2 (288 sq inches) of vent area above a porch on the opposite side of the house, and there is a thermally operated 30 cm (12 inch) diameter flap-damper in a cupola on the ridge. The house is part of Winston Gardens, a housing project for the elderly in the County of Butte.

To ensure a complete data set was collected, a large number of parameters were measured continuously at the site, included outside air dry bulb temperature and dew point, wind speed and direction, total horizontal solar radiation, attic sheathing temperature at four points, wood electrical resistance (to find wood moisture content) at three points, attic air dew point, inside temperature, and inside relative humidity. Readings were taken every ten-seconds, and half-hour averages were stored on magnetic floppy disk[5]. Periodic measurements of attic ventilation rate were made by sulfur hexafluoride injection and decay. The data set is perhaps two-thirds complete for the six-month period. Problems occurred with many parts of the data collection system, including the disk drives and the chilled-mirror dew-point sensors.

RESULTS AND ANALYSIS

Figure 2 shows the outdoor and attic air humidity ratios for four days in January. (Humidity ratio is the weight of water contained in a sample of moist air divided by the weight of the dry air.) There is a distinct 24-hour periodicity to the data. This was unexpected in the outdoor data, and is probably a result of the placement of the hygrothermograph only 45 cm (18 inches) above the ground, directly beneath the attic vent above the porch. What may happen is that dew falls during the night, and is evaporated during the day. The variation in the attic humidity ratio has a similar explanation, since it precisely matches that of the temperature of the underside of the roof sheathing, shown in Figure 3.

The striking correlation between attic humidity ratio and roof sheathing temperature led to the hypothesis that as the sheathing was heated by solar radiation, it emitted water into the attic air. This is in contrast to the classic picture, where the attic humidity ratio is equal to the outside air humidity ratio unless condensation occurs on some surface inside the attic.

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:

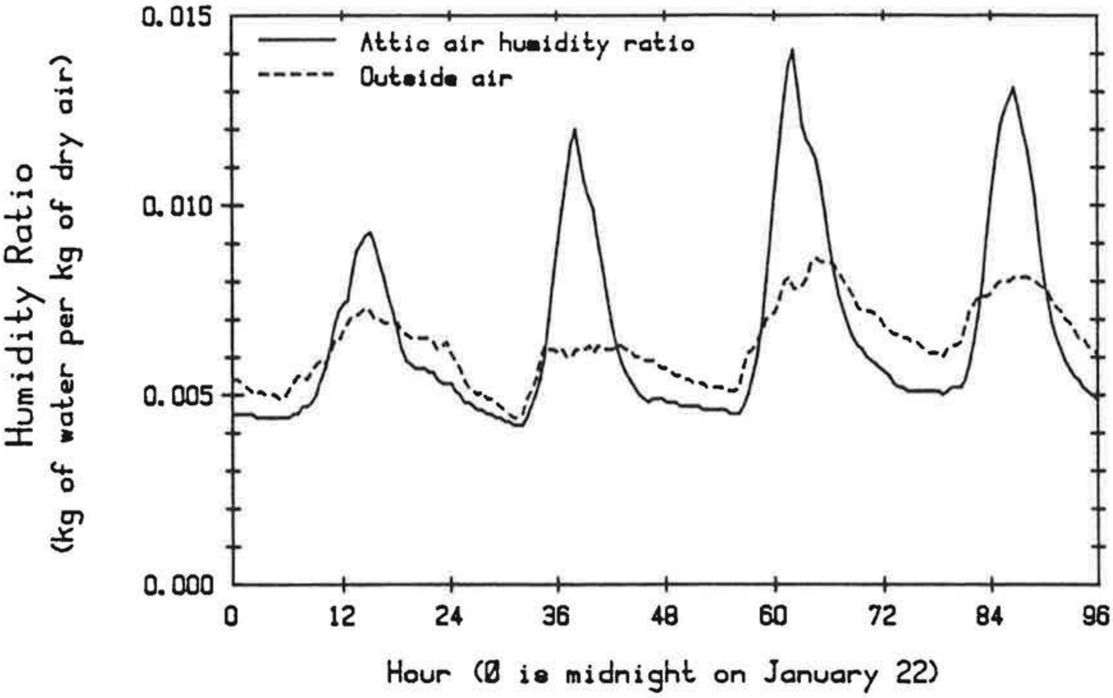

Figure 2. Humidity ratio of the outside air and of the air inside the attic of the Oroville house, January 22 to 25, 1984

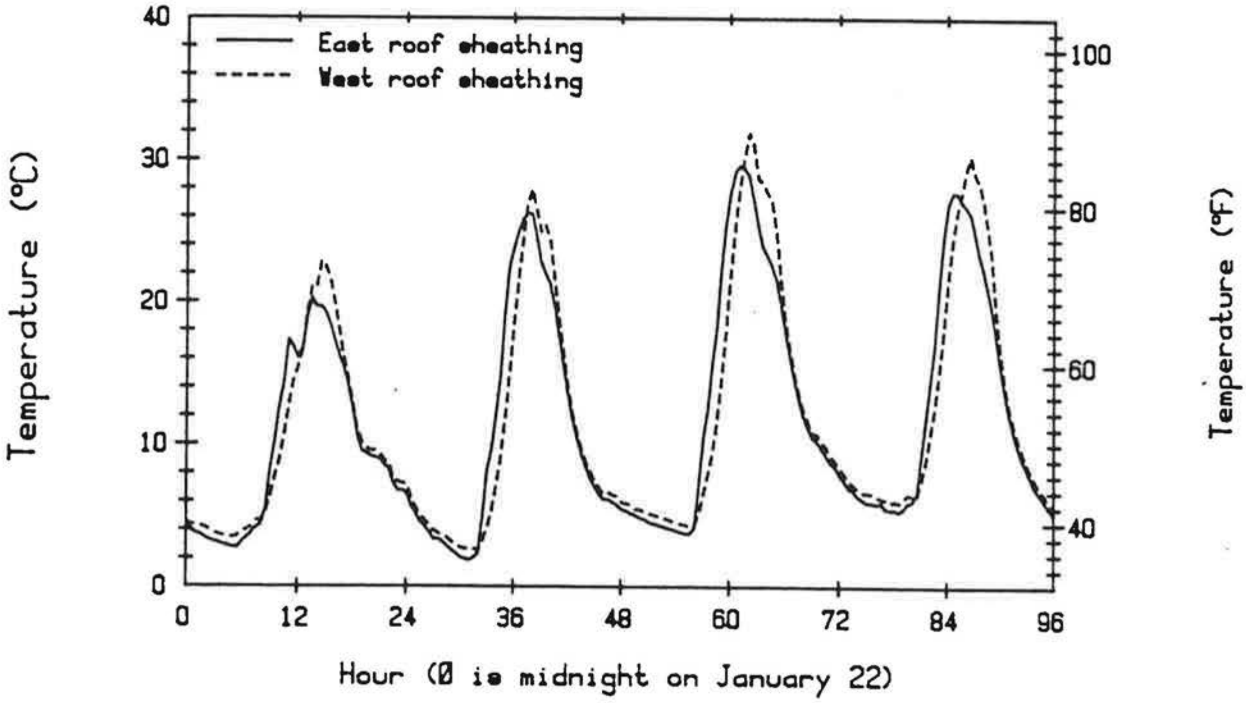

Figure 3. Temperatures of the underside of the roof sheathing in the attic of the Oroville house, January 22 to 25, 1984

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

where

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

M - the (dry) mass flow rate of ventilation air kg/s (lb/hour)

W_{attic} - the attic air humidity ratio, unitless

$W_{outside}$ - the outside air humidity ratio, unitless

In an occupied house, a third term would have to be added for transport into and out of the living space. 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. Attic-outside temperature difference was found not to significantly affect ventilation rate. From the measured windspeed and the correlation, a ventilation rate was found. The calculated moisture flow rate for this period is shown in Figure 4. It can be seen that the flow peaks just after noon each day, and that during the night the attic 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 24 January. Over the four-day period, the attic emits a total of over 10 kg (22 lb) of water. Again, this 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. Research by Ford[6,7] at Princeton indicated the possibility of such dynamics, and later condensation studies by Burch[8] at NBS have confirmed it. Kusuda[9] at NBS has found similar effects in living spaces, following on work by Tsuchiya[10] in Japan.

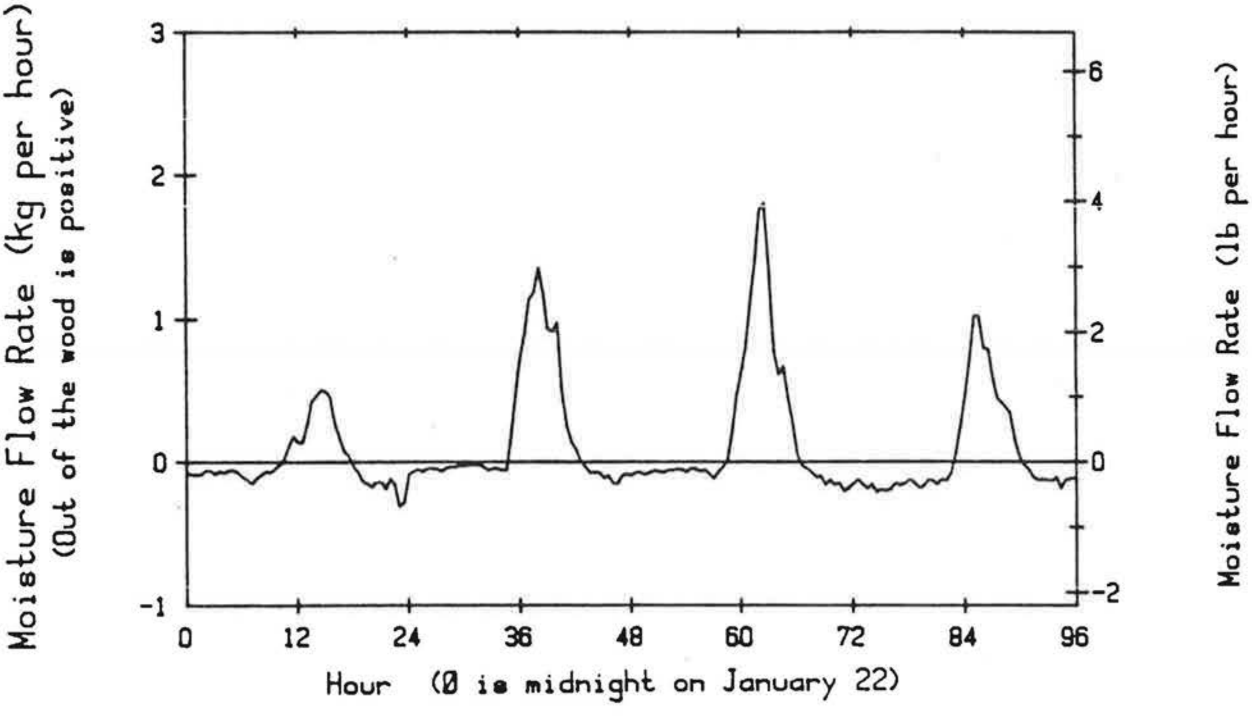

Figure 4. Moisture flows into and out of the wood members of the Oroville attic, January 22 to 25, 1984

A simple model has been developed to predict the flow of water into the roof sheathing. (For a more complete analysis of moisture and heat flow, see Kohonen and Maatta[11]). Following standard models of mass flow, e.g. Kays and Crawford[12], the flow of water from the wood is given by:

$$m = k\ A\ (W_{surface} - W_{free}) \tag{2}$$

<u>where</u>

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

The transfer coefficient, assuming a Lewis relationship of 1.0 (see, for example ASHRAE Fundamentals[13]), is approximately equal to:

$$k = h_c/C_p \tag{3}$$

<u>where</u>

- h_c - the convective heat transfer coefficient, $W/m^2.^oC$ ($Btu/hour.ft^2.^oF$)
- C_p - the specific heat of moist air, $J/kg.^oC$ ($Btu/lb.^oF$)

The surface film humidity ratio may be found from data on wood properties, e.g Table 3-4 of the Wood Handbook[14] gives the moisture content of wood at various temperatures and relative humidities. (The data is said to apply to wood of any species.) Using standard psychrometric routines, this data was transformed into humidity ratio for various combinations of temperature and wood moisture content, and a curve fit made to the data. The curve fit gives the surface film humidity ratio as a function of wood moisture content and temperature.

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

$$W_{attic} = \frac{\dfrac{A\ k\ W_{surface}}{M} + W_{outside}}{1 + \dfrac{A\ k}{M}} \tag{4}$$

This equation predicts attic humidity ratio as a function of roof sheathing area, ventilation rate, outside humidity ratio, and roof sheathing surface film humidity ratio (itself a function of wood moisture content and roof sheathing temperature). A comparison of the predicted (using the average half-hourly roof sheathing temperature) and measured humidity ratio for the Oroville attic is shown in Figure 5. Good agreement is seen.

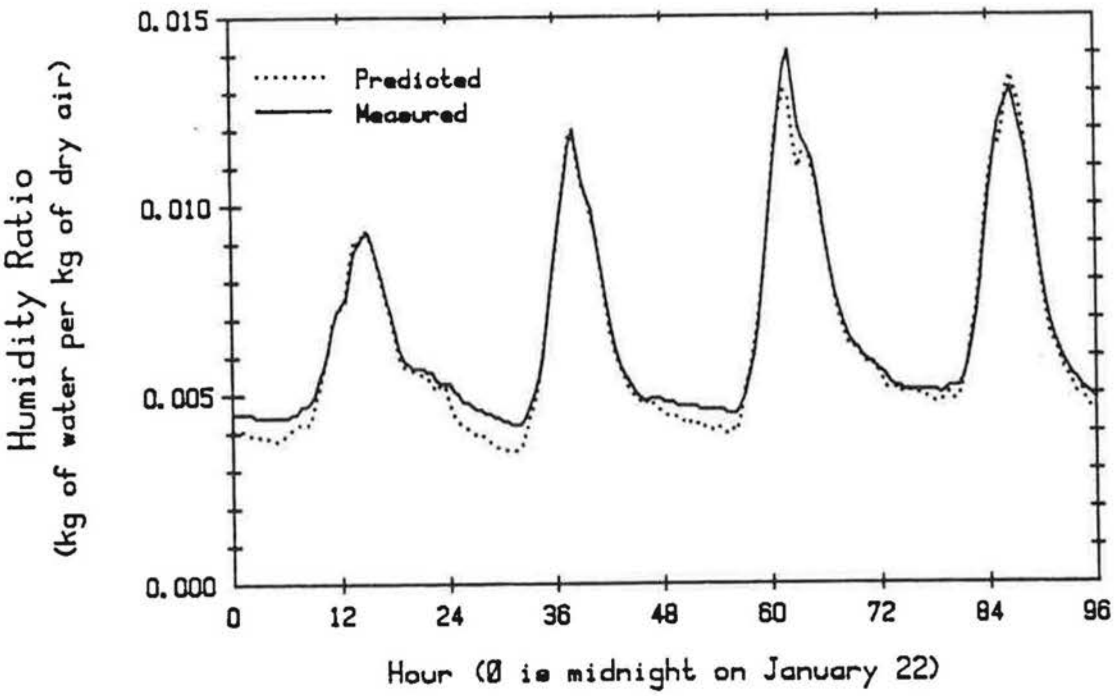

Figure 5. Measured attic air humidity ratio compared with that predicted from Equation 4. Data is for the Oroville attic for the period January 22 to 25, 1984.

The hour-by-hour flows may be integrated to calculate the seasonal variation in wood moisture content. Ford[7], and Dutt[15] have measured the seasonal effects in roofing members. In the houses near Princeton, New Jersey, that they measured, they found that the wood reached a peak moisture content in mid-winter, and that it dried out in the spring. The same effect has been observed by Hans[16] in Madison, Wisconsin. A similar variation, this time in wood samples stored indoors, was observed at the Princes Risborough Laboratories in the U.K. in 1946-1948 and reported by Desch[17]. The results for the Oroville house are shown in Figure 6. It can be seen that during the whole period, 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 70 kg (154 lb) of water.

The model can be used to predict the seasonal storage and release of moisture from the attic. This is done by integrating Equation 2 with respect to time. Because of the gaps in the Oroville data set, this cannot be done for that house. However, the late Gunard Hans of the Forest Products Laboratory, Madison, Wisconsin, collected hygrothermograph data for an attic almost continously over the 1982-1983 winter[16]. (There is a three-week gap in February, 1983 when the hygrothermograph was moved inside the house.) This data has been used to test the model.

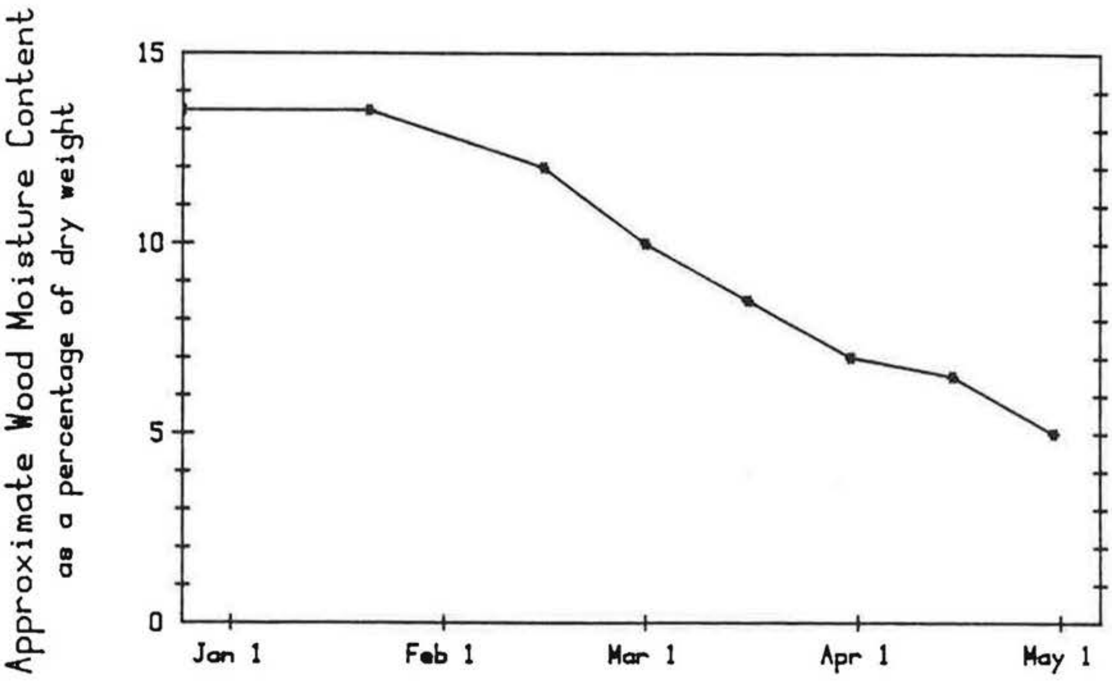

Figure 6. Percentage wood moisture content (kg of water per 100 kg of dry wood) for the Oroville attic for the winter 1983-1984

Flow of water into the attic from the wood lowers the wood moisture content, as given by:

$$\text{delta } C = \frac{-\,m\,t}{A\,r\,d} \tag{5}$$

where

delta C - the change in fractional wood moisture content, i.e weight of water removed divided by dry weight of wood
m - the rate of water flow from the wood, kg/s (lb/hour)
t - the time interval, s (hours)
A - the transfer surface area, m^2 (sq. feet)
r - the density of the wood kg/m^3 (lb/cubic foot)
d - the thickness of the wood, m (feet)

To calculate the variation of wood moisture content with time (given a series of values of wood temperature and attic humidity ratio) the first step is to estimate a starting wood moisture content, C. From the curve fit for this value of C and the wood temperature, a value of $W_{surface}$ is found. This value is used in equation 5 to calculate a value of delta C, which gives a new value for C. This loop is then repeated for the next pair of values of wood temperature and attic humidity ratio. Eventually, there has been so much transfer of moisture into and out of the wood that the wood moisture content is independent of the starting value. The wood moisture content over a long term can be predicted from attic humidity ratio and roof sheathing temperature.

This process has been carried out for Gunard Hans' data, which are attic air temperature and relative humidity. The roof sheathing temperature may be expected to be less than the attic air temperature in winter and more than the attic air temperature in summer, so some systematic error is expected. The comparison between predictions and measurements is shown in Figure 7. Reasonable agreement is seen.

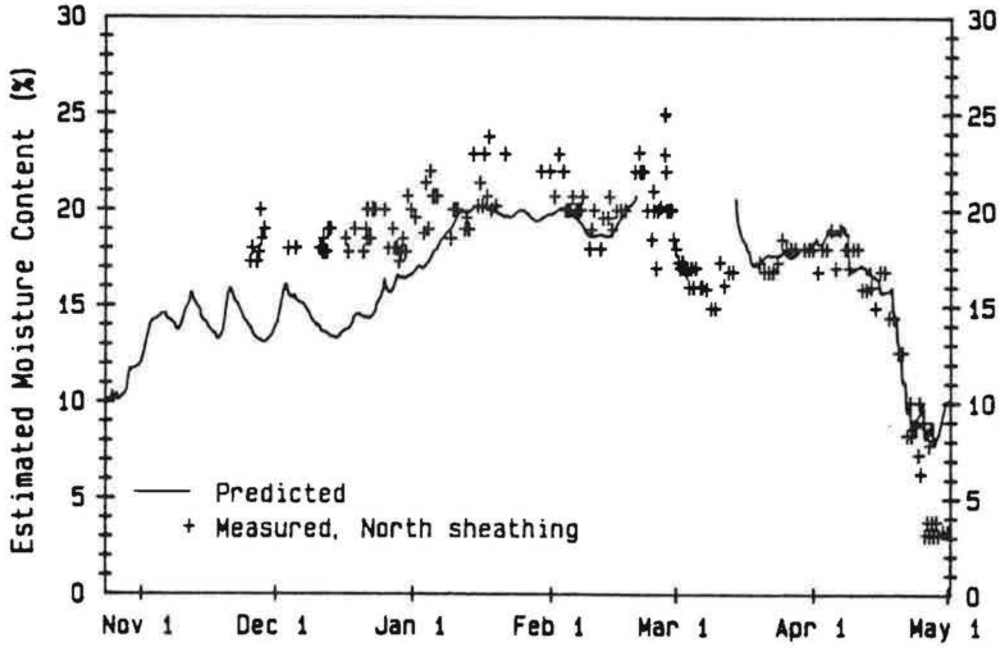

Figure 7. Measured wood moisture content (kg of water per 100 kg of dry wood) compared with that predicted by theory for the winter of 1982-83 for an attic in Madison, Wisconsin.

DISCUSSION

In the classic picture of an attic, the roof sheathing is inert. When its temperature drops below the attic air dew point, condensation occurs. In reality, the roof sheathing is in dynamic equilibrium with the air. There is considerable flow of water into and out of the roof sheathing.

In the Oroville test house, condensation was never observed. As for moisture flows, for one four day period in January, peak flow was almost 2 kg/hour (4.4 lb/hour). A typical moisture generation rate for a family of four is 10 kg/day (22 lb/day). In a leaky house, 25% of air exfiltration[18] could be through the ceiling, resulting in a moisture flow rate of 0.10 kg/hour (0.23 lb/hour) into the attic. In the Oroville attic, such a flow would be seen as only be a small perturbation in the normal daily flux of water, and would be difficult to detect. However, moisture from the house could make a considerable difference over the complete winter, as it would steadily increase the wood moisture content. A vapour barrier or air barrier could control the flow from the house, but would not control the build up of moisture from the ventilation air.

According to this model, condensation will occur when moisture is delivered to the wood surface faster than it can be absorbed. Experience has shown that small jets of warm moist air leaking into the attic can cause condensation. The model presented above assumes perfect mixing, and cannot rule out the possibility of local condensation in an otherwise problem-free attic.

Wood rot will occur when conditions are conducive to fungal growth. The Wood Handbook [19] states that decay is "relatively slow at temperatures below $50^{o}F$ and much above $90^{o}F$", and "Fully air-dry wood usually will have a moisture content not exceeding 20 percent, and should provide a reasonable margin of safety against fungus damage." As a result, wood rot might be expected in the spring and fall; in summer and winter attic temperatures usually fall outside the danger area. Thus if the purpose of attic ventilation is to prevent rot, it should ensure that wood moisture content is at or below 20 % during these periods, perhaps by thermostatically controlled vents. A higher moisture content might be permitted in the depths of winter.

More research is needed before such strategies can developed. For example, there is no model that predicts attic ventilation rate as a function of weather and vent type, location, and size. Present attic thermal models (for example any one of the models discussed in Wilkes[20]) do not include air and moisture transport to and from the living space, and do not consider latent heat from moisture absorption. A basis for a more comprehensive model may be found in Kohonen and Maatta.[11]

CONCLUSION

A simple model has been presented which treats the moisture flow in an attic as a function of roof sheathing temperature, wood moisture content, outside humidity ratio, and attic ventilation rate. The model is shown to predict the hour-by-hour attic humidity ratio well for a house in Oroville, California, and reasonable agreement is shown for seasonal moisture storage in an attic in Madison, Wisconsin.

Once more research has been performed on attic ventilation rates and air and moisture flow between the attic and the living space, the model could be used to determine optimal attic ventilation strategies. For example, it might be determined that to prevent the combination of roof sheathing temperature and wood moisture content could lead to fungus attack, and that attic ventilation was only necessary when these temperatures occurred. If increased ceiling insulation levels are not to lead to increased moisture problems in attics, a better understanding of attic dynamics is essential. This model can form a small part of such an understanding.

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