FIELD MEASUREMENTS OF SEASONAL WOOD MOISTURE VARIATIONS IN RESIDENTIAL ATTICS

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ABSTRACT

Numerous factors influence the moisture levels of wood construction elements in residential attics. Some of the most important parameters influencing moisture buildup include air exfiltration from living space to attic, temperature variations in the attic and outside, solar radiation on the roof planes, and attic ventilation rates. Modeling efforts have added to our knowledge of daily and seasonal moisture trends, but moisture storage within the wood and on the wood surfaces need to be taken into account if more accurate attic moisture balance predictions are to be made.

This paper describes experimental studies on the seasonal variation in wood moisture content in two New Jersey attics. Wood moisture measurements were based on two types of electrical resistance probes. Measurements in wood sheathing revealed moisture levels that were high during late winter; in early spring, the wood dried quickly and it remained dry, at less than 10% wood moisture content, through summer and fall. In addition, air infiltration data were collected using tracer gas techniques. The attic wood moisture adsorption/desorption rate averaged over a season is shown to make a small but noticeable contribution to the total attic moisture balance, which is dominated by airflow to and from the attic.

INTRODUCTION

Moisture problems in attic wood have been a source of concern for the structural integrity of U.S. single family housing (Ford 1982; ASTM 1982). One problem is the migration of water vapor from the living space into the attic. The moisture may condense in cold parts of the attic and could lead to mold growth, wood decay and structural damage. The risk of condensation in attics is increased when insulation is added to the attic floor, since the reduced heat loss from the living space reduces attic temperature (Ford 1982). Increasing attic ventilation rates can lower moisture levels by encouraging wood drying, but this often leads to an excessively cold attic, which increases heat loss by conduction from the living space. Understanding the moisture balance in attics can result in improved building energy efficiency without creating moisture problems.

Previous studies have shown that moisture transport in and out of attics via air movement greatly outweighs moisture transport by diffusion, showing that the best way to keep moisture out of attics is to seal possible air infiltration routes between living space and attic (Dutt 1979). In developing an initial model for attic moisture transport, that study assumed that the time constants related to wood sorption and desorption are considerably longer than fluctuations associated with variations in indoor and outdoor humidity levels and variations in airflows to and from attics. Thus, attic air humidity levels were determined by the rates of airflow among the living space, attic, and the outside, and the humidity of the outside and living space air. This steady-state moisture balance analysis is similar to that of Burch and Luna (1980) who also developed an attic energy balance in their mathematical model for attic

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ventilation. In the absence of significant moisture absorption and desorption, the attic specific humidity, q_a, (mass ratio of water vapor to total air in attic) should simply be a weighted average of the specific humidities of indoor air, q_h, and outdoor air, q_o:

$$q_a = k_h q_h + (1-k_h)q_o, \tag{1}$$

where k_h is constant as long as the various airflows are constant. However, data obtained from a Twin Rivers, New Jersey townhouse did not satisfy this equation. The attic humidity, as shown in Figure 1, did not remain at a fixed proportion of the humidities in the adjacent spaces (living space and outside) over the course of a day, although it stayed between these two levels. The daily fluctuations in q_a were attributed to evaporation and condensation of water from the underside of the attic roof because of diurnal changes in roof temperature. However, it was expected that, due to the small amount of moisture involved in an evaporation cycle, the attic specific humidity would remain between the specific humidities of living space and outdoor air.

A later researcher collected a large quantity of humidity data in a Pennington, New Jersey home (Ford 1982). The attic specific humidity, q_a, was compared to q_o and q_h. The data set frequently contained instances in which q_a was beyond the range defined by q_o and q_h, contrary to the earlier hypothesis. This anomaly was attributed to condensation/evaporation cycles involving large amounts of moisture.

The study reported here is based on measurements of wood moisture content carried out in an attic over a year-long period, both to understand the nature of the seasonal variations and to see the effects of long term wood sorption and desorption on attic moisture balance. In order to relate long term trends with short term variations, measurements of attic air humidity were also attempted but proved to be unreliable.

THE TEST HOUSES

Most of the measurements were made in a simple one-story house, with basement and attic, built around 1960 and located in Griggstown, New Jersey ("G" house). A one-story structure was chosen because air infiltration calculations become simplified, as the number of chambers or major air spaces is reduced to two: the living space and the attic. The home was occupied by two adults and two small children. No moisture problems were reported by the residents.

The attic is rectangular in shape and covered by a hip roof. The attic floor, approximately 1400 ft^2 (130m^2) in area, contains a three-inch layer of mineral wool insulation. Ventilation paths are provided via two eight-inch diameter roof louvers and one fifteen-inch louver with a fan that is thermostatically controlled. The vents are covered with screens. The free area of the vents is approximately 1 ft^2 (0.09m^2). Typical recommendations for attic ventilation call for 1 ft^2 of free vent area for every 300 ft^2 of attic floor area, when a vapor retarder is present (ASHRAE 1985). The ventilation area in the G attic is thus considerably lower than the 4.67 ft^2 (0.43m^2) recommended. There is some additional ventilation, through an attic access hatchway (from the garage), which is only loosely covered with a fiberboard panel. The panel is replaced with a screen by the homeowner during the summer months. The G house is built on an east-west axis, and the major roof planes face north and south. A soffited ceiling above kitchen cabinets with a recessed light fixture above the sink provides a site for moist living space air to enter the attic. Above this air leak, delamination of the roof sheathing was visible and presumably caused by previous moisture buildup.

A second house ("P" house) with a previously known attic condensation problem was also investigated as part of our experiment. We visited this house less frequently than the G house because we were only interested in observing seasonal trends of attic wood moisture content. This was a larger, split-level wood-frame house, built in the mid 1950s. The roof and the attic end walls are of tongue-in-groove wood construction rather than the plywood sheathing of the G house. The smaller attic, where the condensation was localized, had a floor area of 340 ft^2 (31.6m^2) and 2 ft^2 (0.19m^2) of vent area with screening, amounting to a free area of opening approximately equal to the recommended value. There existed an air passage from a bathroom into the attic around the soil pipe. There was evidence of ceiling damage in the bathroom as well as mold growing on the underside of the roof and on an end wall. The insulation on the attic floor was nearly saturated with water at the time of our mid-winter visit.

EQUIPMENT AND TEST PROCEDURES

In order to examine moisture levels, and as a step towards a microcomputer-based data acquisition system in the G house, some new measurement techniques were investigated. Air humidity has always proven to be difficult to measure accurately, especially at low temperatures and dusty environments such as attics. A relatively new commercial product was tested in the laboratory. The sensor is constructed of a porous noble metal. Moisture entering the sensor changes its electrical resistance by the process of electron tunneling. This device was unfortunately found to have poor accuracy and reproducibility, especially at high relative humidities of interest in condensation studies.

Other humidity measurement techniques proved also to have operational difficulties. An automatic aspirated psychrometer, developed by Ford (1982) at Princeton, is reasonably accurate but cannot operate over a long time period with the high dust levels which usually exist in attics. Nor does it operate if temperatures fall below freezing. The device consists of a fan which draws an air stream over wet and dry bulb thermometers. Two mechanically operated temperature/humidity chart recorders (hygrothermograph) were also considered, but their accuracies were not acceptable. The temperature sensor is a bimetallic strip, and relative humidity is indicated by the changing length of a bundle of hair kept in tension. While the device is useful at typical interior temperatures and moderate relative humidity, it tends to give poor results at high relative humidities. In earlier studies we had found these devices to be reading 30 percentage points off under saturation conditions, even shortly after they had been calibrated at moderate humidities. Both the variation and the high relative humidity levels found in winter attics made the hygrothermograph inadequate for our purpose. Chilled-mirror devices which measure dew point directly were not considered because of their expense but have since been used in attics successfully by Cleary (1984). The device finally used was a conventional sling psychrometer which measures wet and dry bulb temperatures to within approximately 1^{o}F (0.5^{o}C), but which has the disadvantage of requiring the presence of an experimenter.

Also tested in the laboratory were wood moisture detectors. A common method of measurement uses an electric resistance probe working on the principle that the resistance of wood decreases with increasing moisture content. Two such detectors used are the two-pronged "hammer" probe and the "matchstick" probe. The former is a portable device with two metal nail-like pins 1" (2.5cm) apart, which are hammered into the wood specimen, having a constant voltage applied across the pins. The latter is a small wooden stick (with electrodes bonded to opposite sides) that is inserted into a hole drilled into a wood sample. The "matchstick" probe must be allowed to come into moisture equilibrium with the wood sample. The voltage input yields a current output that is related to the wood moisture content. The moisture content was read visually using a commercially available wood moisture meter.

The inexpensive matchstick probes are convenient for long term measurement applications. To test these devices, wood samples were obtained from various moisture environments, weighed and tested with the probes. The samples were then heated in a low temperature oven for several days, until their weights no longer changed. The weight of the water lost was determined from each sample's tare weight, thus revealing the initial moisture level. Over the range of moisture levels expected to be encountered in the test house, the probe readings were correct to approximately seven percent of the reading. This generally amounts to an uncertainty of one percentage point in wood moisture content (e.g. 14 $\pm$ 1 percent moisture) and is adequate for our task.

Moisture measurements were begun in the G house on February 24, 1983, and were continued for more than a year. Matchstick probes were installed in six locations in the roof sheathing, and hammer probe measurements were made, near each matchstick location, in the ceiling joists and roof rafters as well as in the roof sheathing. The probes were inserted into the wood to a depth of approximately one-quarter inch in the sheathing and one-half inch in the joists.* A diagram of the attic and the probe locations is presented in Figure 2. At each visit the dry and wet bulb temperatures were measured in the attic, outdoors, and indoors, on the main floor

*Due to delamination problems successive sheathing moisture measurements were often made in the same hole. Very little difference was noted between measuring the wood moisture content in the same holes or "hammering" in new holes each time.

and in the basement. Daily temperature and humidity cycles would affect the air temperature and humidity data greatly, but the wood moisture content should have much less fluctuation.

After several weeks of moisture data were obtained, it was possible to observe some trends in the storage of moisture in the attic wood. In order to determine how well the moisture probes operated, the results of the two probes, when used at the same location, were compared for the first six weeks of testing and are presented in a scatter plot in Figure 3. With the 45° line indicating perfect correlation, it can be seen that the hammer probe consistently reads slightly lower than the matchstick probes. This is presumably due to the fact that small air spaces exist between the square matchstick and the round hole into which it is inserted, allowing some drying to occur in the gaps. Nevertheless, the general agreement was encouraging.

AIRFLOW MEASUREMENT

As mentioned previously, moisture transport is generally dominated by the flow of moist air, rather than by diffusion through structural elements. The rate of moisture flow between two spaces is given by:

$$W_{12} = V_{12} \ \rho_1 q_1 \tag{2}$$

<u>where</u> W_{12} = rate of moisture flow from space 1 to space 2

V_{12} = rate of airflow from 1 to 2

ρ_1 = density of air in space 1

q_1 = specific humidity in space 1

Figure 4 shows a large number of possible airflow paths (Ford 1982). In practice, many of the airflow rates are small. For instance, major basement-to-attic airflow paths were absent in this house so that the flow paths involving the basement become irrelevant to the attic airflow balance. Furthermore, airflow from attic to living space is usually negligible because of stack effect. This was confirmed by measurements described below. The primary flows of interest are between living space to and from the outside, living space to attic, and attic to and from the outside.

The first airflow measurement was made using a blower door. A blower door consists of a calibrated high flow fan mounted on a frame, temporarily secured in an exterior doorway of the house. Air flow rates were measured at inside-outside pressure differences of 0.05, 0.07, 0.10, 0.14, 0.20 and 0.25 inch of water (12.5, 17.5, 25, 35, 50, and 62.5 pascals). The airflow at 0.20 inch (50 Pa), a significantly higher pressure than normally induced by wind or temperature difference effects, is commonly used as a measure of building tightness but does not correspond to air leakage at naturally occurring pressures. Two relatively simple methods have been developed to estimate the airflow under natural conditions. One simply involves dividing the flow induced at 0.20 inch (50 Pa), Q(50) by 20 (Dutt et al. 1982):

$$AI = Q(50)/20 \tag{3}$$

where AI is the natural air infiltration. The second method involves extrapolating from these relatively high pressure flow measurements down to the lower pressure regime which corresponds more closely to the pressures naturally induced (Sherman et al. 1980). Using the flow at 4 pascals, Q(4), an Effective Leakage Area (ELA), is calculated from:

$$ELA = Q(4) / \sqrt{(2 \Delta P / \rho)} \tag{4}$$

where ELA is in m^2, ΔP is 4 Pa (0.016 inch of water) and ρ is the density of air at room temperature. Q(4) is the 4 pascal flow rate resulting from a curve fit through the measured flows and pressures. The ELA does not bear a simple relationship to actual physical opening areas in the building envelope but instead characterizes the total effect of all these openings. This number, combined with pressure coefficients analytically related to the building's location and shape, outdoor temperature, and wind speed and direction, yield a natural air leakage rate.

The ELA measured with the basement door closed and opened were approximately 88 and 90 in^2 (570 and 580 cm^2) respectively. The small difference in these two measurements signifies either that the basement is extremely air tight or that there is good communication between the basement and living space even with the basement door closed. Since the house has a warm air heating system with ducts connecting basement and living space, the latter would be anticipated. The air leakage flow of this house under average heating season conditions with the basement door open is approximately 6200 and 5600 ft^3/h (175 and 159 m^3/h) using the 50 pascal leakage divided by 20 and ELA methods respectively. When the basement door is closed, the flows are approximately 6100 and 5300 ft^3/h (173 m^3/h and 150 m^3/h for the two methods respectively. Thus the air leakage rate varies from about 0.24 to 0.55 house volumes per hour depending on the method and whether the 11,200 ft^3 basement volume is added to the 11,200 ft^3 (317 m^3) living space in the calculation.

Another airflow measurement technique which directly yields the natural infiltration rate involves the use of a tracer gas (Harrje et al. 1982). A small quantity of tracer gas is introduced into the space whose ventilation rate is being evaluated and the gas concentration measured over time. The slope of the exponential decay curve yields the natural air infiltration rate, expressed in a number of space volumes per hour or air changes per hour (ACH). Tracer tests were performed several times to determine airflow rates. In one test, approximately 8 cc of SF_6 was injected at each end of the attic. At five minute intervals after the tracer gas was released bottle samples of attic air were taken at two widely separated locations in the attic. The samples were then returned to the laboratory and analyzed with a gas chromatograph. Graphs of the concentration decay at both attic ends are presented in Figure 5. The attic air leakage rate, determined by a log-linear least squares curve fit, was approximately 3.6 attic volumes per hour at both attic locations. The uniformity of the decay in the two halves of the attic and the high values of R^2 for the curve fit (approximately 0.99) both signify good mixing (which can be a problem in measurement of attic air exchange). In the second test, we took the SF_6 detection system to the G house. By programming it to automatically sample and analyze gas samples from the living space and attic at regular intervals, we could determine both attic infiltration and flow from attic to living space. Use of a single tracer to measure airflows among two zones of a house and the outside has been successfully applied in earlier studies. (Hernandez 1982; Ford 1982) During this test the attic air leakage rate was measured to be only 2.1 ACH. The flow rate from attic to living space was found to be negligible as expected. The lower value of attic infiltration rate in the second test is presumably due to different weather conditions. We did not have an anemometer on site. The wind speed was low in each case (below about 10 mph).

The third test again employed the SF_6 detection system on site, this time during the summer, when the attic exhaust fan was usually operating in the afternoons. Tracer gas concentration measurements were made in the attic, first with the fan turned off, (using a manual switch to override the thermostatic control) and then with the fan on. The air leakage rate with fan off was 3.3 attic volumes per hour, in close agreement with the original bottle-sample test. When the fan was switched on, the air mixing patterns within the attic became quite non-uniform, as indicated by a wide variation in concentration and air leakage rates from the east to the west side. It seems that, rather than uniform exponential decay of concentration, local effects such as airstreams from the attic hatch to the fan dominate the decay in concentration levels. Our measurements indicated that the average leakage rate increased by a factor of five to ten with the fan on.

In the final experiment we seeded tracer gas into the furnace air return duct and measured living space tracer gas concentrations to see if the attic fan significantly increased the house air leakage by drawing living space air into the attic. With the fan off, the living space infiltration rate was 0.16 air change per hour (ACH). When the fan was turned on the rate was 0.17 ACH, not a significiant increase. During the summer, low rates of air infiltration such as exhibited in these tests are quite common.

The experimental results for attic ventilation can be compared to an empirical model used by ventilation designers (Hinrichs and Wolfert 1974). According to the model,

$$Q = EAV_w \tag{5}$$

where Q = airflow rate (ft^3/min),

E = effectiveness factor of vent (dimensionless),

A = free area of all vents (ft^2),

V_w = wind velocity (ft/min)

Estimating for our test attic, a free area of 1 ft^2, and a value of E equal to 0.2 for roof louvers, (Hinrichs and Wolfert 1974) the flow rate should be about 1.3 ACH for a wind speed of 5 mph (2.2 m/s). This empirical estimate is much smaller than our measured values of 3.6 and 2.1 ACH. The empirical model neglects any stack driven airflow variation. Moreover, currently there is no model which predicts living space to attic airflow, although some recent multi-zone building airflow models might be applicable (e.g., Walton, 1983).

MOISTURE STORAGE TRENDS

Moisture storage effects were investigated using wood moisture probe data. Data from the first several weeks of testing reveal that moisture levels were highest around location 5 (see Figure 2), near the kitchen bypass -- an expected result. In addition, the entire north side of the house, locations 4-6, averaged higher moisture levels than the south side, locations 1-3.

Displayed in Figure 6 are the average sheathing moisture levels for the two roof orientations. Two trends are striking in the spring data. First, the average moisture level shows a steady decrease until August (Julian date 213), undoubtedly caused by the warming trend from late winter into summer, as higher temperatures decrease both the likelihood of water vapor condensing on the roof and the adsorption of water vapor in wood. It should be noted that the periods from March 9 to 17 (Julian 68 to 76) and from April 22-29 (Julian 112 to 119) were relatively warm and dry (mostly clear, temperatures between 50 and 80°F), while March 17 through 28 (Julian 76 to 87) and April 9 through 20 (Julian 99 to 110) were cool and rainy (rain throughout most of this period, with temperatures below 60°F), explaining the deviations during those weeks. Second, the moisture level on the south roof sheathing stayed more or less constant from the start of the measurements through the middle of April (Julian 105) -- around 9.5 percent -- whereas on the north side, there was a rapid decrease from 18% to 10%. Figure 7 shows similar seasonal variations for the roof rafter and ceiling joist measurements. This cannot be explained by variations in ventilation, infiltration, or moisture production, as such events would affect both sides of the roof equally. Although the outside air temperature experienced by both roof orientations was the same, the roof surface temperature is also influenced by incident solar flux and is different for the two orientations. Figure 8 shows the sun angles at noon with respect to the two roof orientations. From Dec. 21 (Julian 355) on, as the winter progresses, the solar angle of incidence becomes smaller for both roof orientations. However the change was much more marked on the north-facing roof. Whereas on Dec. 21 (Julian 355) the sun's rays make almost a grazing incidence on the north roof, the incidence angle drops to 51° by April 21 (Julian 111). By contrast, the angle of incidence of solar radiation on the south side drops from 43° to 7° over the same period. The incident energy is proportional to the cosine of the angle of incidence and increases much more rapidly for the north-facing roof. Thus the more rapid drying rate of the north roof appears to be brought about by the increased solar radiation on that roof. The importance of solar radiation on wood drying is also apparent from short-term variations in solar radiation. In Figure 6, note the rapid drying during the clear period from March 9 to 17, (Julian 68 to 76) followed by the readsorption of moisture during the following week which was rainy and overcast. The winter wetting trend at the end of 1983 completes the annual cycle, and the increase in moisture sheathing content is more rapid on the north side. (See Figure 6).

From wood sorption data (Simpson 1980) it is possible to determine the equilibrium attic wood moisture level. Such information is useful to see how closely wood moisture can be predicted from air humidity measurements. Using the attic air relative humidity and the sheathing temperature, the equilibrium moisture content (EMC) of wood can be determined. The

EMC values predicted from air humidity data are compared with moisture content measurements in Figure 9. The reference 45 degree line corresponds to perfect agreement. The air film at the sheathing can be expected to be in equilibrium with the surface of the plywood (Tenwolde 1984) However, both our matchstick and uninsulated-tip hammer probes will sense the humidity of the layer which provides the least resistance to moisture flow. Thus we would not expect the wood moisture content measured to be at equilibrium with the attic air humidity. However, the general agreement indicates that air humidity measurements and wood sorption properties may provide a reasonable estimate of wood moisture content in attics.

To determine what factors affect the attic humidity, we compared it to humidities in the living space and outside. Specific humidities for inside, outside, and attic air are plotted over the test period in Figure 10. It should be noted that humidity levels can change much more rapidly than the intervals shown; in fact, substantial changes can occur in just a few hours (see Figure 1 and Cleary 1984). Therefore the lines connecting data points do not represent actual changes. The indoor humidities weakly follow the outdoor level, but the important information is in the relative positions of the three points on a given date. By our early hypothesis (Dutt 1979), the attic humidity should always lie between the other two points. In fact, this is only true on one-third of the occasions. A proper understanding of the air humidity balance would require extensive hour by hour data such as collected by Cleary (1984).

From the long term wood drying data described above it is possible to calculate the rate at which moisture is leaving the wood. The wood mass weight exposed to the attic air is approximately 8000 lb (3636 kg). From Figure 6, we see that the average moisture content decreased from 14% to 10% in eight weeks, or 0.5% per week. This means that moisture was released at the rate of 0.005 x 8000 = 40 pounds per week or 0.2 pound per hour (0.1 kg/h) averaged over the eight week period. The moisture flows into and out of the attic by air movement could be estimated from corresponding airflow and air humidity data. Unfortunately, we do not have data on living space to attic airflow, and only spot measurements of air humidities. Nevertheless, we can make a number of crude estimates to arrive at a hypothetical air and moisture balance for the attic.

From the blower door data we estimate a heating-season-average house air infiltration rate of 6000 ft^3/h. (170 m^3/h) or 450 lb/h (205 kg/h). We further assume that two-thirds of the house air exfiltration goes into the attic. We estimate the total attic infiltration from our spot tracer decay measurements to be 12,600 ft^3/h (357 kg/h) or 950 lb/h (432 kg/h). The resulting hypothetical attic air balance is shown in Figure 11a.

To calculate the moisture balance, we neglect moisture flow by diffusion. We further assume that the average living space, attic and outside specific humidities are 0.0075, 0.007, and 0.005 (based on the first eight weeks of data in Figure 10). Combining with data from Figure 11a, we arrive at the moisture balance shown in Figure 11b. Despite the crudeness of our estimation, calculations suggest that the average contribution of moisture from attic wood drying is small compared to the typical flow rates from air movement in and out of the attic.

All of the measurements and analysis above relate to the Griggstown ("G") house where the bulk of the data were collected. Attic wood moisture content was measured in several locations in the second test attic (the P house), during a number of visits in the period March to May 1983. The data, summarized in Table 1, show that the wood moisture was extremely high in some locations at the time of our visit in the beginning of March, but by the second visit had dried out to an acceptable level. This suggests that the attic could recover from high humidity in a short time without suffering any permanent structural damage. We suspect that the reason there was no wood damage in this particular attic after more than 30 years was that the roof was made of solid tongue-in-groove sheathing which could absorb a great deal of water. A plywood roof, on the other hand, has glue joining the different layers together. The glue acts as a vapor retarder which limits the mass of wood available for moisture storage. Excessive moisture causes the plywood to delaminate and become structurally weak. It is this effect which causes structural problems rather than the effect of the moisture on the wood itself. Based on our experiences in the second test attic, the observed capacity to recover from extremely high moisture levels in the wood and extensive condensation in the winter period suggests that designing an attic to completely avoid condensation may be unnecessary from a moisture damage perspective.

CONCLUSION

Measurements of wood moisture content in a New Jersey attic showed large seasonal variations. The moisture content was highest in winter, fell in the spring, reach its lowest point in the summer, and increased again in the fall. The roof sheathing facing north showed a much stronger seasonal trend. The north sheathing moisture content was high -- approaching 19% -- in the cold part of the year, compared to 10-11% for the ceiling joists, roof rafters, and south facing sheathing. However it dried out at a rapid rate in early spring and became identical in moisture content to other attic wood. One important factor in the drying seems to be the increased solar radiation on the north-facing roof. Our measurements in a second attic showed extensive condensation and very high moisture content in the winter with rapid drying in the spring and no sign of wood decay.

The effect of these seasonal variations in wood moisture content must be included in models and practices designed to control moisture in attics.

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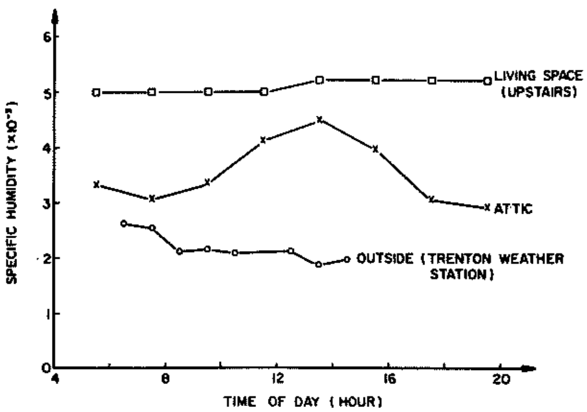
Table 1
Wood Moisture Data from Second House

Date	Number of Measurements	Wood Moisture Content (%)			
		Mean	Standard Deviation	Minimum	Maximum
3-7-83	22	21.2	5.7	14.5	42.0
5-2-83	16	12.0	1.3	11.0	13.5
5-9-83	9	11.1	0.6	10.2	12.2
5-23-83	9	11.7	1.0	11.5	13.0



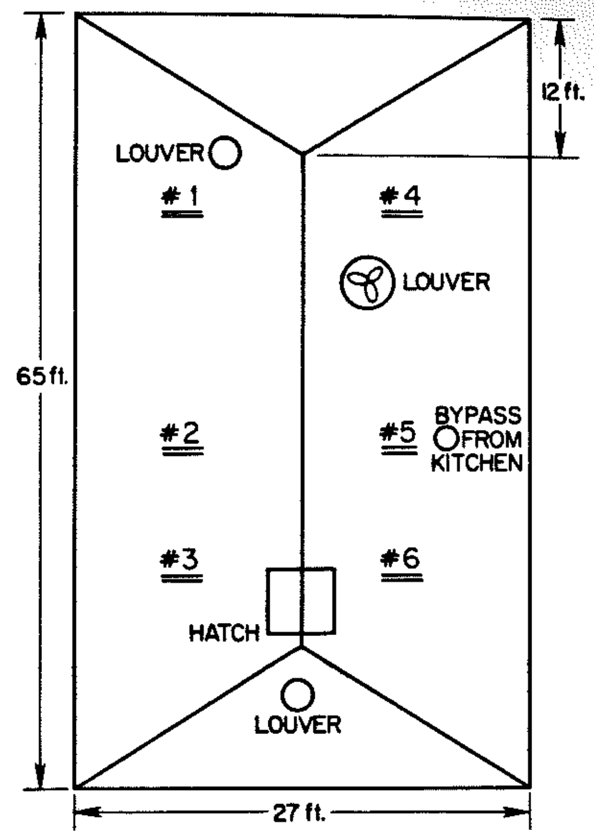


Figure 1. Humidity in a Twin Rivers townhouse, March 8, 1977

Figure 2. Attic layout with probe locations

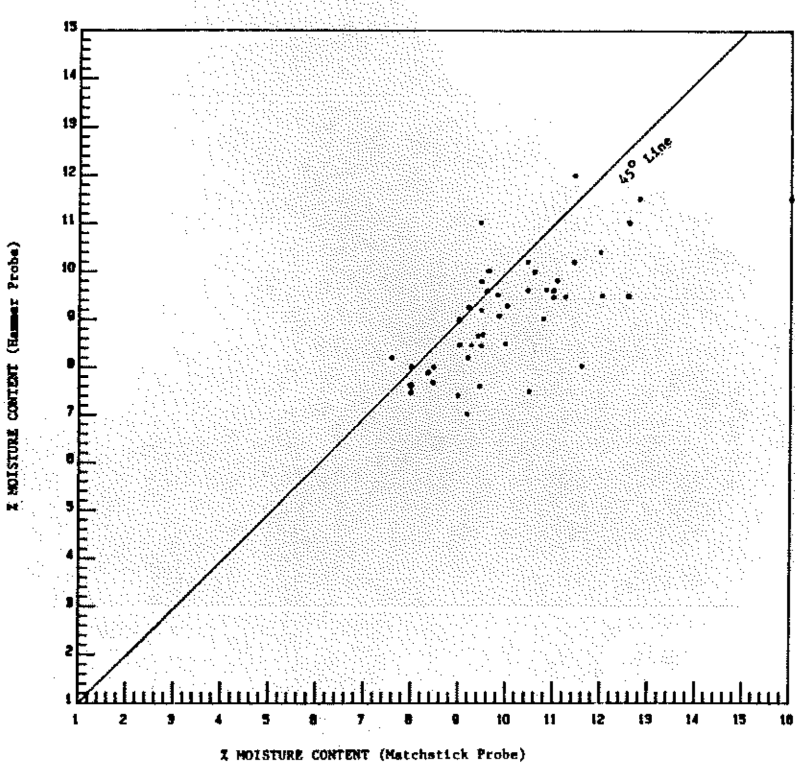


Figure 3. Moisture probe correlation

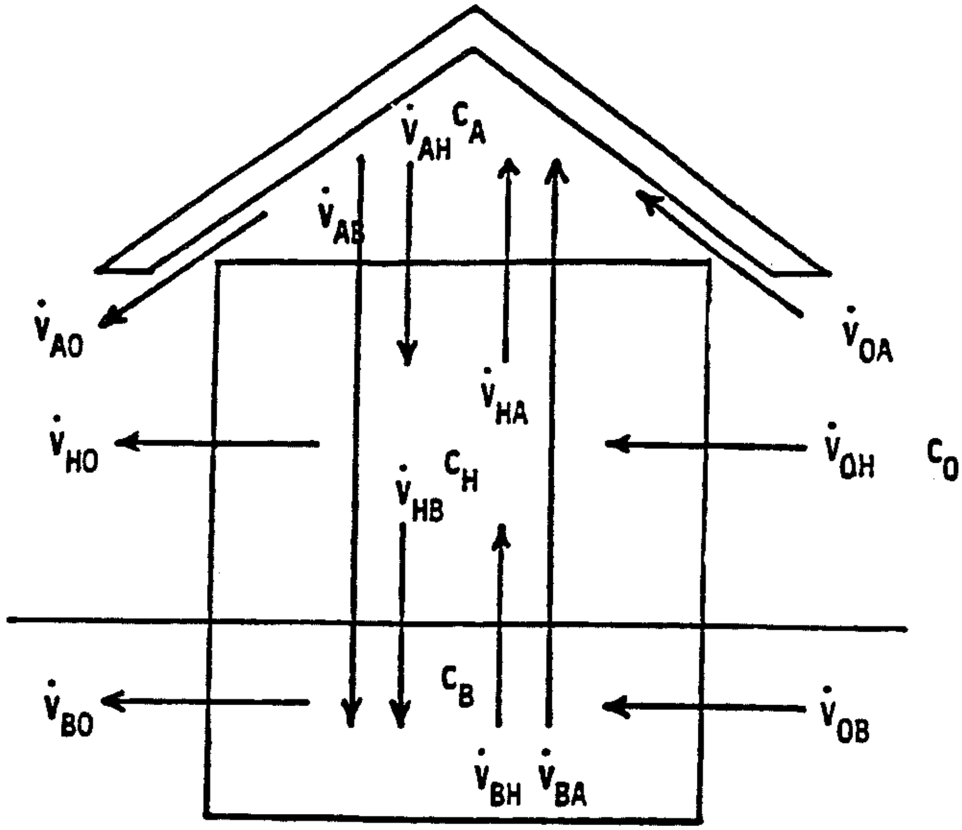


Figure 4. Three-chamber airflow model with 12 possible convective airflows

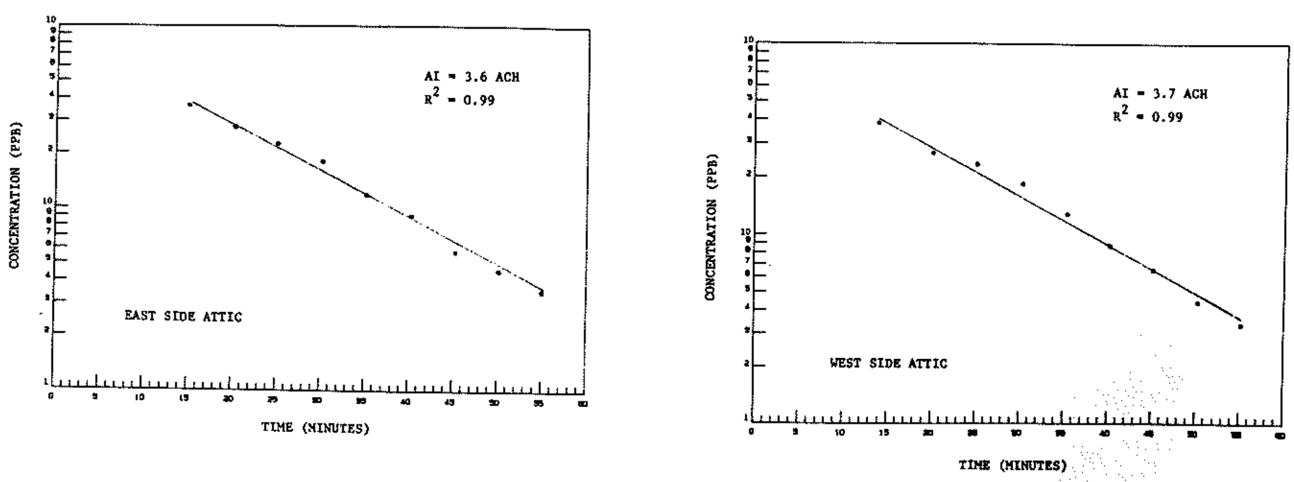


Figure 5. Tracer gas decays

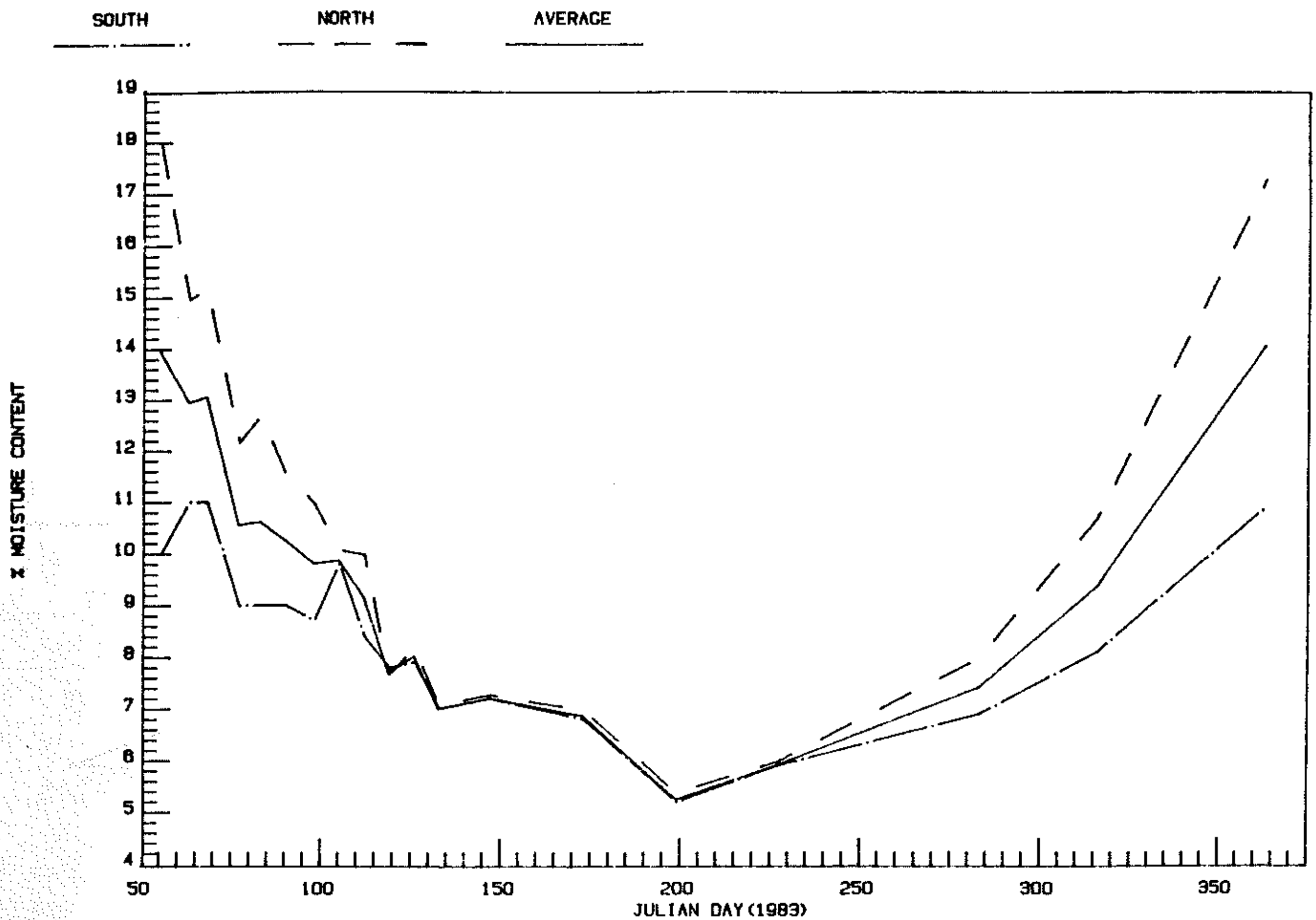


Figure 6. Sheathing moisture content vs. Julian day

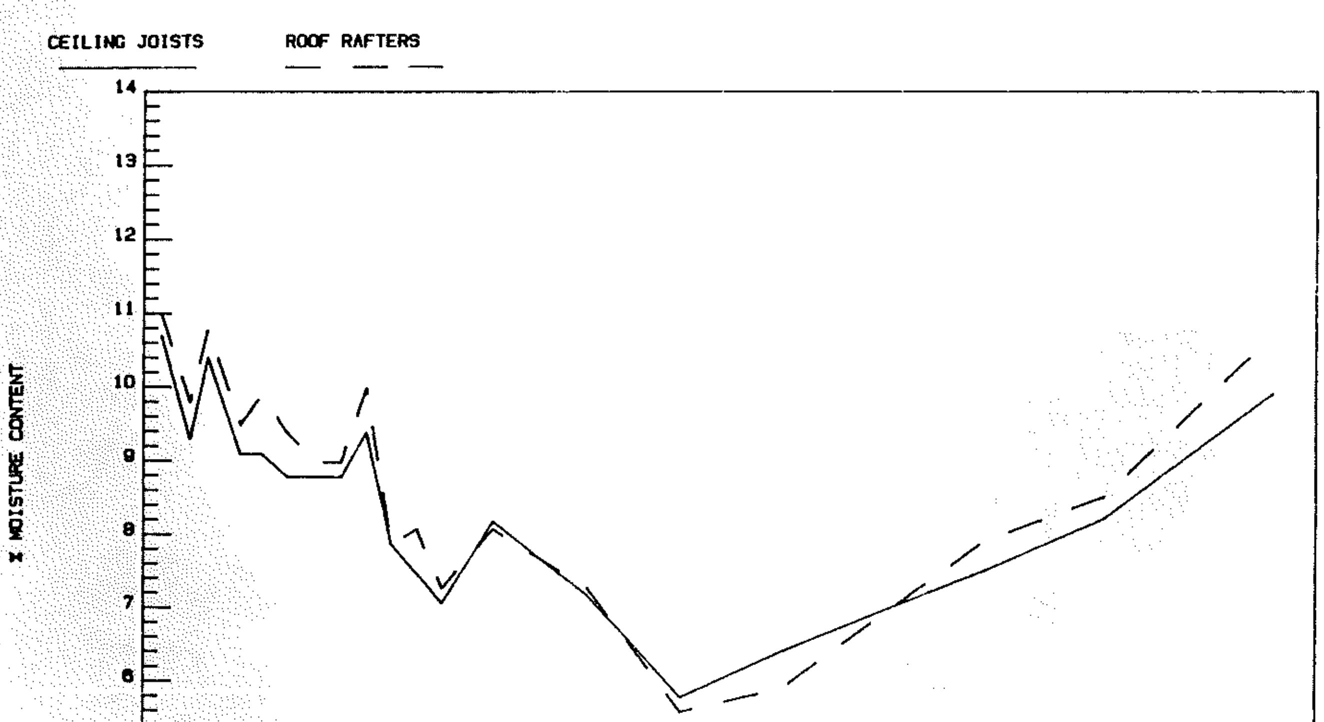


Figure 7. Ceiling joist and roof rafter moisture content vs. Julian day

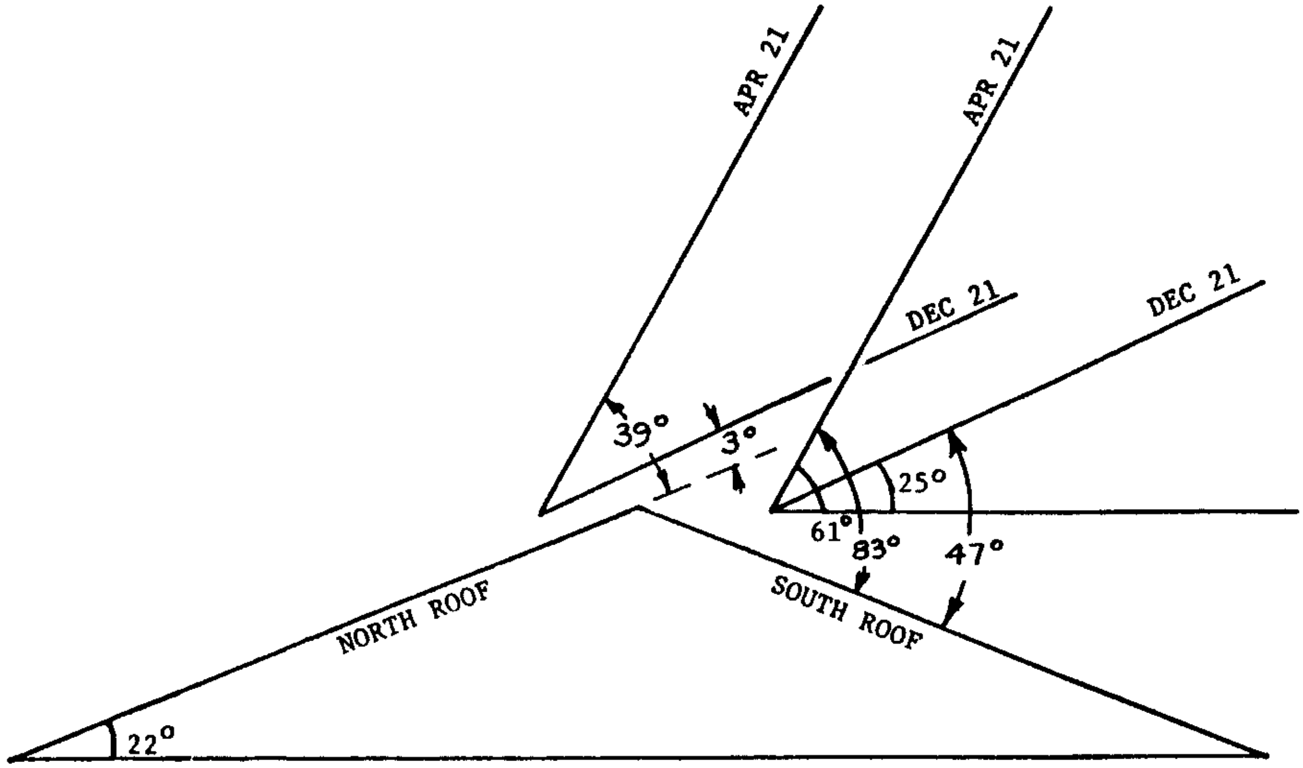


Figure 8. Change of sun angles from December 21 to April 21

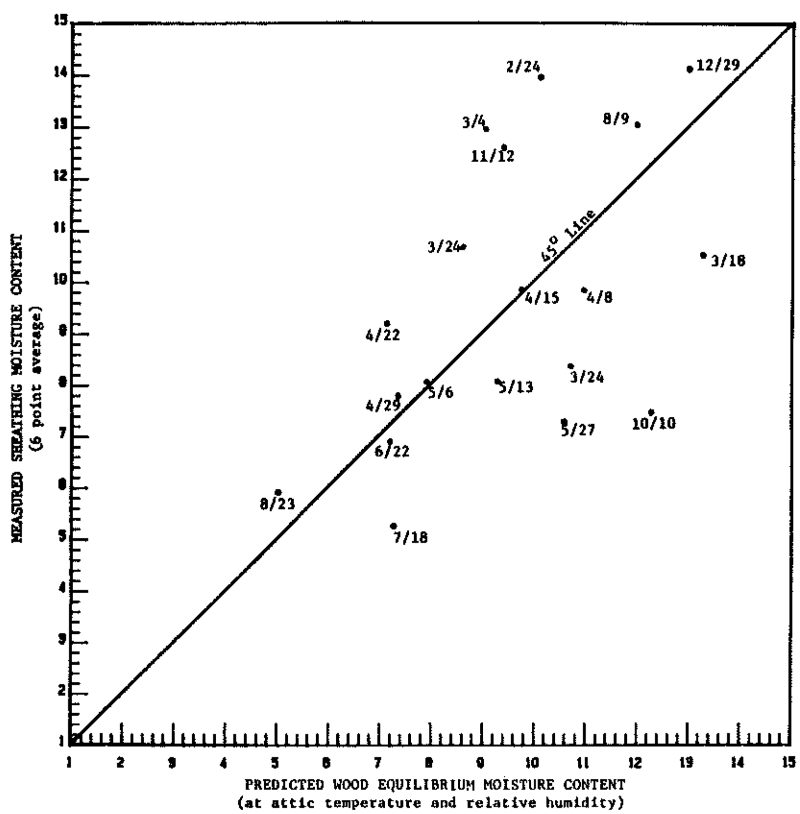


Figure 9. Measured attic sheathing vs. predicted equilibrium moisture content

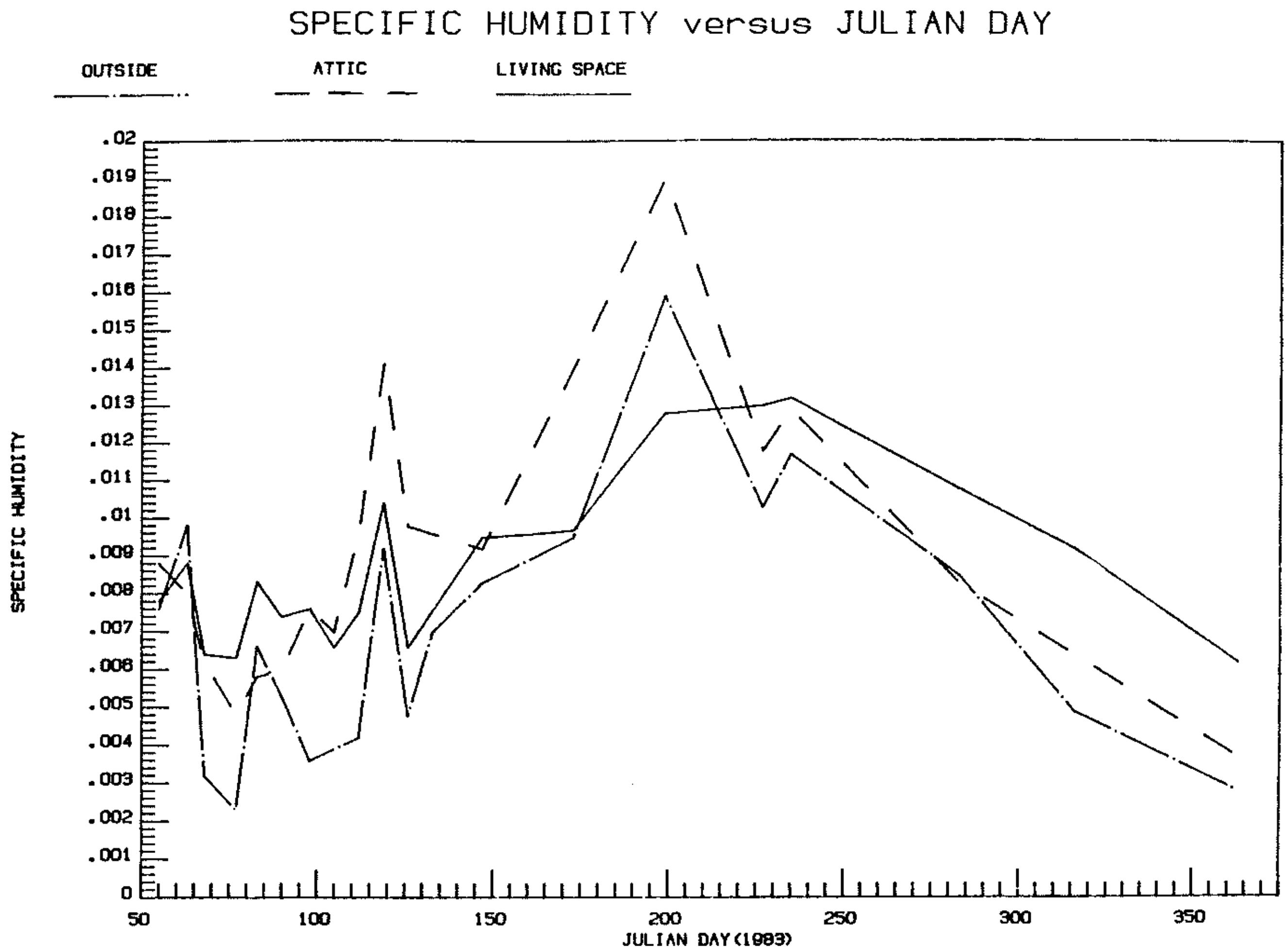


Figure 10. Specific humidity vs. Julian day

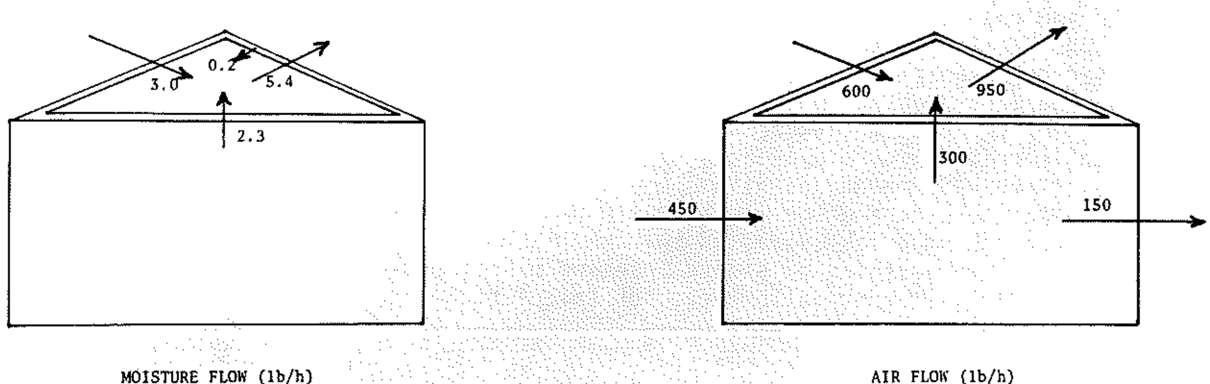


Figure 11. Air and moisture flows