IX.

A State-of-the-Art Research Assessment For Residential Attic Condensation

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ABSTRACT

A brief synopsis of recent analytic and experimental studies is given. These recent studies lead to the following conclusions. Convective transfer of water vapor into an attic from the living space below often transports more moisture than diffusive transfer through the ceiling construction. Large quantities of moisture are stored in the roof sheathing during cold winter periods and subsequently released during warm spring and summer periods. Solar loading during mild winter periods can produce desorption of moisture from the sheathing.

In view of the inherent protection against attic condensation offered by moisture storage at wood surfaces, it is likely that the current practices of HUD and past practices of ASHRAE for preventing condensation are adequate. However, a comprehensive field survey to assess rigorously the adequacy of these current and past practices is badly needed.

Mathematical models are needed to extend the results of individual experiments to different attic configurations and different outdoor climates. This paper reviews the formulation of mathematical relationships among physical parameters governing moisture transfer within attics. In order to model completely all moisture-transfer processes, further experimental measurements are needed to quantify attic ventilation rates and convective air flows into the attic from the house below. In addition to models that characterize attic moisture transfer over short time periods, dynamic models for predicting seasonal variations in the moisture content of roof sheathing also need to be developed and experimentally validated.

1. INTRODUCTION

During the winter, the household activities of the occupants in unhumidified homes release as much as 25 pounds of water vapor per day for average American [1]. Humidification of the indoor space greatly adds to these numbers. A significant fraction of this water vapor is transported into the attic principally by convective air penetration through the ceiling construction, and a smaller amount by diffusion. Once water vapor is introduced into an attic, unless it is properly ventilated to the outdoor environment, it may be either adsorbed or condensed at the cold roof sheathing. When attics in cold climates are closed off (i.e., little or no ventilation is provided) and extremely large quantities of water vapor are introduced, it is possible for a thick layer of frost to build up at the underside of a sloping roof (as shown in Figure 1).

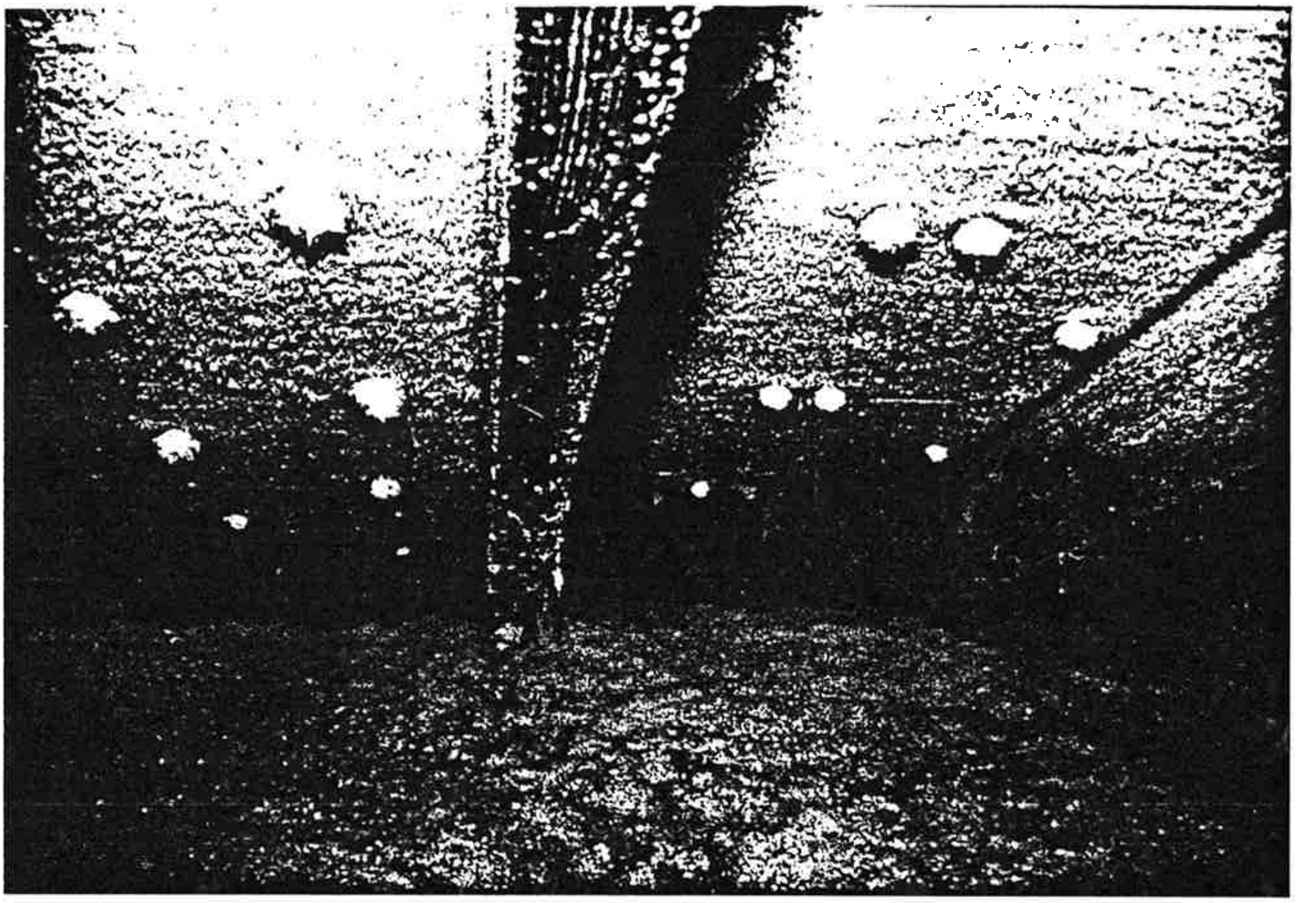


Figure 1

During warm periods, this frost layer may melt and drip down wetting the insulation on the attic floor. Water may penetrate through light fixtures and stain the ceiling. The sloping roof may absorb moisture making it susceptible to fungus decay. Depending upon the severity of the damage, it may eventually be necessary to replace rotted portions of the roof. Although this paper is primarily directed to houses with sloping roofs with an attic, many of these same moisture problems occur in houses with flat roofs often to greater severity.

2. SYNOPSIS OF RECENT FIELD STUDIES

In 1983, a field study [2] was conducted under the direction of David Harrje at Princeton University in which the moisture content of the roof sheathings of a house was monitored over a one-year period. This study found that the north sloping roof adsorbed water vapor during cold winter periods and reached a high moisture content of 20% during mid-winter (see Figure 2).

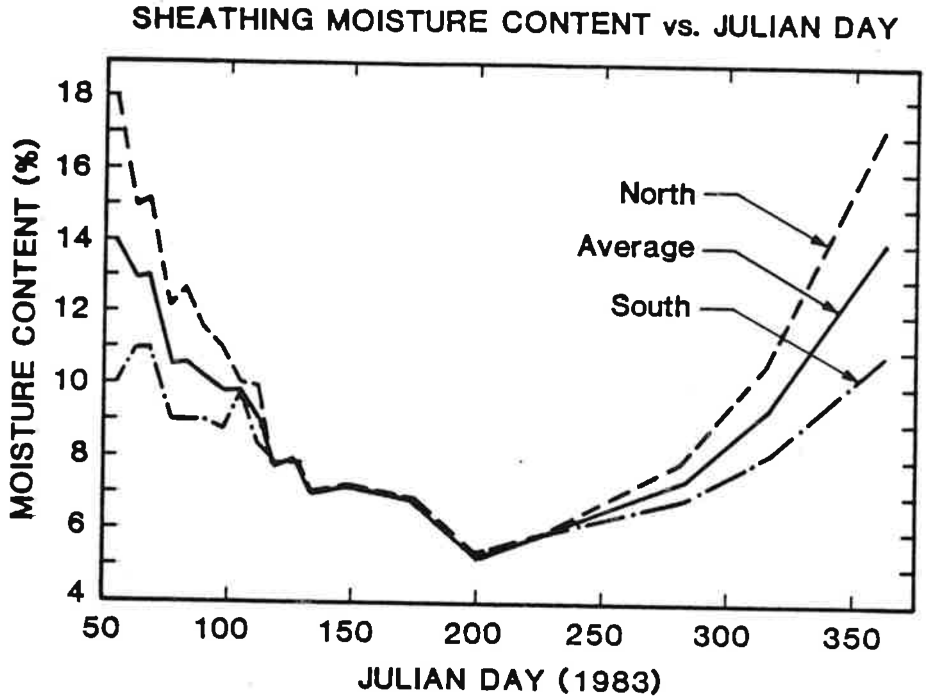


Figure 2. Seasonal variation in moisture content of the roof sheathing for a test house at Princeton, NJ [2].

The roof sheathing desorbed moisture and the moisture content decreased to a low of 5% during the following summer. The same cyclic behavior was found in the wood moisture levels of the south sloping, but here the maximum moisture levels reached only the 11% mark. The results indicated that solar warming limited the moisture build-up in the south sloping roof. Similar cyclic variations in roof moisture content have been observed by others [3, 4].

In a series of residential building studies conducted over the past decade, Princeton University researchers have consistently found the attic floor (ceiling of the living space) to be a prime location for convective air movement into the attic. Some of the key air leakage sites are shown in Figure 3.

These sites of "attic bypasses" overwhelm the diffusion transfer mechanism when evaluating the transfer of moisture through ceiling construction. This is pointed out by Dutt in Ref. [5]. A significant fraction of the exfiltration air follows this route to the attic. As the figure points out, interior partitions, areas above soffited ceilings, electrical, plumbing, and heating-related breaks in the ceiling structure, as well as

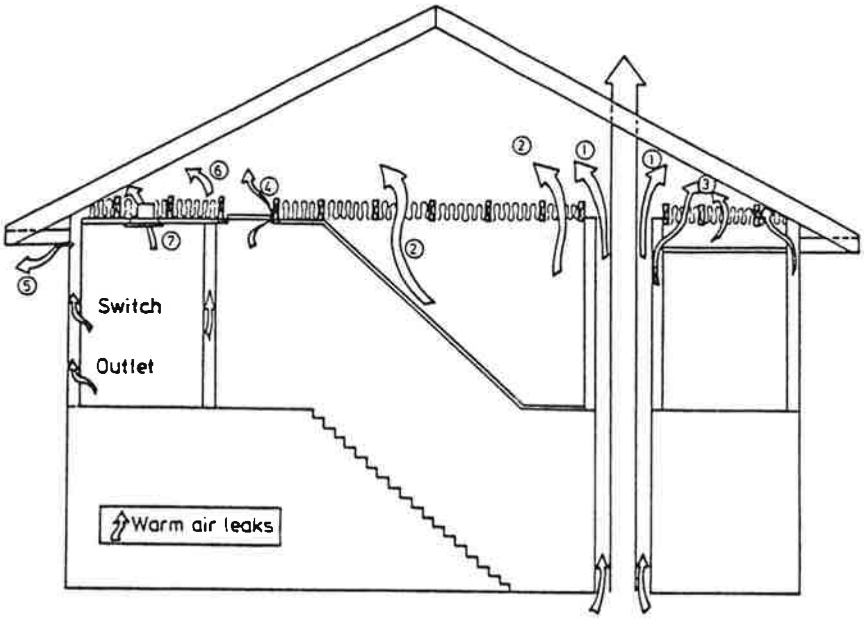


Figure 3. Common air exfiltration paths from the living space at the portions of the house: (1) around flue and plumbing stack, (2) through the insulation, (3) above dropped ceilings, (4) around entries, (5) penetrations in outer walls and eaves, (6) leakage up through interior walls and electrical systems, and (7) recessed lights.

any attic or hatch doors, all play a part in the moisture transfer. If we are dealing in houses with basements, moisture sources are often located there, and the pathways for moist air can then lead directly to the attic [e.g., path (1)].

In a Lawrence Berkeley Laboratory study [4] carried out in 1983 by Peter Cleary, diurnal temperature variations in the roof sheathing of a test house were found to adsorb moisture during cold night periods and desorb moisture during warm day periods (see Figure 4). These results illustrate the important role played by diurnal roof temperature variations on the attic moisture balance.

3. MATHEMATICAL MODELS

The amount of attic ventilation required to prevent condensation (or frost) formation at the roof sheathing of ventilated attics is a complex function of the house construction, including such factors as the air tightness and water-vapor permeability of the ceiling construction, the thermal resistance of the ceiling, as well as the size and location of the vents. Moreover, the amount of attic ventilation needed is also a function of the climate including such factors as: wind speed; outdoor temperature; solar radiation; and air moisture content. These factors vary considerably with house construction and geographic location. Individual experiments have tended to

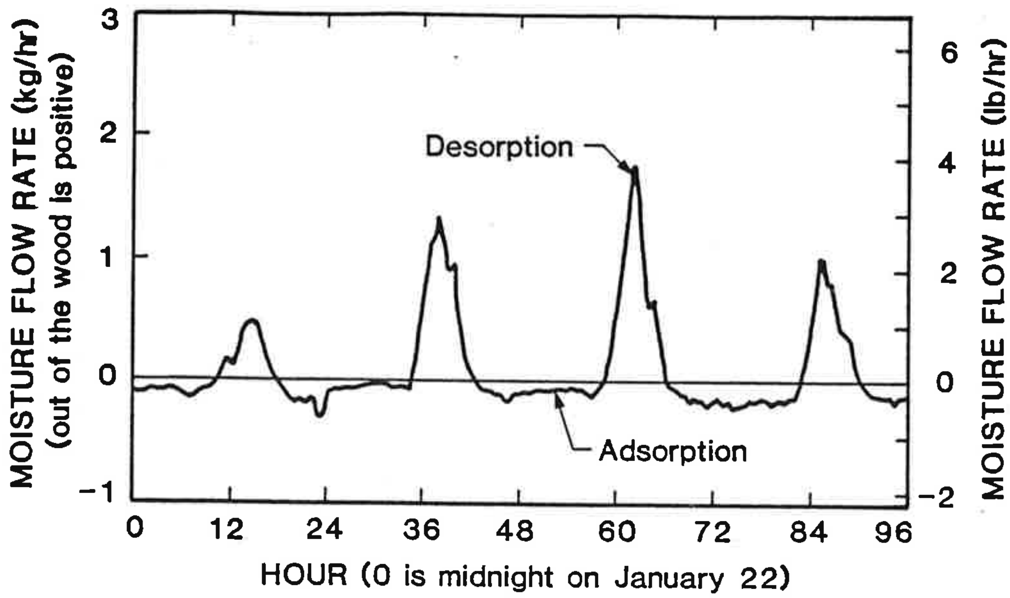


Figure 4. Moisture flow out of the roof sheathing of a test house at Oroville, CA [4].

investigate the performance of attics over a narrow range of climatic conditions when compared to the entire U. S. climate. Extrapolations to other climates and other attic configurations are not possible without the formulation of mathematical relationships among the physical parameters that govern attic performance.

A mathematical model for predicting the moisture transfer processes within an attic was developed by Doug Burch [6]. This model was later improved to include adsorption/desorption at wood surfaces and was verified by way of comparison to a series of experiments [7]. In this model, a moisture balance is performed on an attic. The moisture gains to the attic including diffusive and convective transfers through the ceiling construction are equated to the moisture loss by ventilation and moisture storage at wood surfaces. This model is described below. A limitation of the model is that the moisture content of the roof sheathing must be specified.

3.1 Moisture Storage at Wood Surfaces

Wood surfaces in an attic are hygroscopic and possess substantial storage capacity to adsorb large quantities of water vapor during cold periods and to desorb this moisture during warm periods. A boundary layer exists at wood surfaces in an attic. Water-vapor is transported across this boundary layer by convection. Within the wood, moisture is transferred by diffusion. The adsorption (or desorption) of moisture at a wood surface is small compared with the moisture storage capacity of the wood itself. As a result, the moisture content at a wood surface is small compared with the moisture storage capacity of the wood itself. As a result, the moisture content at a wood surface changes slowly as a function of time. Over short time periods (i.e., one week), the moisture content at wood surfaces usually may be treated as being constant [4,7].

The rate of water-vapor adsorption (or desorption) is governed by a convective mass-transfer coefficient for the water-vapor boundary layer adjacent to the wood surface. The laminar sublayer for this boundary layer may be assumed to be in a state of moisture equilibrium with the wood surface [4]. The rate of moisture adsorption or desorption (W_{wood}) at a wood surface may be predicted from the relation:

$$W_{wood} = A_w \cdot h_w \cdot (\omega_a - \omega_w) \tag{1}$$

where

h_w = convective mass-transfer coefficient at wood surface, lb./h·ft^2;

ω_a = humidity ratio of attic air, lb. moisture/lb. dry air;

ω_w = humidity ratio at wood surface, lb. moisture/lb. dry air; and

A_w = surface area of wood surfaces, ft^2.

The convective mass-transfer coefficient (h_w) may be predicted from the well known Lewis relation:

$$L_e = \frac{h_c}{h_w \cdot C_p} \tag{2}$$

where

L_e = Lewis number, dimensionless;

h_c = convective heat-transfer coefficient, Btu/h·ft^{2}·^{o}F; and

C_p = specific heat of air, Btu/lb.·^{o}F.

The humidity ration (ω_w) at a wood surface may be predicted from the equilibrium moisture content data for wood contained in The Wood Handbook [8] providing that surface condensation or frost is not present. Peter Cleary [4] has fit these data to the following empirical relation:

$$\omega_w = e^{T_{s/A}} (B + C \cdot U + D \cdot U^2 + E \cdot U^3) \tag{3}$$

where

T_s = wood surface temperature, ^oF;

U = moisture content of wood; and

A, B, C, D, E = empirical constants.

Various sensible heat-transfer models [9-12] have been developed to predict the surface temperature (T_s). These models have been verified in [13, 14]. Latent heat of vaporization associated with the adsorption, desorption, or condensation process has been shown to have a small effect on the surface temperature [7].

Wood surfaces in an attic will continue to adsorb moisture until they reach moisture equilibrium with the attic air. Such a condition frequently occurs at a wood moisture content of about 28% (by weight) [7]. This moisture content corresponds to the fiber-saturation point for wood exposed to very cold temperatures at saturated humidity conditions. After this point, condensation will occur, providing that the wood surface temperature is below the dewpoint temperature of the attic air. When liquid water or ice is present at a wood surface, the rate of moisture transfer at the surface is governed by Eq. (1), except that $_w$ is determined from equilibrium data for water or ice instead of wood [3].

The existing sensible heat-transfer models for predicting the roof sheathing temperature (T_s) have been validated for simple attic geometries that have not included convective heat transfer from the living space into the attic. This convective heat transfer has been shown to be important [5], and it needs to be incorporated into the existing sensible heat-transfer models.

3.2 Attic Ventilation

The rate of moisture loss by attic ventilation may be predicted from the relation:

$$W_{vent} = I_a \cdot V_a \cdot \rho \cdot (\omega_a - \omega_o) \qquad (4)$$

where

I_a = attic ventilation rate, volume changes/h;

V_a = volume of attic, ft^3;

ρ = density of air, lb/ft^3;

ω_a = humidity ratio of attic air, lb moisture/lb dry air; and

ω_o = humidity ratio of outdoor air, lb moisture/lb dry air.

Hinrichs [15] has measured "effective" attic ventilation rates using a smoke technique for a test house fitted with various ventilation systems and correlated the measurements with respect to wind speed. The ventilation rate was determined by releasing smoke and measuring the elapsed time for the smoke to clear. The effective ventilation rate was computed as the ratio of the attic volume to the elapsed time. Ford [3] has pointed out that, since the decay of smoke within an attic is more closely approximated as an exponential decay process rather than a piston flow process and the smoke clears after approximately three time constants, the effective ventilation rates measured by Hinrichs are approximately one-third of the actual rates.

A limited number of attic ventilation measurements using a tracer-gas technique for various attic configurations are reported in [2, 16]. A strong need exists to carry out a more comprehensive series of tracer-gas measurements to determine attic ventilation rates as a function of wind speed.

3.3 Ceiling Diffusion

The rate of water-vapor transfer (W_{diff}) by diffusion through opaque ceiling construction may be predicted by Fick's law, or

$$W_{diff} = A_c \cdot M_c \cdot (P_i - P_a) \qquad (5)$$

where

A_c = ceiling area, ft^2;

M_c = permeance of ceiling, lb./h ft^2 in. Hg;

P_i = indoor vapor pressure, in. Hg; and

P_a = attic vapor pressure, in. Hg.

Permeance values for typical ceiling construction may be predicted by equations given in Ref. [17]. However, such common situations as permeance values for multiple layers of paint in older houses is often unknown.

3.4 Convective Air Penetration

Convective air penetration into an attic from the living space below has been shown to be an important mechanism for transferring water vapor into the attic [5]. The rate of water-vapor transfer (W_{conv})

$$W_{conv} = v \cdot \rho \cdot (\omega_i - \omega_a) \qquad (6)$$

where

v = rate of convective air penetration, ft_3/h;

ρ = density of air, lb/ft3;

ω_i = humidity ratio of indoor air, lb moisture/lb dry air; and

ω_a = humidity ratio of attic air, lb moisture/lb dry air.

Very little information is available concerning representative rates of convective air penetration in typical houses. Part of this lack of data is the problem of measurement. For the tracer-gas technique, it is assumed that perfect mixing of the air within a space occurs. With high attic ventilation rates and numerous exits, such a situation may not exist.

3.5 Moisture Balance

In performing a moisture balance, the sum of the rates of water-vapor transfer by diffusion and convective air penetration through the ceiling construction are set equal to the loss of moisture by exchange of attic air with outdoor air and the loss (or gain) of moisture by adsorption (or desorption) at wood surfaces or:

$$A_c \cdot M_c \cdot (P_i - P_a) + v \cdot \rho \cdot (\omega_i - \omega_a) = I_a V_a \cdot \rho \cdot (\omega_a - \omega_o) + A_w \cdot h_w \cdot (\omega_a - \omega_w) \quad (7)$$

This moisture-balance equation has been verified by a series of experiments at the National Bureau of Standards in which a small test house (see Figure 5) was exposed to steady and dynamic outdoor temperature conditions in an environmental chamber. Measured and predicted results for a diurnal cycle test are compared in Figure 6. Note the good agreement between the measured and predicted attic air dewpoint temperature, thereby supporting the validity of the moisture balance given by Eq. (7).

For the above analysis the moisture content of the roof sheathing was specified. Mathematical models for predicting the seasonal variations in moisture content of roof sheathing as a function of time need to be developed. At the wood surface, the convective mass transfer at the wood surface would be equated to the diffusive transfer into the wood.

4. ADEQUACY OF CURRENT AND PAST PRACTICES FOR PREVENTING ATTIC MOISTURE PROBLEMS

A prescribed amount of attic vent open area and a ceiling vapor retarder are customarily prescribed to prevent attic moisture problems. The following recommended past practices are given in the ASHRAE Handbook of Fundamentals [17]: attics shall be ventilated with a net open area equal to 1/300th of the attic floor opening. In addition, a ceiling vapor retarder shall be provided in all U.S. geographic locations, except for those generally defined as the mid-Atlantic, sun belt, and west coast regions. A similar practice prescribing that the ventilation

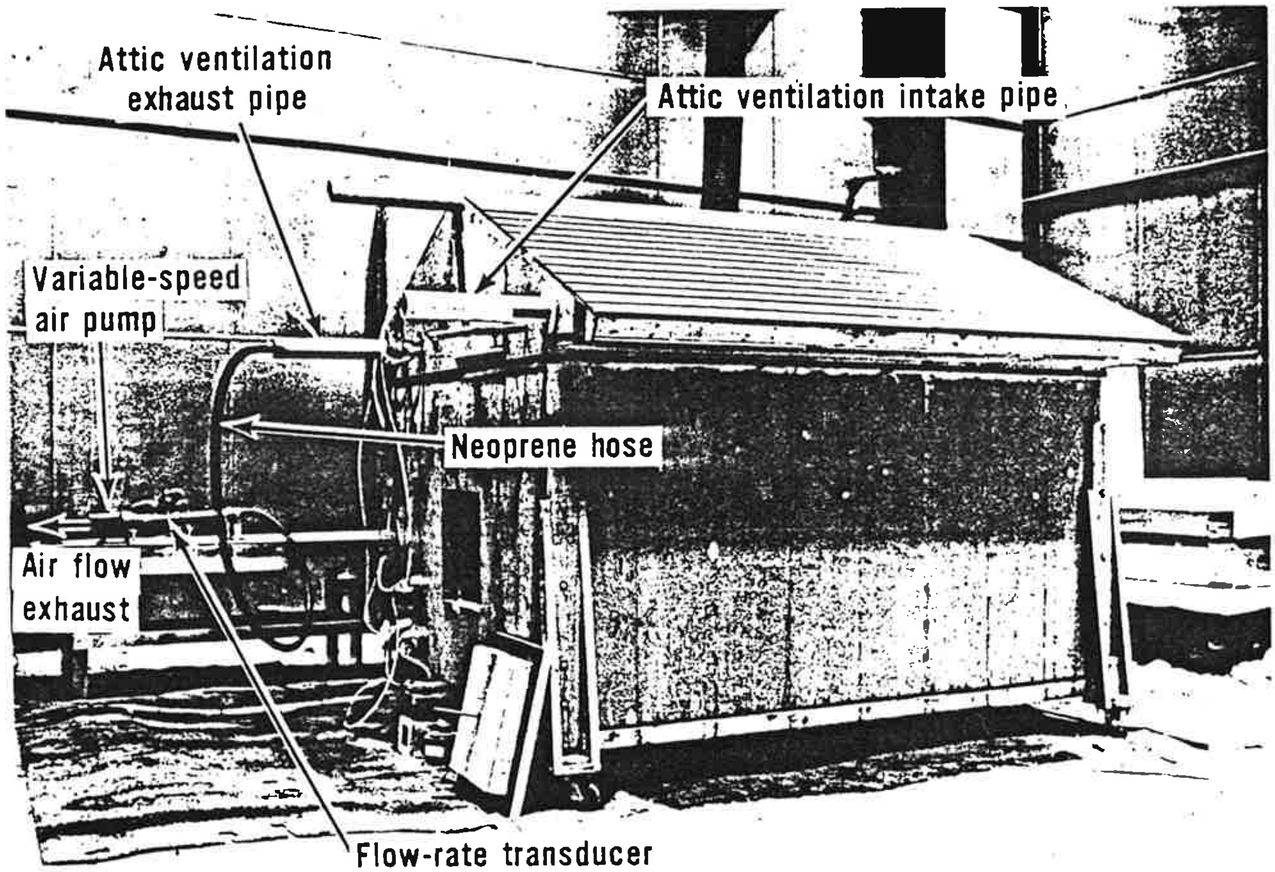
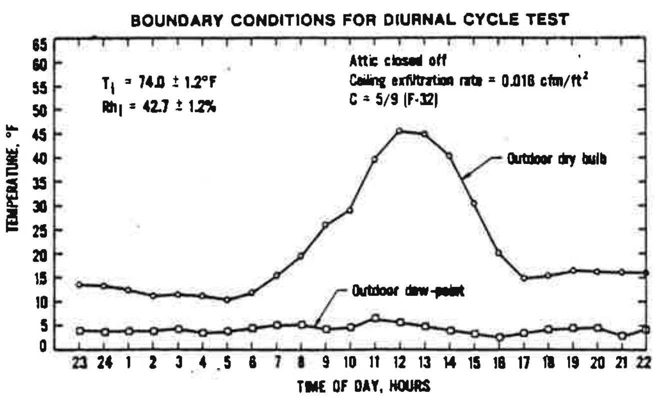
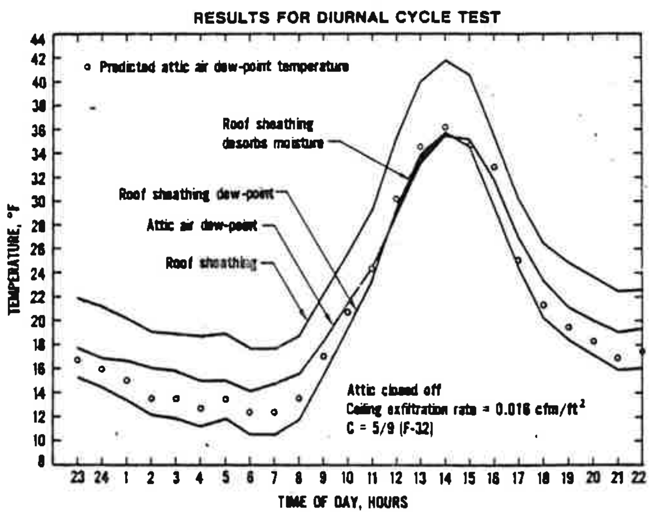


Figure 5. A photograph of the test house located in the environmental chamber.



A. Outdoor conditions



B. Test results

Figure 6. Diurnal outdoor cycle test

area be 1/150th of the attic floor area is given in the HUD Minimum Property Standards (MPS) [18]. Here the prescribed amount of attic vent open area may be reduced by a factor of two, if a vapor retarder is installed or at least 50 percent of the ventilation area is provided in the upper region of the attic and the remainder is provided at eaves or soffits. The authors would like to emphasize that field studies have indicated significantly higher ventilation rates are achieved when ventilation openings are located at different levels. These guidelines were developed approximately 35 years ago, and they were based on the experience and knowledge of persons in the building industry.

The above recommended practices have generally proven to be successful in preventing attic moisture problems provided that an "out-of-the-ordinary" source of moisture is not present. Such a source of moisture might be a bathroom exhaust fan, a clothes dryer vented into an attic, a defective flue pipe exhausting combustion products into an attic, or a leaky roof. Even when the recommended practices are not followed, a moisture problem does not always occur. For instance, Ref. [2] cites moisture measurements in an under ventilated attic where the wood moisture cycled seasonally from 40% in mid-winter to less than 10% in mid-summer. The 30-year-old wood sheathing showed no evidence of fungus deterioration, however mold growth was very apparent. If this roof had been constructed of plywood instead of wood, it may have delaminated under such moisture cycles.

In view of recent experimental studies that have shown wood within attics to be capable of storing significant amounts of moisture, thereby reducing the likelihood of surface condensation, it would appear that the recommended practices for controlling condensation are adequate. However, a strong need exists to carry out a comprehensive field survey on a statistically significant sample of residences covering a range of U.S. climates in order to assess rigorously the adequacy of these recommended practices.

5. SUMMARY OF RESEARCH NEEDS

Existing mathematical models need to be refined to predict seasonal variations in moisture content of roof sheathing as a function of time in order to permit individual experimental studies to be extended to other attic configurations and different outdoor climates. Experimental measurements are needed in various house types to quantify: convective air flows into attics from the house below and attic ventilation rates. These mathematical models need to be verified through a series of field experiments.

A comprehensive field survey needs to be conducted in order to assess rigorously the adequacy of current and past practices for controlling attic moisture problems.

REFERENCES

1. L.O. Anderson, "Condensation Problems: Their Prevention and Solution," USDA Forest Service Research Paper FPL 132, Forest Products Laboratory, Madison, Wisconsin, 1972.

2. D.T. Harrje, R.G. Gibson, D.J. Jacobson, G.S. Dutt, and G. Hans, "Field Measurements of Seasonal Wood Moisture Variations in Residential Attics," Princeton University, Center for Energy and Environmental Studies, Princeton University, 1984.

3. J.K. Ford, "Heat Flow and Moisture Dynamics in a Residential Attic," Master Thesis, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, 1982.

4. P. Cleary, "Moisture Control by Attic Ventilation -- An In Situ Study," Lawrence Berkeley Laboratory Report No. LBL-18062, July 1984.

5. G.S. Dutt, "Condensation in Attics: Are Vapor Barriers Really the Answer?," Energy and Buildings, The Netherlands, Vol. 2, 1979.

6. D.M. Burch and D.E. Luna, "A Mathematical Model for Predicting Attic Ventilation Rates Required for Preventing Condensation on Roof Sheathing," ASHRAE Transactions, Vol. 86, Part 1, 1980.

7. D.M. Burch, M.R. Lemay, B.J. Rian, and E.J. Parker, "Experimental Validation of an Attic Condensation Model," ASHRAE Transactions, Vol. 90, Part 2, 1984.

8. <u>Wood Handbook: Wood as an Engineering Material</u> Agriculture Handbook No. 72, Forest Products Laboratory, Forest Service, U.S. Department of Agriculture, August 1974.

9. B.A. Peavy, "A Model for Predicting the Thermal Performance of Ventilated Attics," Proceedings of Workshop entitled "Summer Attic and Whole-House Ventilation," NBS Workshop, NBS Special Publication 548, pp. 119-149, July 1979.

10. T. Kusuda, "NBSLD, The Computer Program for Heating and Cooling Loads in Buildings," NBS BSS 69, U.S. Department of Commerce, July 1976.

11. "TRNSYS, A Transient Simulation Program," University of Wisconsin, Engineering Experiment Station, Report 38-9, February 1978.

12. R.S. Blancett, et al, "A Model for Predicting Residential Attic Space Air Temperatures," ASHRAE Transactions 85, Pt. 1, 1979.

13. K.E. Wilkes, "Modeling of Residential Attics," Proceedings of the ASHRAE/DoE-ORNL Conference, Thermal Performance of Exterior Envelopes of Buildings, ASHRAE SP28, 1981.

14. F.C. McQuiston, S.B. Sandoval, and S.L. Der, "Thermal Simulation of Attic Ceiling Spaces," ASHRAE Transactions, Vol. 90, Pt. 1, 1984.

15. H.S. Hinrichs, "Comparative Study of the Effectiveness of Fixed Ventilation Louvers," ASHRAE Transactions, Vol. 68, 1962.

16. D.M. Burch and S.J. Treado, "Ventilating Residences and Their Attics for Energy Conservation," Proceedings for Summer Attic and Whole-House Ventilation Workshop, NBS Special Publication 548, July 1979.

17. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia, 1981.

18. "Minimum Property Standards for One- and Two-Family Dwellings," HUD 4900.1, Department of Housing and Urban Development, 1982 edition.