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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.

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INTRODUCTION

The classic picture of an attic is that it is an unconditioned buffer space, protecting the ceiling below from the full force of the weather. An attic is usually naturally ventilated, so that its air temperature and relative humidity are determined both by the weather, and by air and moisture transport from the living space below. The aim of the ventilation is to prevent condensation. Moisture enters the attic from the house (both by convection and diffusion), and mixes with the usually drier ventilation air. During the day, the attic is heated by solar radiation. At night, the roof sheathing cools down due to sky radiation losses; its temperature can drop below the outside air temperature. If it drops below the attic air dew point temperature, condensation will form on the roof sheathing. More ventilation can prevent this, since it will result in a generally drier air mixture in the attic.

The rules of thumb for attic vent areas that prevent condensation were developed several decades ago. At that time, very little insulation was installed in attics, and so attics were rather warm on winter nights because of heat transfer through the ceiling. The current trend is towards ever-increasing depths of insulation, and thus ever colder attics. If the classic attic picture applies, colder attics require more ventilation, or a better method to prevent moisture transport from the house. A study was begun at Lawrence Berkeley Laboratory to determine how much more ventilation was needed to prevent condensation in a well-insulated attic. This work was begun at the request of the late Gunard Hans of the US Department of Agriculture's Forest Products Laboratory. He was a major contributor to the 1981 revision of Chapter 21 of the ASHRAE Fundamentals Handbook, "Moisture in Building Construction". In this edition, the status of the attic ventilation rules was changed from "Recommended Good Practice" to "Past Practice".[1]

A literature survey, and communications with Doug Burch at the National Bureau of Standards, Gautam Dutt at Princeton University, and Gunard Hans himself revealed a general consensus that the classic attic picture was incomplete. The missing piece was thought to be moisture storage in the wood members of the attic. To investigate this possibility, an experimental study of an attic was carried out, with the aim of quantifying moisture storage.

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 itself. The winter is mild. Chico, about 30 miles away in the same climate-zone, has the following 30-year averages[2]: January minimum temperatures 2.2 ^{o}C (36.0 ^{o}F), 1599 base 18.3 ^{o}C centigrade annual heating degree-days (2878 base 65 ^{o}F Fahrenheit degree-days), and an annual rainfall of 66 cm (26 inches). Figure 2 shows outside dry bulb temperature and total horizontal solar radiation measured at the site for four days in January, 1984.

The house is 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^2) and a thickness of 12.7mm (0.5 inch), is 923 kg (2030 lb). 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 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, and there is a thermally operated 30 cm (12 inch) diameter flap-damper in a cupola on the ridge. The unit shares part of one wall with an adjacent unit; there is no connection for air flow between the attics. The house is part of Winston Gardens, a housing project for the elderly in the County of Butte.

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[3]. 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.

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 small. On the one occasion when it was measured, 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 house heating system is a forced-air heat pump, which was thermostated at 17 ^oC (63 ^oF) for the early winter and later at 23 ^oC (73 ^oF). It was found that 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 inexpensive ($600) chilled-mirror hygrometers. 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. 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 calibrated AD590 solid-state sensors, two terminal integrated circuits which produce a current of 1 micro-ampere per degree Kelvin. The sensors were epoxied to copper discs, and the copper disks nailed on 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 roof sheathing 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 every three minutes with an inexpensive solid-state ohm-meter developed at Lawrence Berkeley Laboratory. It was found to range from a low of 10^7 ohms to a high of 10^{12} ohms.

Wood resistance varies with both moisture content and temperature. It varies with temperature according to the equation[4]:

$$R = A\,e^{B/T} \qquad (1)$$

where R is the measured wood resistance, ohms
A is a constant, ohms
T is the wood temperature, K (R)
B is a constant, K (R)

The values of the constants vary with wood moisture content. To reduce the values to a standard temperature, plots were made of the logarithm of wood resistance against 1/T, and a linear extropolation (or interpolation) made to a wood temperature of 25 $^{\circ}$C (77 $^{\circ}$F). Figure 3 shows this data for two selected days. The corresponding wood moisture content was found from table 1 in Electric Moisture Meters for Wood[5]. The table entry for coastal Douglas Fir was taken.

RESULTS AND ANALYSIS

Figure 4 shows the outdoor and attic air humidity ratios for the same four days in January shown in Figure 2. 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 unit 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 5.

The striking correlation between the attic humidity ratio and the 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 of attics, 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:

$$m = M(W_{attic} - W_{outside}) \tag{2}$$

where:
m is the rate of water flow from the wood kg/s (lb/hour)
M is the (dry) mass flow rate of ventilation air kg/s (lb/hour)
W_{attic} is the attic air humidity ratio, unitless
$W_{outside}$ is 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. Temperature differences between the house, the attic and outside were not found to have a significant effect on the ventilation rate. Figure 6 shows the measurements and the correlation. The scatter is assumed to result from the effects of different wind directions. From the measured windspeed and the correlation, a ventilation rate was found for each half hour. The calculated water flow rate for this period is shown in Figure 7. 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. (It should be noted that all this water is released in the form of water vapour; no condensation was observed during the course of this study.) 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 careful condensation studies by Burch and co-workers[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.

These daily flows accumulate to produce a seasonal variation in wood moisture content. Ford[7] and Dutt[11] 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[12] 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 in Desch[13]. The results for the Oroville house are shown in Figure 8. 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.

THEORETICAL MODEL

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[14]). Following standard models of mass flow, e.g. Kays and Crawford[15], the flow of water from the wood is given by:

$$m = k\ A\ (W_{surface} - W_{free}) \qquad (3)$$

where m is the flow of water kg/s (lb/hour)
k is a transfer coeffficient, kg/m^2.s (lb/ft^2.hour)
A is the transfer surface area, m^2 (ft^2)
W_s is the humidity ratio of the air surface film, unitless
W_{free} is 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[16]), is approximately equal to:

$$k = h_c/C_p \qquad (4)$$

where h_c is the convective heat transfer coefficient W/m^2.°C (Btu/hour.ft^2.°F)

C_p is the specific heat of moist air, J/kg.°C (Btu/lb.°F)

In imperial units, this transfer coefficient for the roof is, within the limits of overall experimental error, equal to unity (Burch and co-workers[8] 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[17] 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 is homogeneous, and that the surface film humidity ratio is a function solely of temperature and wood moisture content, this data can be used to find $W_{surface}$. 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:

$$W_{surface} = e^{T/A} \{B + Cu + Du^2 + Eu^3\} \qquad (5)$$

where T is the wood temperature, ^{o}C (^{o}F)
u is the weight of water in the wood divided by the dry-weight of the wood (unitless)
A = 15.8 ^{o}C (28.6 ^{o}F)
B = −0.0015 (−0.00049)
C = 0.053 (0.0172)
D = −0.184 (−0.060)
E = 0.233 (0.076)

This curve fit, together with the data points from Table 3-4 of the Wood Handbook, is shown in Figure 9. Note the logarithmic scale. The units used are ^{o}F because the original data is in imperial units. Note that the temperature appears as an exponential, i.e. the humidity ratio is very sensitive to the wood temperature. As a result, the modelling of roof sheathing temperature must be very accurate if the humidity ratio is to be predicted.

The term for water flow may be eliminated from Equations 2 and 3, giving an equation for the attic air humidity ratio:

$$W_{attic} = \frac{\dfrac{A\,k\,W_{surface}}{M} + W_{outside}}{1 + \dfrac{A\,k}{M}} \qquad (6)$$

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 temperature). A comparison of the predicted (using the average half-hourly roof sheathing temperature) and measured attic air humidity ratio is shown in Figure 10. Good agreement is seen.

Seasonal Storage

The model may also be used to predict seasonal storage of moisture by the wood. However, the small errors in the prediction of hour-by-hour humidity ratio could add up to very large errors over a season. Also, the model assumes that the wood moisture content is uniform. This is true when the roof is in equilibrium with the attic air, but when the wood is adsorbing moisture the surface will be damper than the core of the wood. However, if the roof is always close to equilibrium with the attic air then the model may give good results. It is expected that the model will not apply if a rapid transition occurs from one equilibrium state to another distant one, since the wood moisture distribution would be extremely non-uniform. The model can only be expected to model slow changes.

It has not been possible to model the winter for the Oroville house because of missing data. However, Hans[12] collected hygrothermograph and wood moisture data for a Madison attic for a complete winter, except for a short break in February-March. This data 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 clearly 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.

The initial wood moisture content is unknown. A value of 10% was chosen. Equation 5 was used to calculate $W_{surface}$ for this moisture content and the temperature for the first time period. From Equation 3 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:

$$\text{delta } u = \frac{-m\,t}{A\,r\,d} \qquad (7)$$

where delta u is the change in wood moisture content, unitless
m is the rate of water flow from the wood, kg/s (lb/hour)
t is the time interval, s (hour)
A is the wood surface area, m^2 (ft^2)
r is the density of the dry wood, kg/m^3 (lb/ft^3)
d is the thickness of the wood, m (ft)

This gives a new value for the wood moisture content, which is used for the next time step. After a large number of time steps, the initial value chosen for the wood moisture content has no effect. A comparison of measured and predicted wood moisture content is shown in Figure 11. Reasonable agreement is seen. Perhaps this is because the attic remains at one moisture content in the winter, and then dries out to a summer condition.

DISCUSSION

Measurements have been made which show that there is considerable flow of water into and out of the roof sheathing of a residential attic. This is in contrast to the classic picture of attics, and agrees well with studies carried out recently by other researchers.

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). 25% of air exfiltration[18] can 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 house, such a flow would be a small perturbation in the normal daily flux of water in the attic, and would not be seen in the hour-by-hour measurements. However when cumulated over the course of a winter such a flow would make a large difference in the amount of moisture stored in the wood. A vapour barrier or air barrier could control the flow from the house, but would not control the build up of moisture from ventilation air.

The main purpose of attic ventilation is to prevent condensation and wood decay. This model cannot predict when condensation will occur. The data from the Wood Handbook do not cover relative humidities greater than 98%. Also, condensation occurs when more moisture is delivered to the surface of the wood than can be absorbed. This could happen if the body of the wood were at a high moisture content - a condition which the model can predict - or if the wood cannot transport moisture away from the surface fast enough - a dynamic process not handled by the model.

It is likely that condensation will be preceeded by a period of high wood moisture content. Given a precise thermal model of an attic and an attic ventilation model, it should be possible to predict vent areas which would prevent such a moisture buildup. Of course, good building practice is necessary to prevent local leakage of moist air into the attic, where local condensation could occur. For example, the practice of venting bathrooms directly into the attic may be ill advised in well-insulated attics.

Wood decay, according to the Wood Handbook[19], "is relatively slow at temperatures below 50°F and much above 90°F " [10°C and 32°C] and "Fully air-dry wood usually will have a moisture content not exceeding 20 percent, and should provide a reasonable margin of safety against fugus damage." One possible way to prevent decay could be to provide increased ventilation between these temperatures.

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 attic humidity ratio well, and reasonable agreement is shown in predicting seasonal moisture content using a less precise data set.

The model could form part of an attic model to determine optimal attic ventilation strategies. For example, it might be determined that a certain combination of roof sheathing temperature and wood moisture content could lead to fungus attack. The model could provide the ventilation rate required to prevent this combination of conditions in a given climate.

ACKNOWLEDGMENTS

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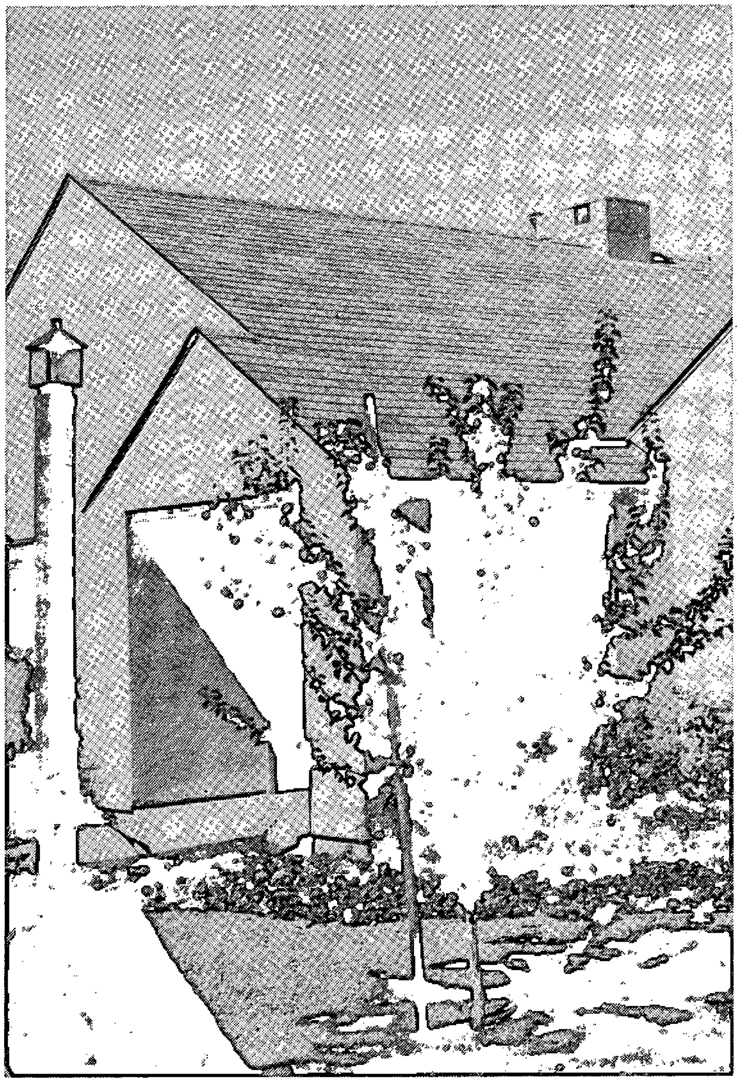

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Figure 1. The test house. It is part of Winston Gardens, public housing for the elderly in Oroville, California.

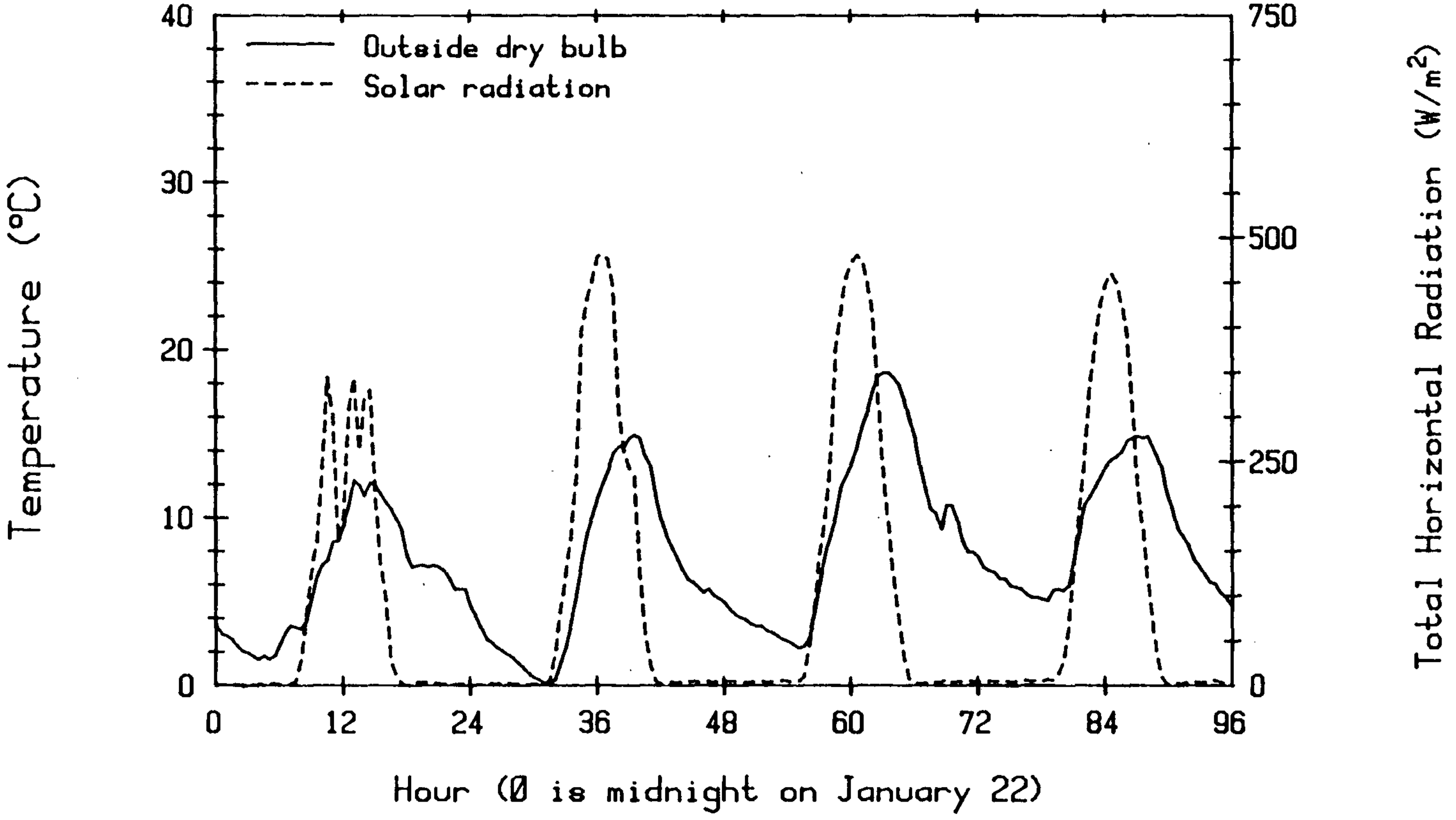

Figure 2. Outdoor conditions at the Oroville test house January 22 through 25, 1984

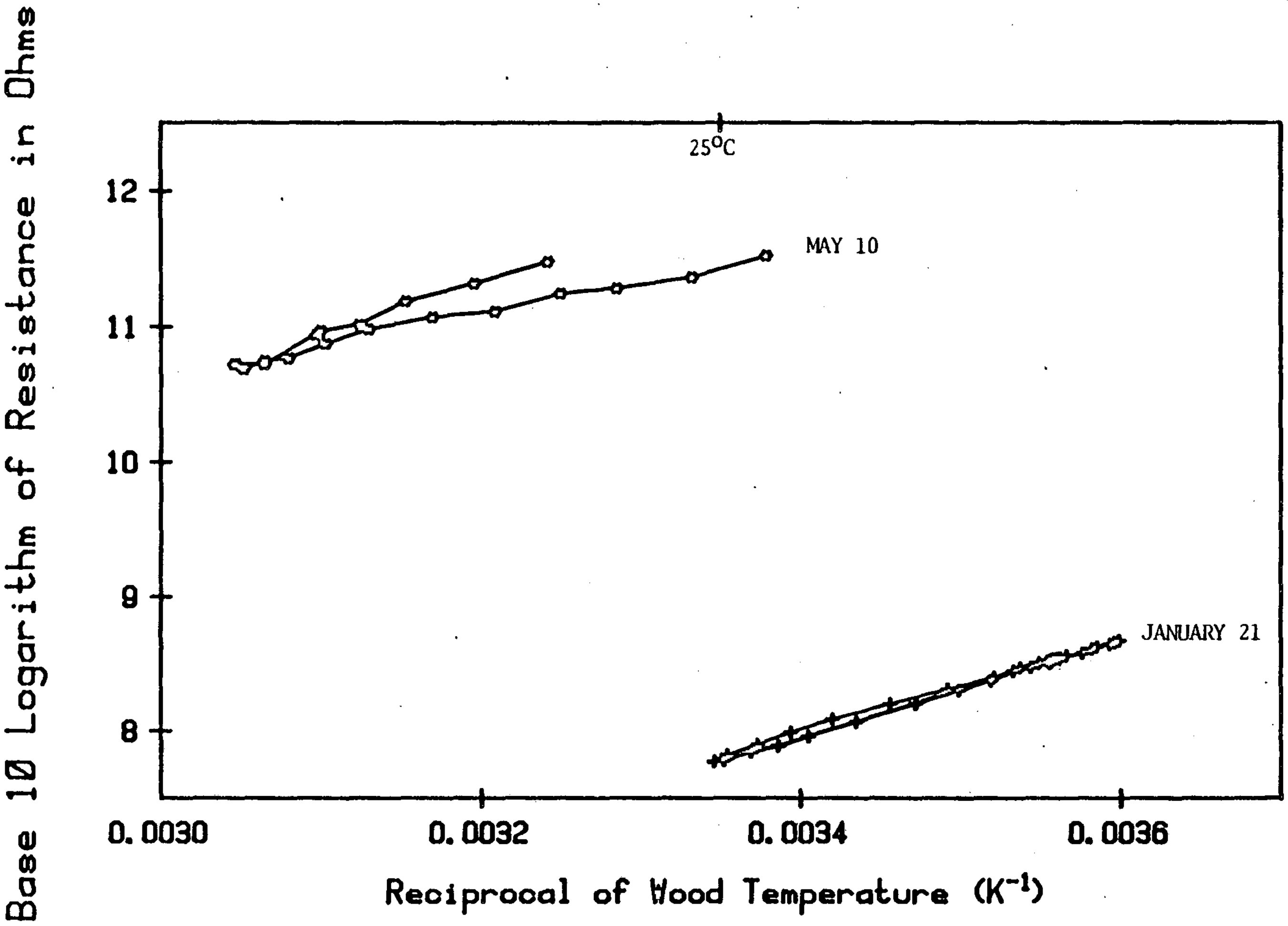

Figure 3. Electrical resistance measured between the electrodes in the West roof sheathing at the Oroville test house. Readings are half hour averages for the two days shown. Note that there is some hysteresis, especially for the May 10 results. The resistance is interpolated to a standard value at 25°C.

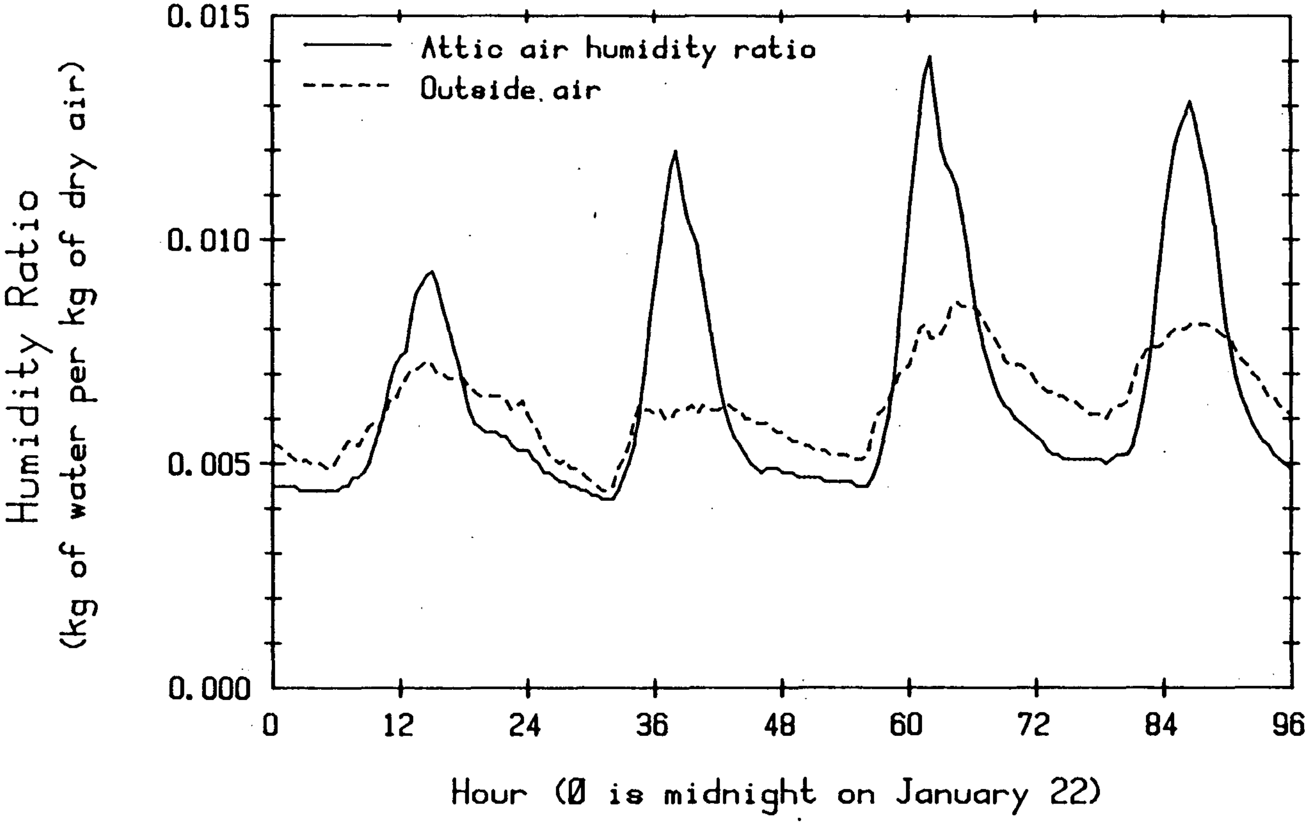

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Figure 4. Humidity ratio of the attic and outside air at the Oroville test house from January 22 through 25, 1984.

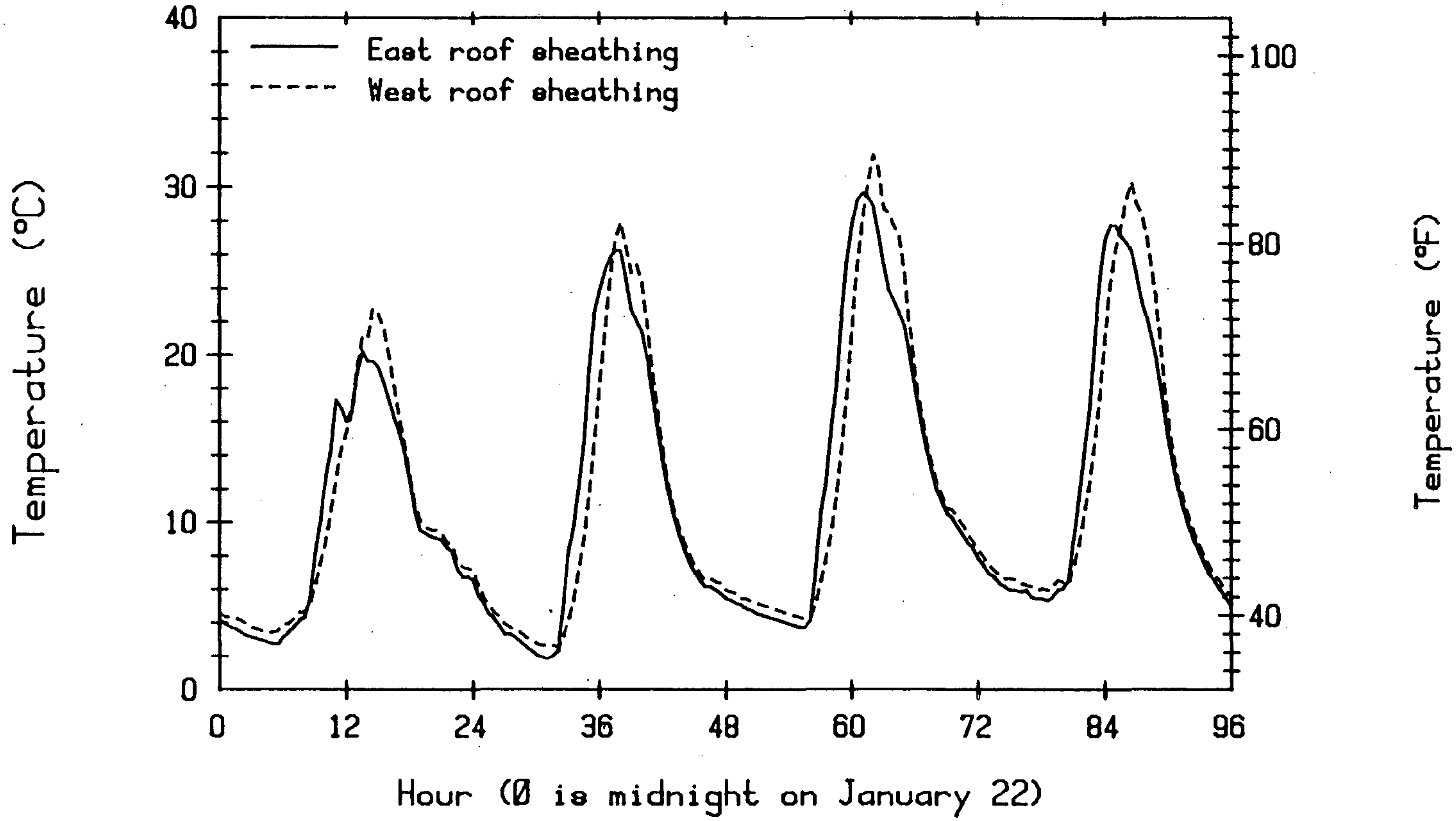

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Figure 5. Roof sheathing temperatures at the Oroville test house for the period January 22 through 25, 1984. Temperatures were measured with solid state sensors attached to the inner surface of the sheathing.

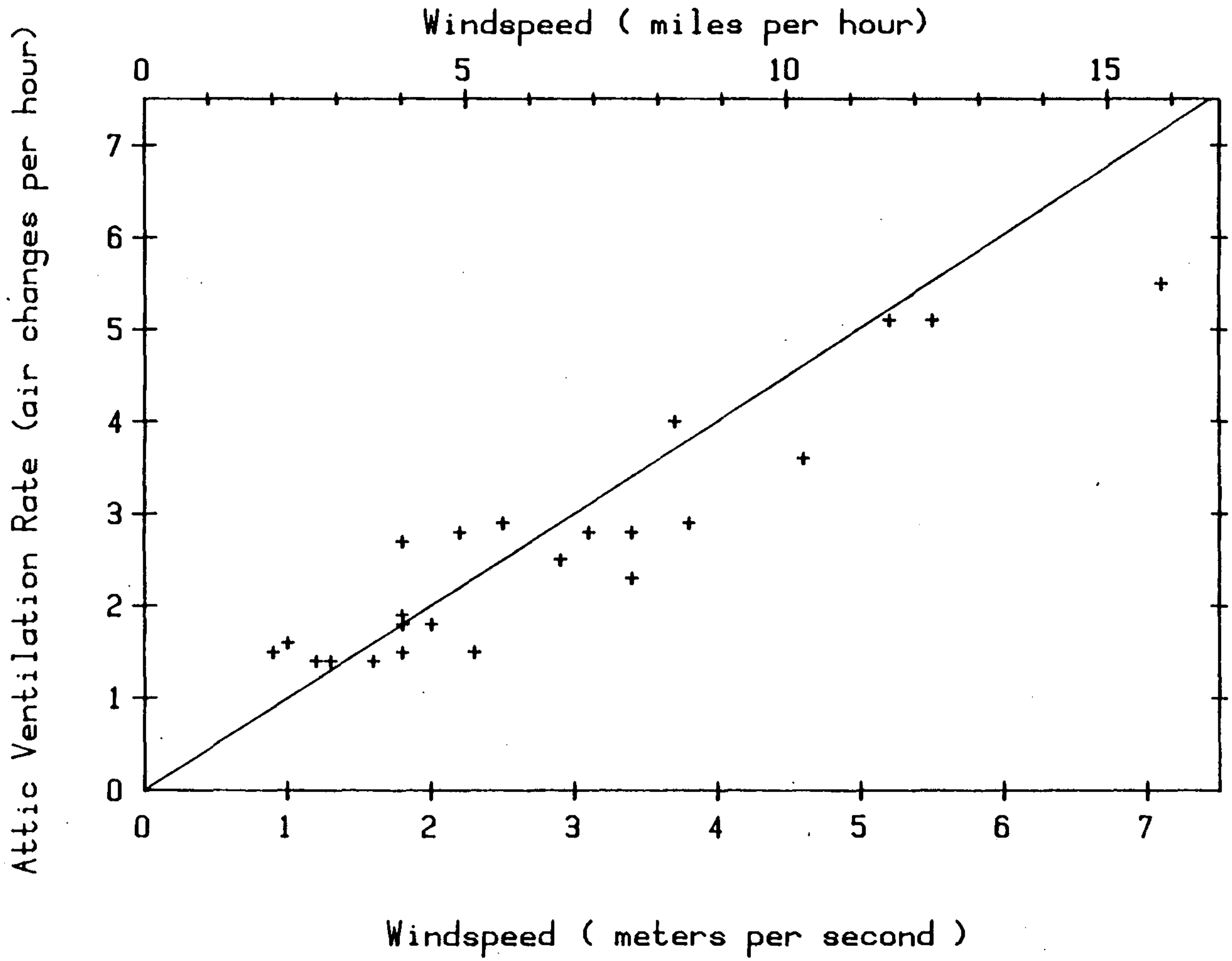
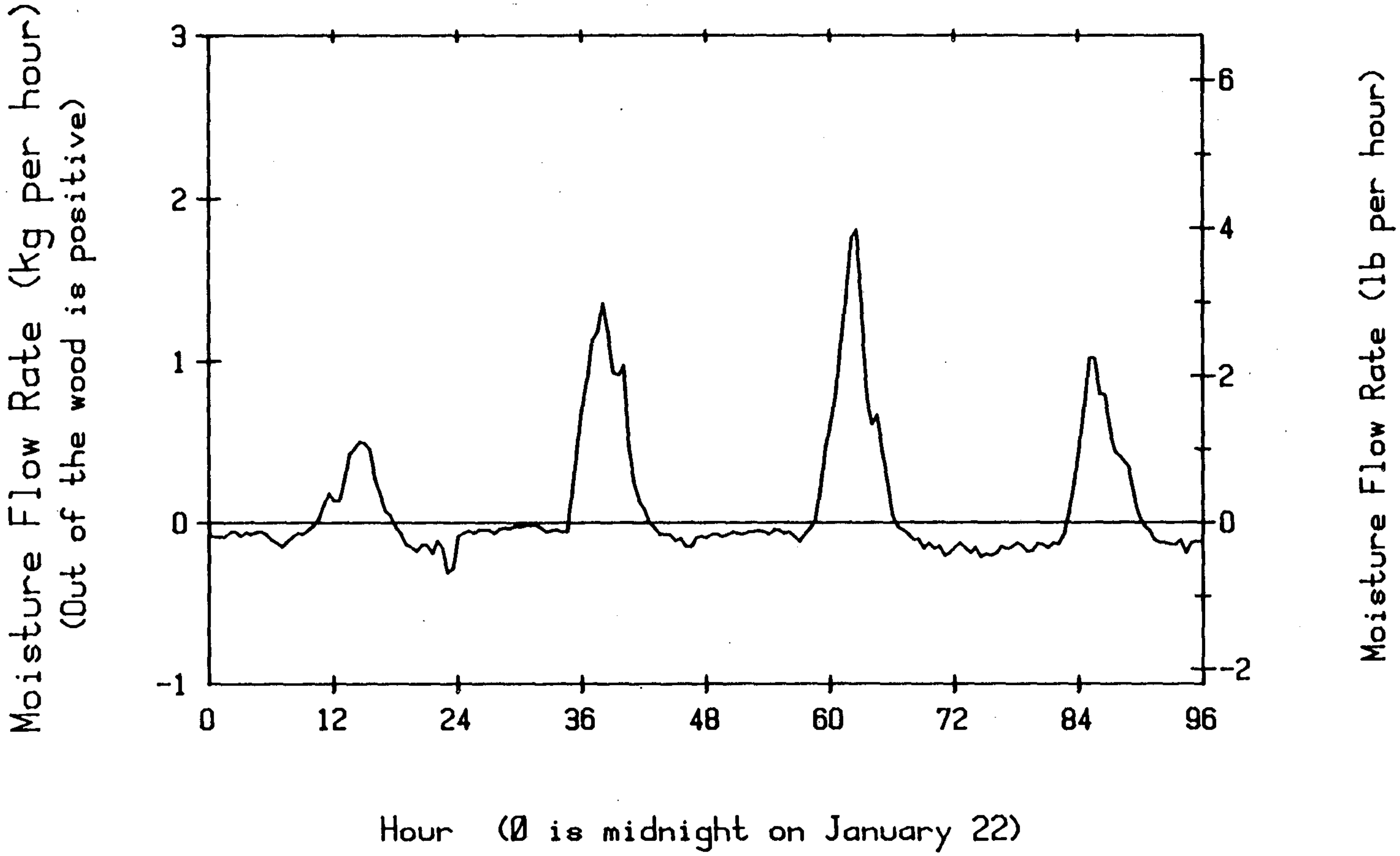


Figure 6. Attic ventilation rate as a function of windspeed measured approximately 3m (10 ft) above the roof ridge. The solid line shows the best linear fit to the data, constrained to pass through the origin.



XBL 845-1958

Figure 7. Moisture flow into the wood of the Oroville test house attic for the period January 22 through 25. The flow is calculated as the difference between attic and outdoor humidity ratios times the ventilation mass flow rate.

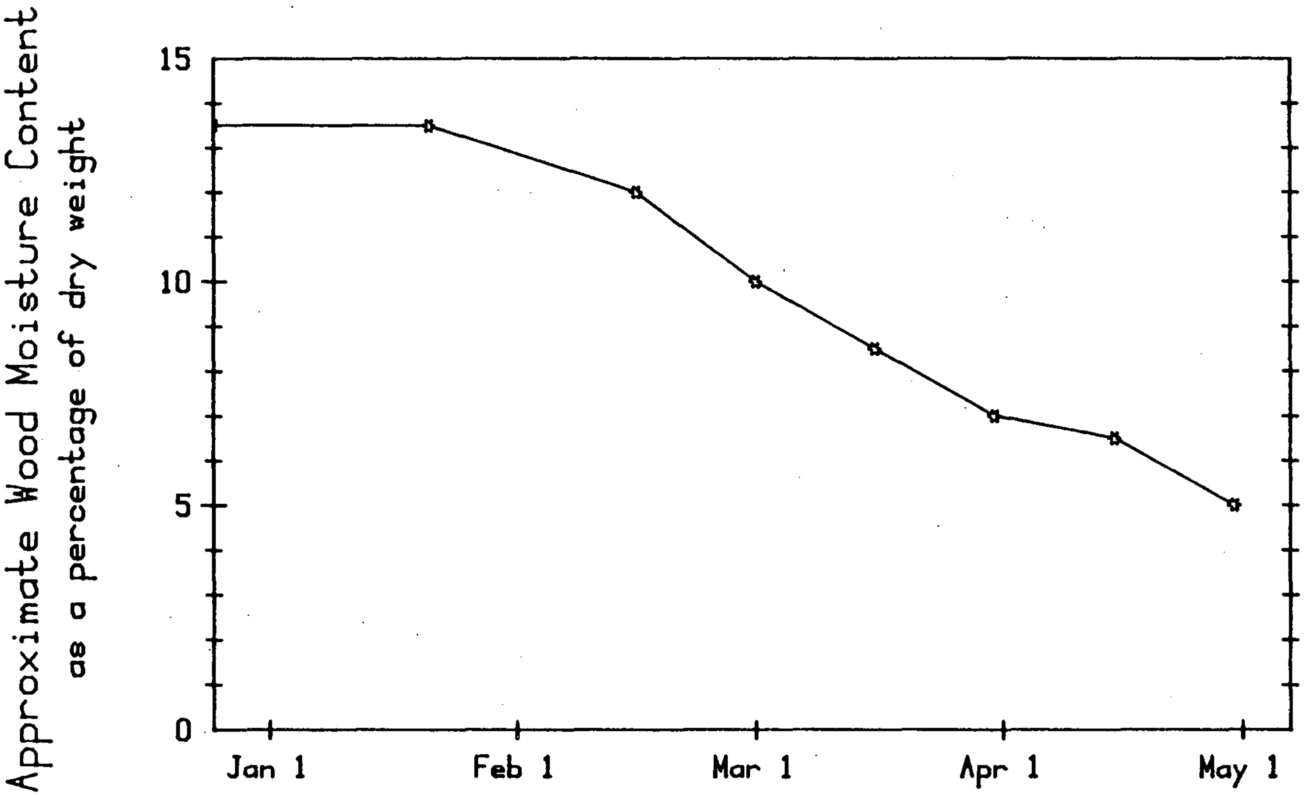


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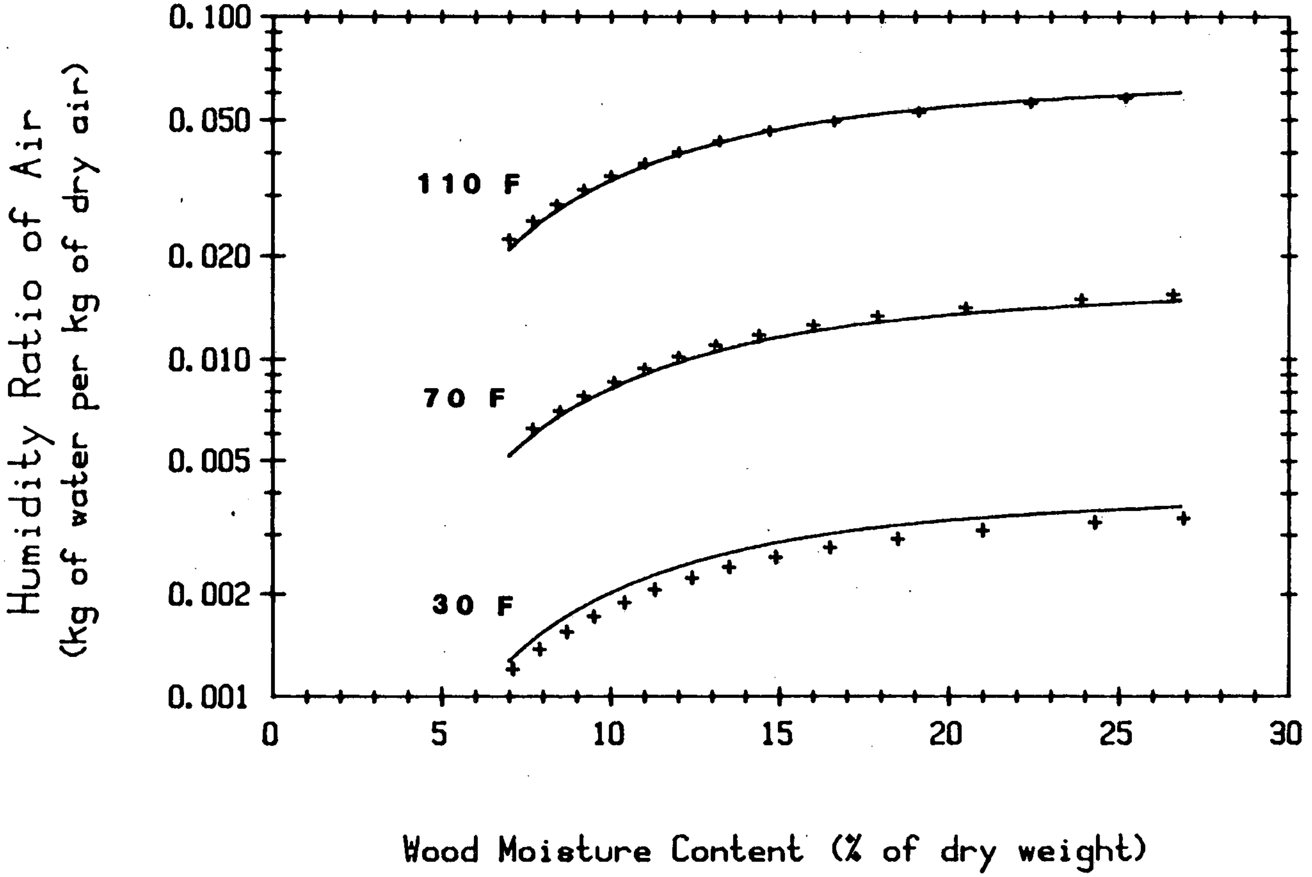
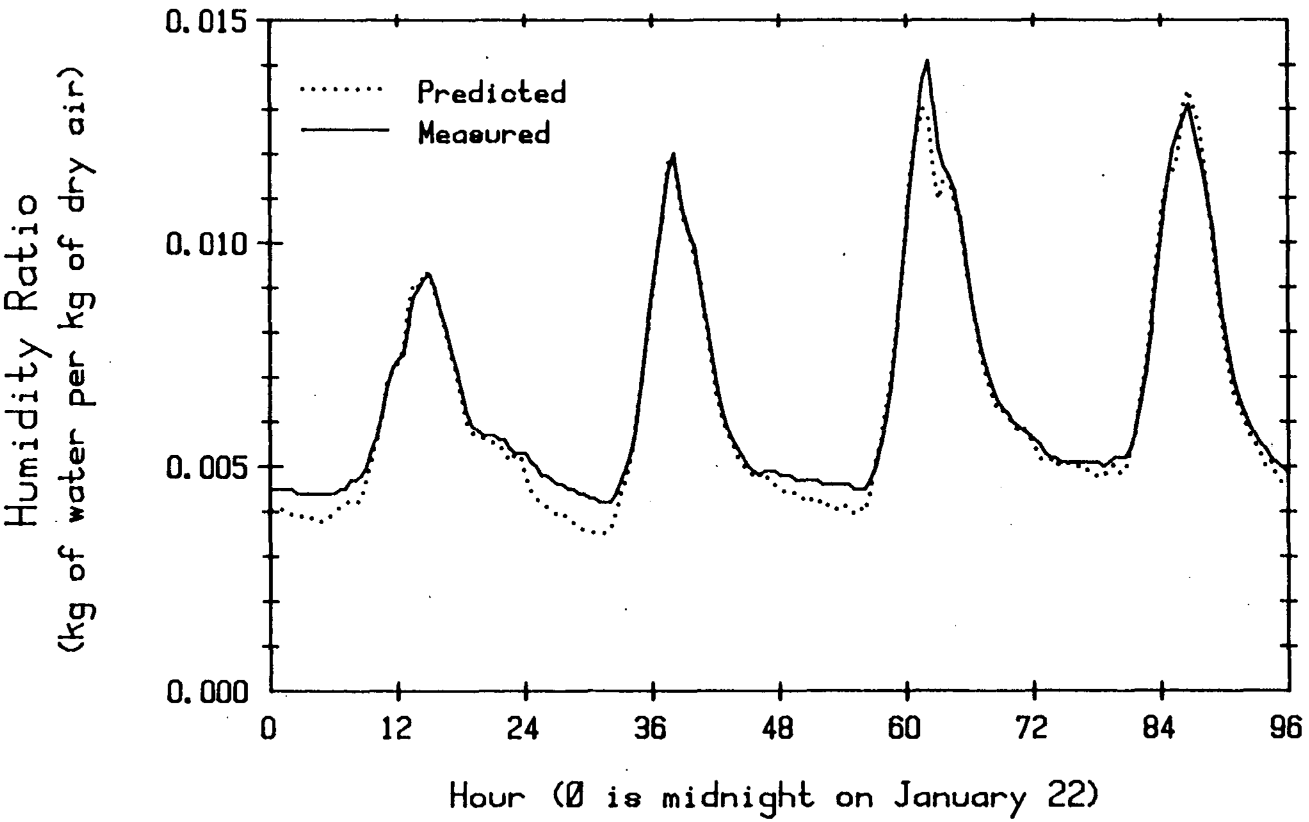
Figure 8. Approximate wood moisture content for the Oroville test house attic for the period January to May, 1983. The moisture content is derived from the electrical resistance of the wood; there are inherent uncertainties in this method.



XBL 845-1960

Figure 9. Data from the Wood Handbook for the relative humidity of air in equilibrium with wood at a given temperature and moisture content, transformed into humidity ratio, and fit to a polynomial. The solid line is the curve fit, " + " indicates a point from the Handbook. The temperatures are in °F because the original data are in those units. (110 °F = 43.3 °C ; 70 °F = 21.1 °C ; 30 °F = -1.1 °C)



XBL 845-1957

Figure 10. Hour-by-hour attic air humidity ratio for the Oroville attic, predicted and measured. The infiltration rate was calculated from the linear fit of Figure 6. The wood moisture content was assumed constant for this period.

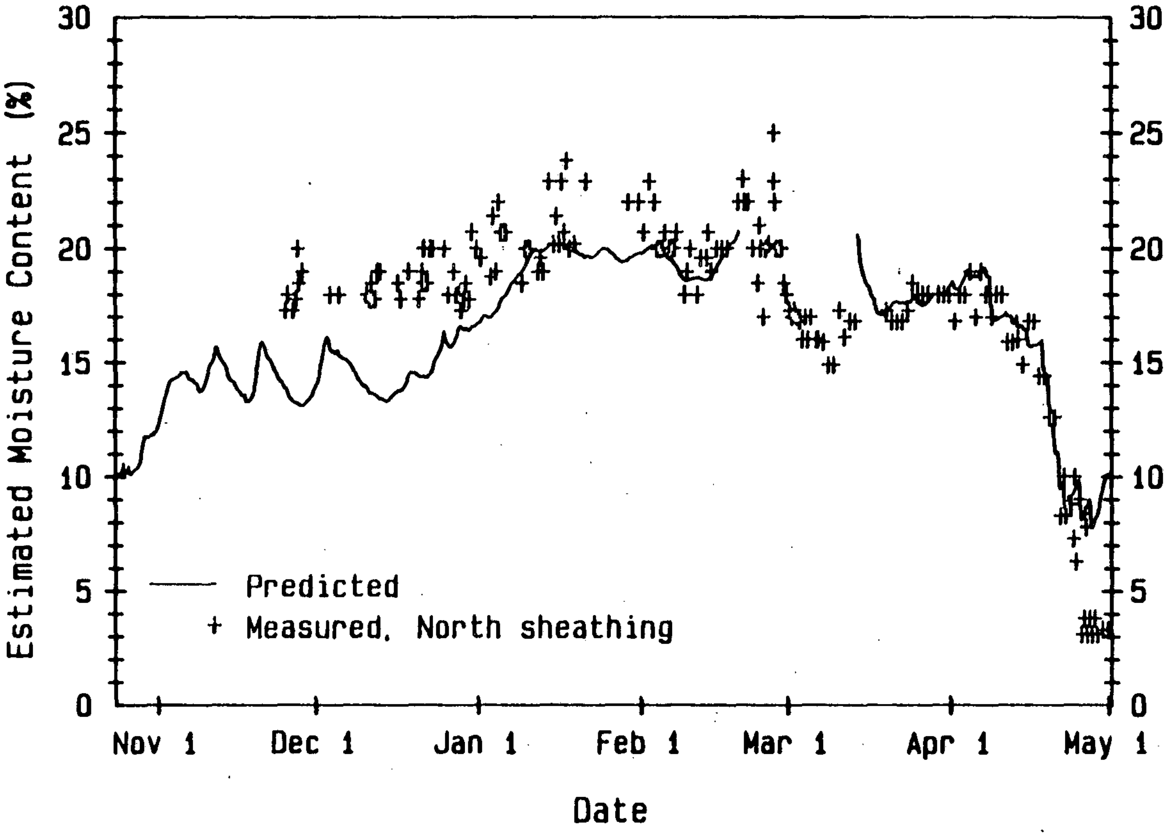


Figure 11. Predicted and measured wood moisture content for an attic in Madison, Wisconsin. Input data for the prediction are hygrothermograph traces of attic air temperature and relative humidity; the model expects wood temperature, not air temperature. This introduces a systematic error in the prediction.

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