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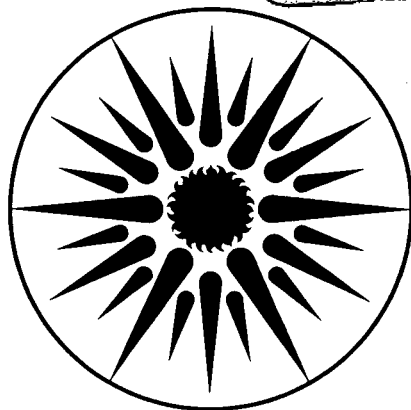
To be presented at the International Symposium
on Moisture and Humidity-1985, Washington, DC,
April 15-18, 1985

SEASONAL STORAGE OF MOISTURE IN ROOF SHEATHING

P. Cleary and M. Sherman

December 1984

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To be presented at the International Symposium "Moisture and Humidity - 1985", Washington, DC, April 15-18, 1985.

Seasonal Storage of Moisture in Roof Sheathing

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December 1984

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Seasonal Storage of Moisture in Roof Sheathing

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.

Keywords: Moisture in attics, ventilation, wood moisture content.

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 occurrence 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 °C (50 and 90 °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 $(10/1100) \times 100 = 0.91\%$. 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:

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

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:

$$m = k A (W_{\text{surface}} - W_{\text{attic}}) \quad (2)$$

where:

- m = flow of water kg/s (lb/hour)
- k = transfer coefficient, $\text{kg/m}^2\cdot\text{s}$
($\text{lb/ft}^2\cdot\text{hour}$)
- 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:

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

where:

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

This transfer coefficient for the roof is, within the limits of overall experimental error, $0.08 \text{ kg/m}^2\cdot\text{s}$ ($1.0 \text{ lb/hour}\cdot\text{ft}^2$). (Burch and co-workers (4) used a value of $1.1 \text{ lb/hour}\cdot\text{ft}^2$). The surface film humidity ratio may be found from data on wood properties, e.g Table 3-4 of the Wood Handbook¹⁰ 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:

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

- 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:

$$W_{\text{attic}} = \frac{\frac{A k W_{\text{surface}}}{M} + W_{\text{outside}}}{1 + \frac{A k}{M}} \quad (5)$$

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 °C (2 °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:

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

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, m² (ft²)
- r = density of the dry wood, kg/m³ (lb/ft³)
- 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. Alaska, 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

The authors are grateful for the assistance and critical comments of their colleagues at Lawrence Berkeley Laboratory.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, of the US Department of Energy under Contract No. DE-AC03-76SF00098.

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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 m² (406 ft²). The dry weight of the roof sheathing, assuming a density of 480 kg/m³ (30 lb/ft³) 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 cm² (156 sq inches) of soffit vents along one side of the house, approximately 1850 cm² (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 SF₆ 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 SF₆ decays.) It was found that the attic ventilation rate was 124 m³/h (73 cfm), the house ventilation rate was 16 m³/h (9.4 cfm), and there was a

flow of $4 \text{ m}^3/\text{h}$ (2.4 cfm) from the attic to the house. The ventilation rate was not measured continuously, 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 $17 \text{ }^\circ\text{C}$ ($63 \text{ }^\circ\text{F}$) for the early winter and later at $23 \text{ }^\circ\text{C}$ ($73 \text{ }^\circ\text{F}$). 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 $1.5 \cdot 10^{10}$ to $1.5 \cdot 10^4$ 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):

$$R = R_0 e^{T_0/T} \quad (7)$$

where:

R	=	measured wood resistance, ohms
R ₀	=	a constant, ohms
T	=	wood temperature, K (R)
T ₀	=	a constant, K (R)

The measured value of R must be reduced to standard conditions. The values of the constants R₀ and T₀ vary with wood moisture content. If that wood moisture content remains constant over each 24-hour period, or if these constants vary only slowly 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 extrapolation (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.

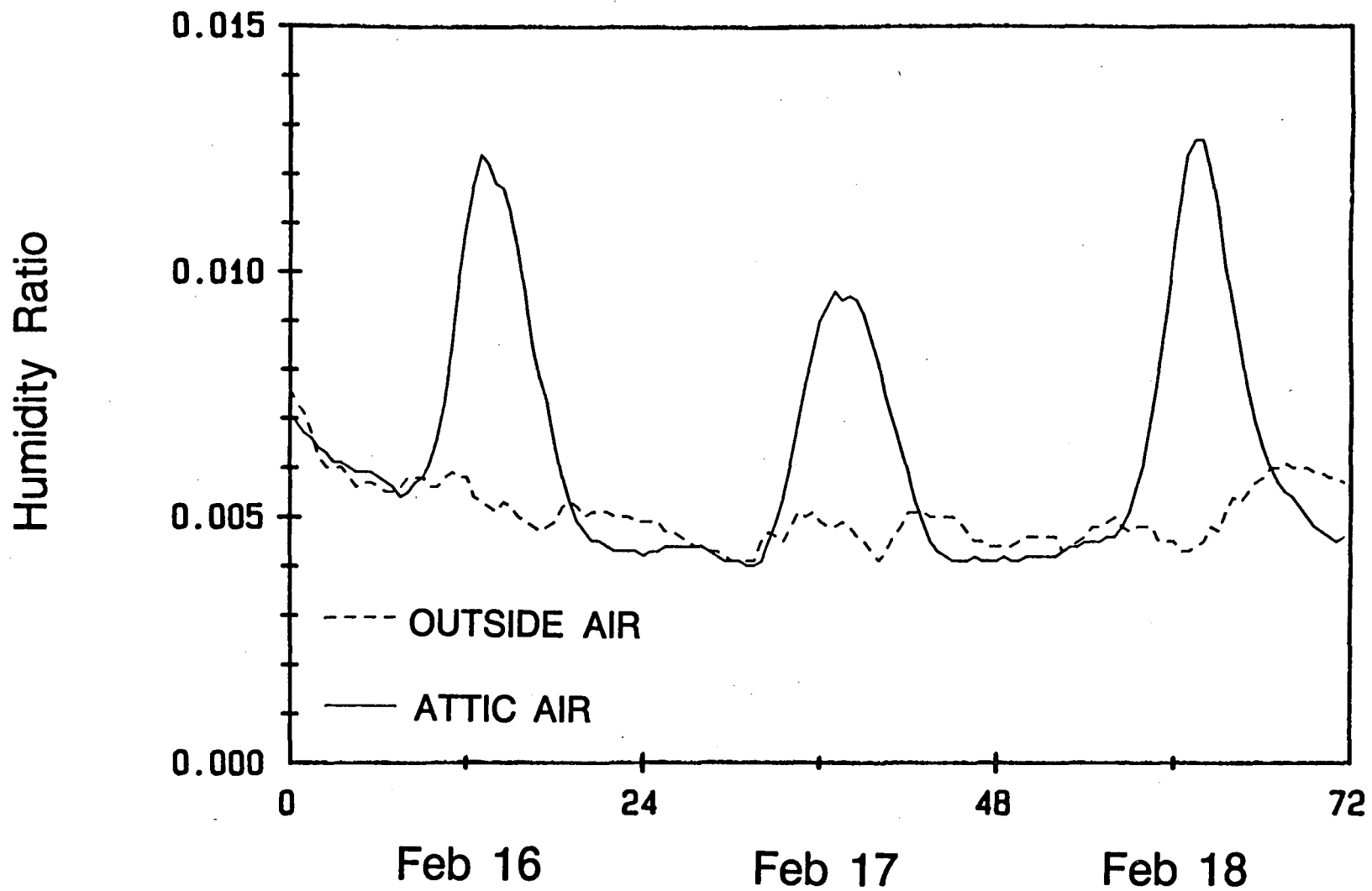


Figure 1. Humidity Ratios At Test House

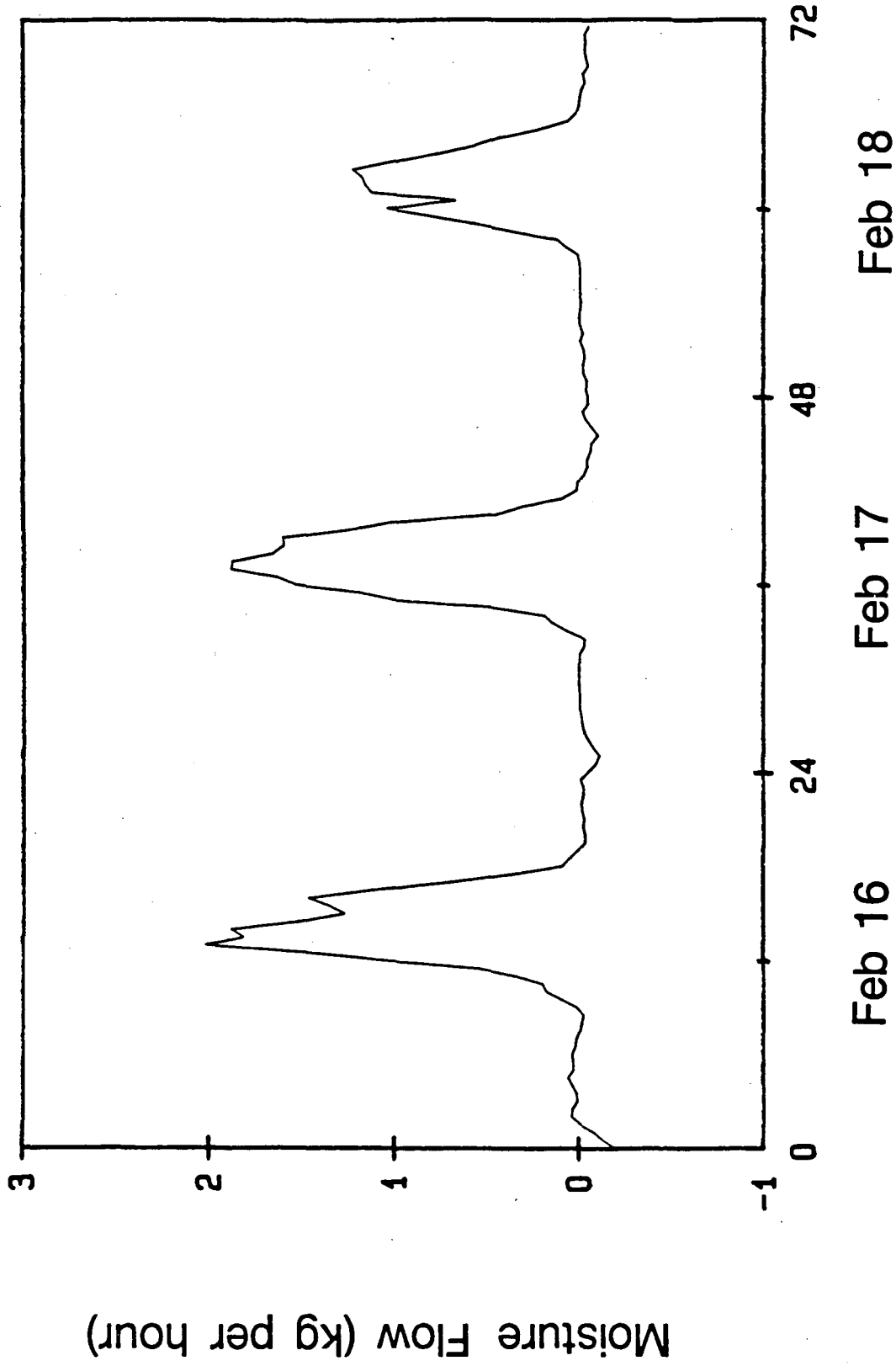


Figure 2. Moisture Flow In Test Attic

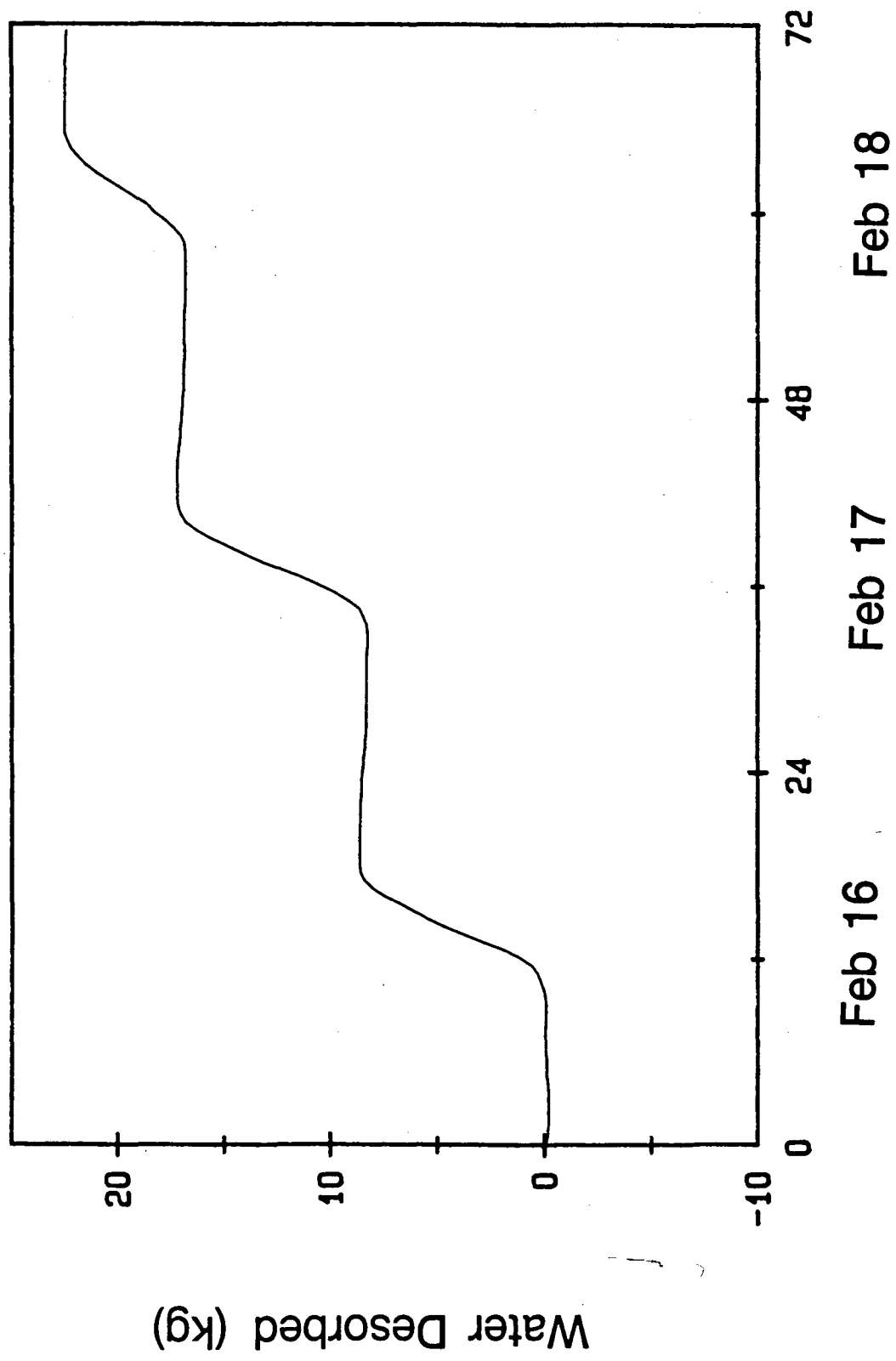


Figure 3. Water Desorbed From The Attic

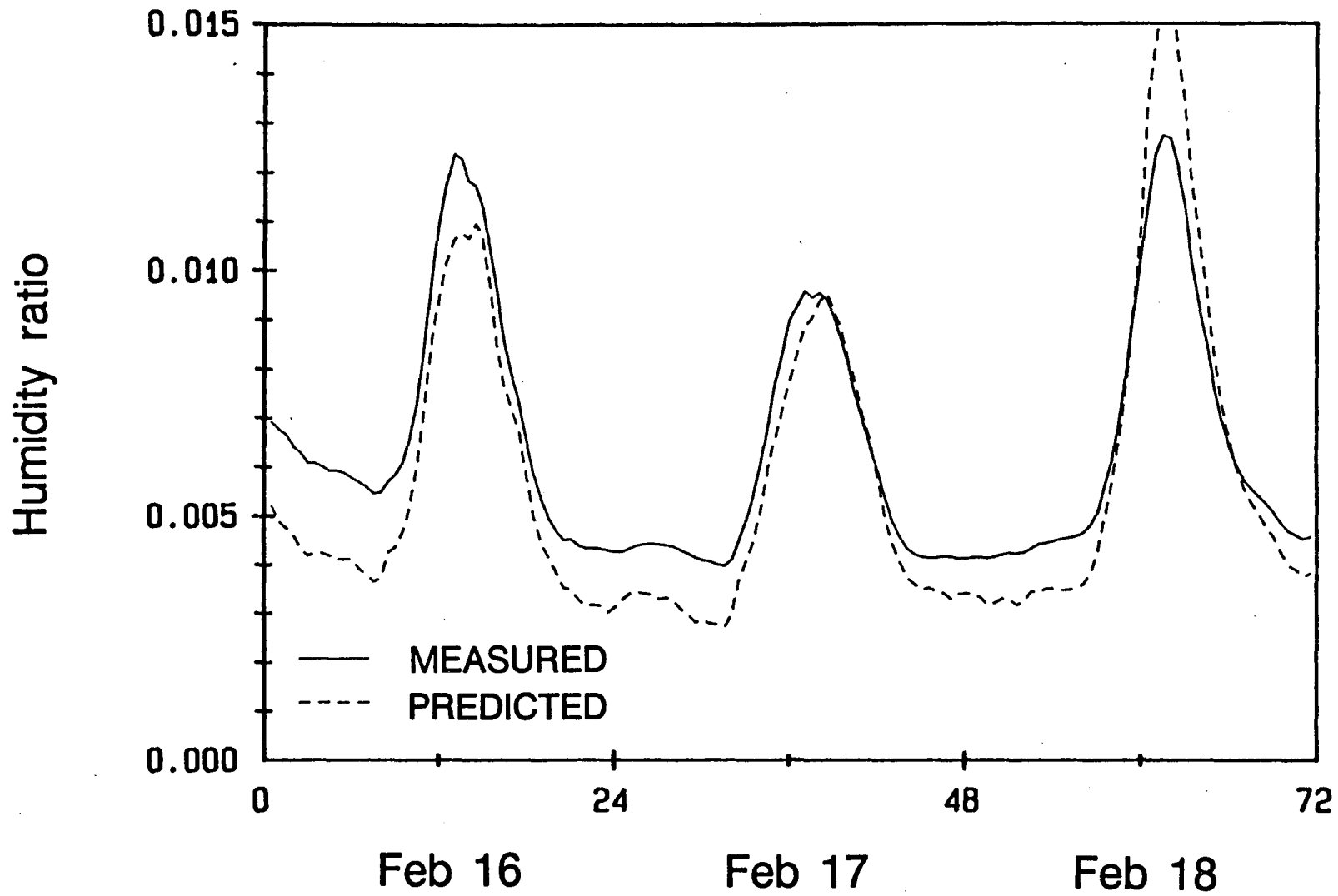


Figure 4. Attic Air Humidity Ratio

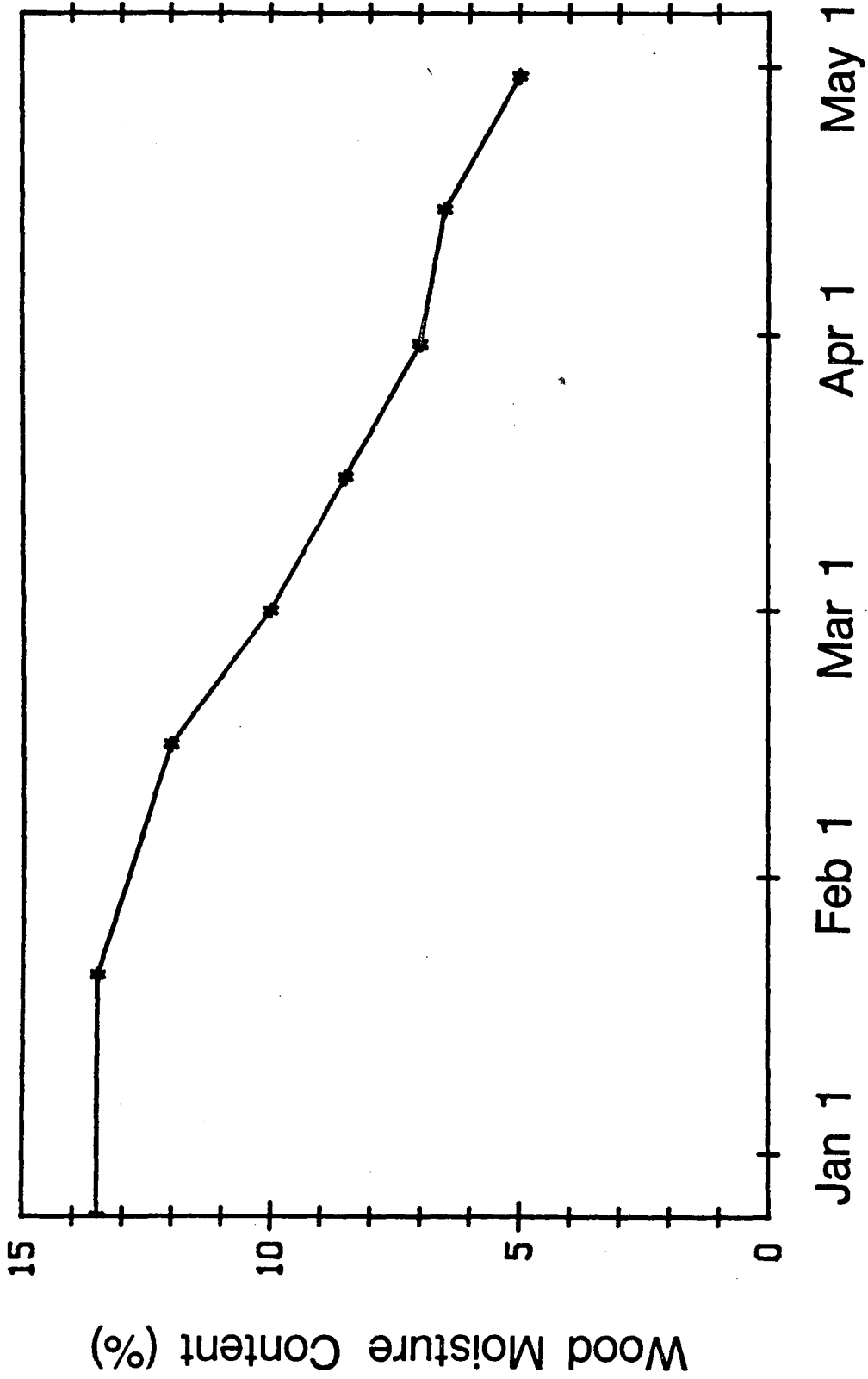


Figure 5. West Roof Sheathing Moisture Content

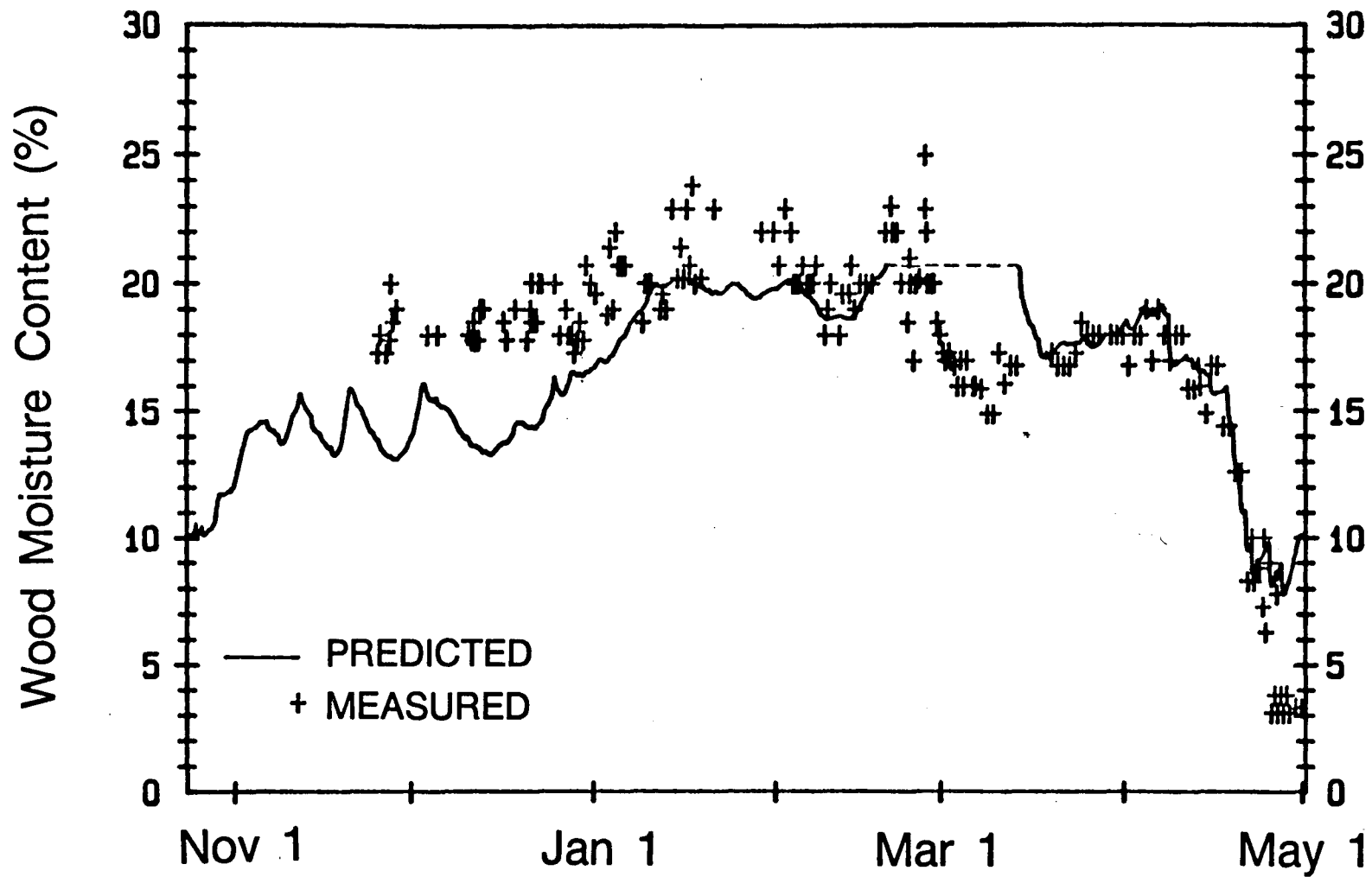


Figure 6. Wood Moisture Content In Madison, WI

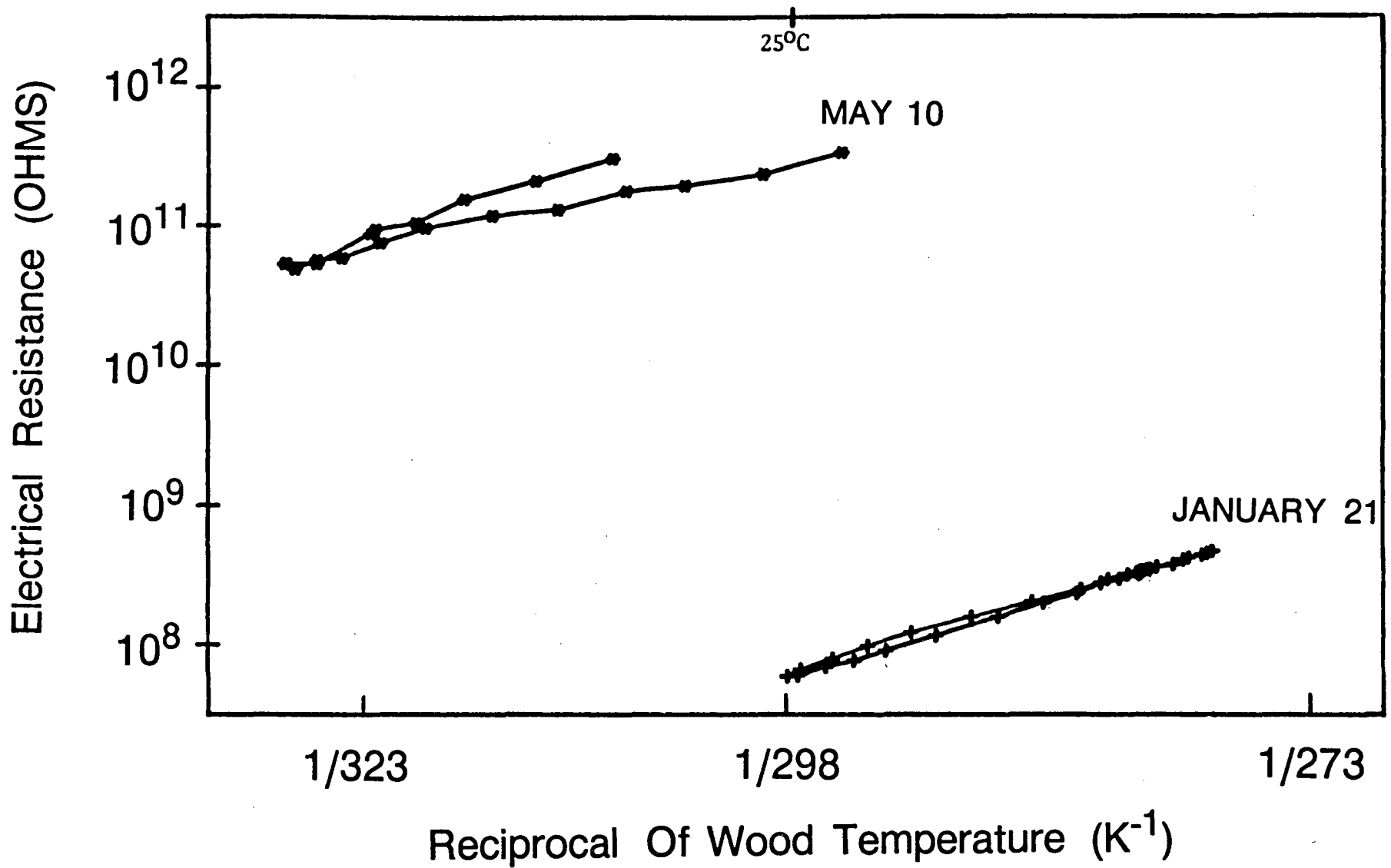


Figure 7. Resistance Of West Roof Sheathing

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