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# A MATHEMATICAL MODEL FOR INDOOR HUMIDITY IN HOMES DURING WINTER

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## ABSTRACT

Many moisture problems in homes during winter are a result of excessively high indoor humidity. Excessive moisture may damage structural wood and wood-based materials as well as other parts of the structure. The most commonly recommended remedy is additional ventilation. To minimize additional energy consumption and to avoid excessively low humidities, it is important to provide the correct amount of ventilation. This will prolong the life of wood-frame buildings and contribute to their satisfactory performance.

The author developed a simple mathematical model, FPLRH1, which predicts indoor relative humidity as a function of occupancy and ventilation rate. FPLRH1 allows the evaluation of the effect of different ventilation strategies on winter indoor humidity. It includes a simple alternative treatment of the effect of moisture storage in hygroscopic materials such as wood. Where previous equations for storage involved calculation of the average moisture content of the hygroscopic storage materials, FPLRH1 expresses storage entirely in terms of current and past indoor humidity levels.

This model was verified with humidity and ventilation data from a test building and three residences, all in Madison, Wisconsin, during the 1984-85 heating season. The test building contained two separate rooms which were individually monitored. A dehumidistat-controlled fan provided the ventilation in one room, while the other room depended on natural ventilation. Each residence was equipped with an air-to-air heat exchanger. Indoor temperature and relative humidity were continuously monitored, and ventilation rates were measured periodically.

Weather data from the local weather station appeared adequate for predicting humidities with acceptable precision, but further verification of the model is needed. Moisture storage proved to have a significant effect on indoor humidity levels. The measurements also showed that a dehumidistat-controlled fan can provide adequate ventilation during the fall, winter, and early spring.

## INTRODUCTION

In recent years many homeowners and tenants have taken steps to reduce air infiltration into the house in an effort to reduce energy consumption and cost. Unfortunately, the resulting decrease in ventilation rate has increased the potential for excessively high indoor humidity during the winter. Relative humidities (RH) over 60% may cause or aggravate health problems, such as allergies and rheumatism, and often lead to condensation and mildew growth during cold weather. Condensation may cause decay in wood or damage other structural materials.

Winter moisture problems can often be traced to high indoor humidity. In northern climates indoor RH as low as 50% has been known to cause severe window condensation and mildew. Good air and vapor retarders can prevent condensation in walls and ceilings in newly constructed homes, but the necessary extra care in design and construction is expensive. Vapor retarders also do not prevent condensation on windows or elsewhere in the house. Adding vapor retarders in existing homes is generally impractical. Increasing ventilation rates to manage indoor humidity levels is often the most practical and economical solution. With proper ventilation design increased ventilation will also lower the concentration of many harmful indoor air pollutants.

Whereas lowering excessive moisture and pollutant levels is beneficial, overventilating can lead to excessively low humidity levels, which also has a negative effect on human comfort and health. Health experts generally recommend an optimal humidity range of 40 to 60% RH. Of course over-ventilating also results in unnecessary energy loss. An ideal ventilation system would maintain RH within a fairly narrow range, simultaneously avoiding condensation and other moisture problems while ensuring a healthy environment for the occupants. The upper end of this range depends on the local weather as well as construction details such as the quality of windows, insulation, and vapor retarders. Such a ventilation system would help prolong the life of wood-frame buildings and contribute to their satisfactory performance.

Although a methodology to calculate minimum ventilation rates recently was published,[1] no attempt was made to calculate maximum rates nor was the effect of moisture storage included. Moisture adsorption and desorption is believed to significantly affect indoor humidity levels.[2-5]

Two recently developed mass balance models for moisture include the effect of moisture storage.[6-8] These models were designed to calculate latent air-conditioning load during the cooling season, but should also apply to heating season conditions. The MAD model, developed at the Florida Solar Energy Center, has been reported to yield reliable results, but the model is large and requires many input data and results from finite differencing subprograms.[7,8] This approach is very valuable but often much of this information is not available for actual residences. A more simple approach is needed along with the more rigorous of the MAD model. The MOBAL3 model offers an alternative approach.[6] It expresses the storage behavior of the building in terms of hygroscopic storage capacity and a moisture exchange time constant. This model has been used to show that storage does not have a very significant influence on average humidity or energy consumption over extended periods during the cooling season. However, during the heating season, when no dehumidification takes place, this conclusion may not hold.

A dehumidistat is a logical choice for a ventilation control device to maintain an optimum range in humidity. Before dehumidistat-controlled ventilation can be accepted in practice, its effectiveness in providing ventilation and humidity control needs to be determined. Storage may affect the behavior of dehumidistat-controlled ventilation, and an RH prediction model including storage would be useful to determine the effectiveness of such a ventilation system.

## OBJECTIVES

The research work presented here had the following objectives: (a) verify a simple mathematical expression for indoor humidity as a function of moisture generation rate, ventilation, and storage parameters; (b) determine moisture generation rates and storage parameter values; (c) determine the effect of ventilation controls on humidity and ventilation rate.

The author based the research approach on the philosophy that a practical analytical tool should only require a minimum of readily available data. His objective, therefore, was not to produce the most accurate model for indoor humidity, but the most simple model that would satisfy the minimum requirements for accuracy.

## THEORY

The theory tested in these experiments is based on a simple mass balance for water vapor with the addition of a term for moisture adsorption and desorption within the building (moisture storage). Ignoring the effect of surface condensation and reevaporation, we can write the water vapor mass balance for a building as

$$Q_g - Q_a - Q_v = 0 \qquad (1)$$

where $Q_g$ = moisture generation rate (lb/h)
$Q_a$ = moisture adsorption rate (lb/h)
$Q_v$ = moisture loss through ventilation (lb/h)

Equation (1) also ignores any moisture loss by vapor diffusion through the exterior envelopes because it is generally small in comparison to ventilation losses. When $Q_a$ is positive, adsorption occurs; when negative, moisture is released from storage (desorption).

The moisture content of hygroscopic materials which serve as moisture storage media is primarily governed by the RH of the ambient air. These storage media continuously strive to be in moisture equilibrium with the ambient air, but there is always a time delay due to the relative slowness of the adsorption and desorption process. It is, therefore, plausible to assume that storage materials are in equilibrium with a time-averaged RH rather than with the instantaneous RH of the air. If we further assume that the rate of sorption is proportional to the deviation of the instantaneous RH from its time average and proportional with the floor area of the building, we can write the adsorption rate as

$$Q_a = k.A\,(\phi_i - \phi_{i,T}) \qquad (2)$$

where $k$ = sorption parameter (lb/hr.ft$^2$)

$A$ = total floor area of the building (ft$^2$)

$\phi_i$ = indoor RH (%)

$\phi_{i,T}$ = indoor RH, averaged over time period T (%)

The value of the parameters k and T likely depend on the type of construction and furnishings (i.e. plaster or gypsum board walls, exposed solid wood floors or carpeting, amount of wood furniture, number of books, etc.).

Moisture loss from ventilation is the difference between the water vapor in the exhaust air and the water vapor contained in the air entering the building:

$$Q_v = h.A.I.(p_{s,i}\cdot\phi_i - p_{s,o}\cdot\phi_o)/64133 \qquad (3)$$

where $h$ = average room height (ft)

$I$ = air change rate (h$^{-1}$)

$p_{s,i}$ = indoor saturation vapor pressure (in. Hg)

$p_{s,o}$ = outdoor saturation vapor pressure (in. Hg)

$\phi_o$ = outdoor RH (%)

The constant 64133 is needed to approximately convert vapor pressures (in. Hg) to vapor concentrations (lbs per cubic feet) at standard atmospheric pressure and room temperature (68 F).

By combining Equations (1), (2), and (3) we arrive at an expression for the indoor RH:

$$\phi_i = \frac{Q_g/A + k.\phi_{i,T} + h.I.\phi_o.p_{s,o}/64133}{k + h.I.p_{s,i}/64133} \qquad (4)$$

Equation (4) constitutes the mathematical basis for FPLRH1. It requires periodic indoor and outdoor temperature to calculate saturation vapor pressures, outdoor RH, house dimensions, ventilation rate, moisture generation rate, and appropriately chosen values for storage parameters k and T.

## EXPERIMENTAL DESIGN AND PROCEDURES

General Objectives. The main objectives of the measurements were to determine the significance of moisture storage, and to test the feasibility of the simple method of calculating moisture storage and indoor humidity described in the previous section. To this end we measured RH, temperature, and ventilation rate in two test rooms with simulated occupancy and in three single-family homes with actual occupants. The measurements in the test rooms with a known moisture source allowed us to isolate the effect of moisture storage. The measurements in the homes served to further examine the results from the test room measurements and to estimate the amount of moisture generated in these homes. All measurements were made between December 1, 1984, and April 30, 1985.

The underlying philosophy to create a practical method for estimating indoor RH led us to use weather data from the local weather station rather than collecting site data: Any method requiring site weather data is less practical than one which allows the use of local National Weather Service data. All the sites were within 12 miles of the National Weather Service weather station.

Description of Unoccupied Test Building. The test building (Figure 1) was located just west of Madison, Wisconsin. The building measured 48 by 8 feet and consisted of two 20- by 8-foot test rooms and an 8- by 8-foot instrument and control room located between the test rooms. The floors consisted of 3/4-inch plywood, and the walls and ceiling were finished with 1/2-inch gypsum board. Both ceiling and floor were insulated with R-38 fiberglass batt. Because this test building had previously been used for wall moisture studies, the wall construction varied. Most of the wall cavities contained R-11 fiberglass batt with the exception of two cavities with R-13, and two 6-inch cavities with R-19 batt.[9] The framing of four former partition walls was left in both test rooms to provide additional moisture storage capacity.

There were no doors or other openings between the test rooms and the instrument room. An exterior door with storm door was installed in each test room. To provide measurable natural ventilation we cut two 2-inch holes at different heights in the north-facing wall of both rooms. The rooms were heated with thermostat-controlled electric heaters. The heaters maintained a temperature of approximately 68 F.

In both rooms a calibrated humidifier on a timer simulated the moisture release from occupants. The humidifier ran for a full hour in the morning and in the early evening releasing 0.6 lb of moisture each time. The rest of the day it released 0.17 lb per hour. Total moisture generation was 5 lb per day for each room. This moisture generation rate represents the approximate moisture release from a family of four in a 1,200-square-foot home, scaled down proportionally to the size of the test rooms.

The room on the west end (West room) relied entirely on natural ventilation. A dehumidistat-controlled exhaust fan provided additional ventilation in the room on the east end (East room). Whenever the RH exceeded 40%, the dehumidistat turned on the exhaust fan. We found that the dehumidistat had a deadband of approximately 7% RH, which would cause the fan to remain on until the RH had fallen to approximately 33%.

Description of Occupied Homes. The three wood-frame residential homes monitored were part of a low-income energy efficiency improvement program sponsored by a local utility. The improvements were performed by Project Home, Inc., a local nonprofit organization. The homes were approximately 30 years old. Floor areas were as follows: home No. 1, 1,090 square feet; home No. 2, 923 square feet; home No. 3, 700 square feet. One of the homes is shown in Figure 2 after the improvements were completed. The homes were built on a concrete slab foundation with minimal insulation in walls and ceiling. A highly insulated outer shell was added as part of the energy improvements: walls were insulated to R-29 and the roof to R-49. A vapor retarder was installed between the old and the new shell. The windows were triple glazed. All three monitored homes had one occupant each who were home only part of the time. When asked to estimate the percentage of time spent at home, the occupant of house No. 1 answered, 83%; house No. 2, 63%; and house No. 3, 45%. All homes were equipped with an air-to-air heat exchanger. Air ducts delivered fresh air from the exchanger into the cold air return of the forced-air gas furnace. Stale air was taken from the bathroom. A timer turned the exchanger on for one-half hour every 2 hours.

Instrumentation and Measurement Procedures. Indoor temperature and RH were recorded continuously with one conventional hygrothermograph in each test room or home. These were centrally located in the test rooms. In home No. 1 it was located in the living room, and in the other two homes in the kitchen to minimize interference with the occupant's activities. Location in the kitchen did not seem inappropriate because there was no partition wall between the kitchen area and the rest of the living space. The hygrothermographs were calibrated in the laboratory before installation in the homes. Measurement errors result from errors in the reading of temperature and RH as well as errors in the clock settings. Temperature and RH errors were in the order of ± 2 F and ± 3% RH, respectively. We estimate that errors in time readings were in the order of ± 15 minutes to ± one-half hour.

We determined ventilation rate with a sulfurhexafloride tracer decay measurement. The gas was injected at the beginning of the test and the concentration was continuously measured with a specific gas analyzer and recorded with a strip chart recorder. When ventilation equipment was present, measurements were made with and without the equipment running. Several room ventilation fans provided mixing. Errors are associated with both the concentration measurement and the data interpretation. Drift provided a source of error in the measurements, while deviations from log linearity in the data gave rise to additional errors during data analysis. The total error is likely to be in the order of 0.05 air change per hour.

In the East test room, periods during which the fan was switched on were recorded with a strip chart recorder.

Weather data were obtained from the National Weather Service for Madison, Wisconsin. Details of the results of the ventilation measurements can be found in the appendix.

The Model. Equation (4) served as the basis for FPLRH1. We used FORTRAN as progam language and the program runs on a Personal Computer (PC). FPLRH1 calculates indoor RH and was primarily designed to compare calculated results with measured results. It is, therefore, not yet in a suitable format for general use. Inputs include 3-hour outdoor temperatures and relative humidities, indoor temperatures, ventilation rates, and moisture source rates. Floor area, storage parameter, and back-averaging period also need to be specified.

If a fan with dehumidistat control is present, the user is asked to specify the set point. The program will assume that the fan will turn on when RH exceeds the set point, and turn off when the RH falls to a level 7% below this point. We will call this the turnoff level. The calculation is first performed with the fan off. If calculated RH is above the dehumidistat setting, the calculation is repeated with the fan running 10% of the time. If the new calculated RH is above the turnoff level, the calculation is repeated again with the fan on for an additional 10% of the time. This procedure is repeated until the calculated RH falls below the turnoff level or the fan is running fulltime. Thus the program calculates fan ontime and ventilation rate as well as indoor RH.

Data Analysis. The measured ventilation rates served as a basis for equations to predict ventilation for all the homes and test rooms as a function of windspeed and temperature differentials between indoor and outdoor. Although ventilation rate is often represented as a quadratic function of windspeed, we assumed a linear relationship for simplicity. We employed linear regression to obtain these relationships. Data for the test rooms indeed showed a nonlinear increase in ventilation for windspeeds above 10 knots (12 mph). We found that this behavior could be predicted with sufficient accuracy with separate linear equations for low and high wind-speeds. Details of the ventilation analysis and results can be found in the appendix.

Ventilation measurements for the three homes showed no clear relationship with weather data. We found that the average ventilation rate for the entire heating season was as good a predictor as any linear equation. We therefore used one average ventilation rate for periods when the heat exchanger was running, and one average for when it was not. More details may be found in the appendix.

To arrive at values for the restroom storage parameters we essentially used a trial and error method. We compared each calculated indoor RH, using different parameter values, with measured RH and calculated the average and standard deviation of the differences to obtain an initial measure of the model performance. Results from the more promising runs were also visually compared with measured results.

Measured RH in the three homes was compared in a similar manner with results from simulations with varying assumptions for the sorption parameter, averaging period, and moisture source rate. Average and standard deviation of the difference was used to assess model performance, along with visual comparison.

Weather Conditions. Daily average temperatures, as reported by the local weather station for the measurement period, varied between -20 F and 70 F, while RH varied between 50 and 98% (Figure 3). Figure 4 shows that daily average wind speeds ranged from 1 to 21 knots (1 to 24 mph). Three-hour data were used in the analysis, rather than daily averages.

## RESULTS

Unoccupied Test Building. Figure 5 shows a comparison of measured indoor RH in the West test room (no exhaust fan) for the period January 22 to February 1, 1985, with results from FPLRH1. It is clear that calculations without moisture storage can lead to large deviations from the measured RH. The measured RH does not appear to vary much during any particular day despite large variations in moisture release and ventilation rates. This indicates that moisture storage does significantly modify hourly variations in RH. The calculated RH with storage follows the measured RH quite closely, but calculated RH without storage exhibits much wider variations. This is especially clear on January 29 when the humidifier malfunctioned.

The period March 23 to April 2 shows greater discrepancies between measured and calculated RH (Figure 6). Without moisture storage, calculations yielded RH of 100%, suggesting widespread surface condensation. Measured RH actually did not exceed 75% during the same period, and there was no evidence of surface condensation. Moreover, outdoor temperatures during this period were too high to cause any condensation in walls or ceiling. After the humidifier malfunctioned on March 30, calculations without storage significantly underestimated actual RH. Calculated RH with storage is considerably closer to the measured RH, but there still are significant discrepancies, especially on March 26 and 27. These errors most likely stem from errors in the ventilation estimates. However, the results show clearly that accounting for storage significantly improves the prediction of indoor RH, especially when abrupt changes in source rate, ventilation rate, or outdoor vapor pressures occur.

In the East test room with the dehumidistat-controlled exhaust fan, storage did not play as important a role during the coldest winter months (Figure 7). The tight control on humidity greatly reduced the amount of moisture moving in and out of storage materials. Thus, in this case including storage only marginally improves the prediction. However, during early spring storage began to play a more important role, as is illustrated in Figure 8. During this change to warmer and moister outdoor air, adsorption of moisture by the wood in the room kept indoor humidity levels below 70%, while calculations without storage would predict condensation. The humidifier was turned off on April 24, and moisture drawn out of storage clearly moderates the effect on RH.

It was difficult to determine the sorption parameter value and averaging period from the East room results because of the limited influence of storage. We assumed that the East room behaved identically to the West room because of its similar construction, and used the same parameter values for the calculations.

The model without storage underestimated the fan runtime by about 11%, but including storage actually resulted in a larger error in calculated runtime (-17%). It may be that the time step of 3 hours in the calculations is too long for accurate simulation of the dehumidistat response in the test room because the calculations assumed the moisture release to be constant and equal to the time average during those 3 hours. The actual moisture release was controlled by a timer and generally occurred each hour in a "burst" lasting 17 minutes. During the simulation of showers in the morning and cooking in the evening, the humidifier would run for 1 full hour.

Table 1 lists some of the input parameter values and statistical results for the runs shown in Figures 5 through 8. We found that the results were not very sensitive to the choice of values for storage parameters k and T. Accounting for storage always resulted in an improvement.

We did find periods of significant discrepancies between measured and calculated RH, independent of the choice of parameters. For instance, FPLRH1 tended to underestimate RH on foggy days. This suggests that the entering outdoor air contains small droplets of liquid water while FPLRH1 only accounts for the water vapor in the air.

Occupied Homes. Results for the three homes are summarized in Table 2. Results for home No. 2 and No. 3 are quite similar, as were the patterns of occupancy. The occupant of home No. 1 began using a humidifier in mid-February, which created such uncertainty about moisture source rate that the second half of the data was not used in the analysis. Analysis of data from a period of absence of the occupant revealed that the back-averaging period was only in the order of 1 week, and that there was an apparent constant moisture source in the home. This could have been water vapor drawn from the soil under the porch which was included within the house with the energy improvements. The other homes did not have a porch.

Figure 9 shows a comparison of measured RH and calculated RH with and without storage for house No. 2. Storage clearly improves the calculation. However, calculated results did not always correlate as well with the measurement, primarily because the calculations assumed a constant ventilation rate and moisture source rate.

## APPLICATIONS

To demonstrate potential application of FPLRH1 we used the model to analyze the effect of alternative controls for the heat exchanger in home No. 2. We calculated indoor RH with a dehumidistat control set at 35% RH, with a timer set at 25% ontime, with the heat exchanger running full time, and without heat exchanger. Some of the results are shown in Figure 10. Humidity without the heat exchanger would be significantly higher.

We also assessed the effect of moisture storage on the response of the dehumidistat-controlled system. Figure 11 shows that the effect on RH is minor. Figure 12 shows a more significant effect of storage on ventilation rate. Calculations with storage result in fewer but more extended periods with the exchanger on. Without storage, the exchanger turns on and off more frequently and runs for shorter periods. This behavior is easily explained: without storage all the moisture remains in the air. When the humidistat turns on the fan, the ventilation quickly removes the excess moisture, lowering the RH to the humidistat turnoff point. If storage is available, the RH will reach the set point slower because moisture is withdrawn from the air. When the set point is reached, the fan will run longer because stored moisture needs to be removed in addition to the moisture in the air. As in the East test room, the actual behavior of the equipment may be better simulated with hourly time steps instead of 3-hour periods.

Analysis of alternative ventilation systems is but one of the many uses of FPLRH1. The model could also be used to determine the minimum ventilation rate required to prevent significant condensation on windows during fall, winter, and spring. Storage most likely decreases the potential for significant condensation during short extreme cold spells or thermostast setback periods, but increases the potential for condensation in the fall.

## DISCUSSION

The primary objective of this study was to establish the significance of moisture storage on indoor humidity and to explore the prospect of estimating the effect with very simple equations. We therefore used a straight time average of RH in Equation (4). However, it may be more appropriate to use a logarithmically weighed back-average. We do not expect this approach to yield substantially more accurate results for RH, but it would better reflect the likely sorption behavior of materials and would allow use of a more widely accepted definition of time constant. We will try this approach in an updated version FPLRH1.

Both FPLRH1 and the MOBAL3 model[6] require two parameter values for storage: one time variable and one capacity or sorption rate. However, MOBAL3 uses a slightly more complex sequence to calculate sorption flows. MOBAL3 assumes that flows are determined by the moisture content of the storage medium and the current indoor RH. FPLRH1 expresses sorption flows in terms of current and past indoor RH, eliminating the need for calculating moisture contents. It also allows one single expression for indoor RH (Equation (4)).

Our verification has been limited to single rooms and small single-family homes over one winter season in one location. The calculation assumes perfect mixing of the indoor air and may, therefore, not yield accurate results for larger multistory buildings. The applicability of FPLRH1 to a broader range of houses should emerge from further validation.

The selection of the "best" values of the storage parameter and averaging period was somewhat subjective. However, we found that the results were not very sensitive to the parameter values. For instance, for the West test room back-averaging 3 weeks led to quite acceptable results, but results with 6 weeks were marginally better. Assuming more rapid storage often seemed to improve the calculation by reducing the hourly variation in RH, but often worked less well for periods with rapidly changing conditions. One explanation is that short-term moisture sorption is limited to a thin surface layer of hygroscopic materials and, therefore, occurs more rapidly than long-term sorption. Long-term sorption is generally slow because it involves slow moisture diffusion within the material. Possibly using a logarithmically weighed back-averaging technique instead of a simple average may alleviate this apparent discrepancy.

Other discrepancies between measured and calculated RH are most likely the result of errors in the prediction of the ventilation rate, but these errors in individual RH prediction should not greatly affect the time-averaged results.

The calculated average source rates for the three homes were not very sensitive to assumed storage parameters: doubling or halving the parameters usually changed the calculated source rate by less than 10%. This is primarily due to the fact that the average was calculated over almost the entire heating season. The moisture source was assumed to be constant, which could lead to an underestimate of storage parameters. However, data from several days of absence of the occupant of home No. 1 confirmed the choice of the parameter values. Moreover, in practical cases in the field, precise hourly moisture release is not known, and the storage parameter values in Table 2 combined with a constant moisture source did yield realistic results.

Simple mass balance calculations based on weekly averages of ventilation rate, source rate, and outdoor conditions for home No. 2 yielded indoor RH values quite similar to the RH results from FPLRH1. Only during rapidly changing conditions would this simple calculation lead to significant errors. However, if RH-controlled equipment is present, storage needs to be taken into account.

## CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that moisture storage can have a significant effect on indoor RH levels in a home during the winter season, especially during periods of rapidly changing conditions. Failure to consider storage can lead to significant error in RH predictions during such periods.

The effect of moisture storage on indoor RH in small homes can be approximated with a RH back-averaging method as outlined in this paper; further verification for larger homes is needed. Although this method does not offer the most rigorous treatment of moisture storage, we believe that the simplifications are justified in light of the level of uncertainty in the data for moisture generation and ventilation rate.

The author recommends two changes in the current model to improve performance: a logarithmically weighed back-average of RH to better represent the sorption phenomena, and an hourly simulation cycle. These changes should be evaluated.

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TABLE 1
Test rooms: input parameter values and the average and standard deviation of the residuals for simulation runs with and without storage.

| | Storage | Sorption parameter ($lb/h.ft^2$) | Averaging period (weeks) | Residual RH[1] Average (% RH) | Residual RH[1] Standard deviation (% RH) |
|---|---|---|---|---|---|
| West test room | | | | | |
| | Without | 0 | 0 | -10.8 | 20.3 |
| | With | $1.0 \times 10^{-4}$ | 6 | -6.0 | 7.6 |
| East test room[2] | | | | | |
| | Without | 0 | 0 | -4.1 | 22.8 |
| | With | $1.0 \times 10^{-4}$ | 6 | 1.9 | 5.3 |

[1] Residual is defined as measured RH minus calculated RH.

[2] Dehumidistat set at 40% RH.

TABLE 2
Occupied homes: home characteristics, input parameter values, and the average and standard deviation of the residuals for simulation runs with and without storage.

| | Home No. 1 | Home No. 2 | Home No. 3 |
|---|---|---|---|
| Home characteristics: | | | |
| Floor area ($ft^2$) | 1,090 | 923 | 700 |
| Number of occupants | 1 | 1 | 1 |
| Percent of time at home | 83 | 63 | 45 |
| Ventilation rate ($h^{-1}$): | | | |
| Heat exchanger off | .32 | .12 | .14 |
| Heat exchanger on | .51 | .38 | .42 |
| Average | .37 | .19 | .21 |
| Approximate moisture gain (lb/h): | | | |
| Unadjusted | .73[1] | .39 | .30 |
| Adjusted for occupancy | .78 | .62 | .66 |
| Results without storage: | | | |
| Residual RH (%)[2]: | | | |
| Average | .22 | -.36 | -.69 |
| Standard deviation | 3.1 | 4.9 | 5.6 |
| Results with storage: | | | |
| Sorption parameter ($lb/h.ft^2$) | $3.3x10^{-5}$ | $3.3x10^{-5}$ | $3.3x10^{-5}$ |
| Storage parameter T (weeks) | 1 | 1 | 1 |
| Residual RH (%)[2]: | | | |
| Average | 1.0 | -.064 | -.055 |
| Standard deviation | 2.1 | 1.9 | 2.9 |

[1] Home No. 1 had an apparent background moisture source of 0.5 lb/h.

[2] Residual RH is defined as measured RH minus calculated RH.

## APPENDIX

## VENTILATION MEASUREMENTS AND EQUATIONS

Test Rooms. Table A1 shows the results from the measurements of the ventilation rates in both test rooms. The measurements displayed a marked increase in ventilation rate with wind speeds over 10 or 11 knots (11 to 12 mph). Two linear equations sufficiently approximate the data:

West room:

$$W \leq 10 \text{ knots: } I = .0022*W + .0062*(T_i - T_o) + .0105 \quad (R^2 = .30) \qquad \text{(A1)}$$

where:
W = wind speed (knots)
$T_i$ = indoor temperature (F)
$T_o$ = outdoor temperature (F)

$$W > 10 \text{ knots: } I = \text{maximum of Equation (A1) and}$$
$$I = .055*W + .013*(T_i - T_o) - .8262 \quad (R^2 = .94) \qquad \text{(A2)}$$

Although scatter in the data causes a low correlation coefficient for equation (A1), the average difference between measured and predicted ventilation rate over all data is only 0.013 ach, and the standard deviation of the difference is 0.075 ach. Figure A1 illustrates the resulting ventilation rates.

East room, fan off:

$$W \leq 11 \text{ knots: } I = .0197*W + .0082*(T_i - T_o) - .203 \quad (R^2 = .89) \qquad \text{(A3)}$$

$$W > 11 \text{ knots: } I = .114*W + .00571*(T_i - T_o) - 1.06 \quad (R^2 = .41) \qquad \text{(A4)}$$

The average and standard deviation of the difference between measured and predicted ventilation rate with the fan off are 0 and 0.029 ach, respectively.

East room, fan on:

$$W \leq 11 \text{ knots: } I = .0699*W + .0183*(T_i - T_o) - .0947 \quad (R^2 = .79) \qquad \text{(A5)}$$

$$W > 11 \text{ knots: } I = .149*W + .0142*(T_i - T_o) - .52 \quad (R^2 = .91) \qquad \text{(A6)}$$

The average and standard deviation of the difference between measured and predicted ventilation rate with the fan on are 0.018 and 0.12 ach, respectively. Figure A2 illustrates the range of resulting ventilation rates.

Homes. Table A2 lists the ventilation rates in the three homes as measured. The data did not produce a clear relationship between ventilation rate and weather data. The heating season's average measured value was a sufficiently accurate predictor. These averages are listed in the table. Using the average leads to a standard deviation of the difference between measured and predicted ventilation from 0.02 to 0.09 ach with the exchanger off, and from 0.06 to 0.1 ach with the exchanger on.

The heat exchangers added a modest 0.2 to 0.3 ach. Mixing of fresh air into the house was also not optimal because the furnace air distribution fan generally did not run when the heat exchanger was on.

TABLE A1

Results of ventilation rate measurements in test rooms.

| | Date | Temperatures | | Wind speed (knots) | Fan | Ventilation rate ($h^{-1}$) |
|---|---|---|---|---|---|---|
| | | Indoor (F) | Outdoor (F) | | | |
| West room | 11/23/84 | 70 | 39 | 5 | NA | 0.16 |
| | 12/13/84 | 70 | 28 | 8 | NA | .22 |
| | 1/04/85 | 65 | 22 | 10 | NA | .24 |
| | 1/15/85 | 65 | 7 | 4 | NA | .40 |
| | 1/29/85 | 70 | 15 | 11 | NA | .44 |
| | 2/12/85 | 68 | 17 | 19 | NA | .99 |
| | 2/15/85 | 65 | 5 | 9 | NA | .30 |
| | 2/19/85 | 69 | 27 | 10 | NA | .42 |
| | 4/04/85 | 70 | 36 | 12 | NA | .22 |
| | 4/12/85 | 74 | 58 | 12 | NA | .05 |
| East room | 11/23/84 | 70 | 39 | 5 | Off | .13 |
| | | | | | On | .68 |
| | 12/13/84 | 70 | 28 | 11 | Off | NA |
| | | | | | On | 1.58 |
| | 1/04/85 | 70 | 27 | 12 | Off | .55 |
| | | | | | On | 1.81 |
| | 1/15/85 | 66 | 4 | 0 | Off | .34 |
| | | | | | On | 1.04 |
| | 1/29/85 | 68 | 11 | 8 | Off | .38 |
| | | | | | On | 1.48 |
| | 2/12/85 | 68 | 14 | 18 | Off | 1.30 |
| | | | | | On | 2.91 |
| | 2/15/85 | 68 | 10 | 8 | Off | .42 |
| | | | | | On | 1.35 |
| | 2/19/85 | 68 | 18 | 4 | Off | .27 |
| | | | | | On | 1.31 |
| | 4/12/85 | 74 | 12 | 12 | Off | .35 |
| | | | | | On | 1.30 |

TABLE A2

Results of ventilation rate measurements in homes No. 1, 2, and 3.

| | Date | Temperatures | | Wind speed (knots) | Heat exchanger | Ventilation rate ($h^{-1}$) |
|---|---|---|---|---|---|---|
| | | Indoor (F) | Outdoor (F) | | | |
| Home No. 1: | 12/10/84 | 76 | 37 | 6 | Off | .31 |
| | | | | | On | .47 |
| | 12/18/84 | 75 | 19 | 8 | Off | .37 |
| | | | | | On | .51 |
| | 1/08/85 | 80 | 21 | 10 | Off | .30 |
| | | | | | On | .62 |
| | 1/23/85 | 80 | 23 | 12 | Off | .33 |
| | | | | | On | .50 |
| | 2/28/85 | 74 | 46 | 20 | Off | .45 |
| | | | | | On | .57 |
| | 4/01/85 | 74 | 41 | 20 | Off | .18 |
| | | | | | On | .34 |
| | Average: | | | | Off | .32 |
| | | | | | On | .51 |
| Home No. 2: | 12/10/84 | 70 | 43 | 4 | Off | .26 |
| | | | | | On | .41 |
| | 12/18/84 | 70 | 14 | 11 | Off | .14 |
| | | | | | On | .40 |
| | 1/08/85 | 70 | 21 | 6 | Off | .10 |
| | | | | | On | .36 |
| | 1/23/85 | 70 | 20 | 10 | Off | .05 |
| | | | | | On | .44 |
| | 2/28/85 | 70 | 38 | 14 | Off | .05 |
| | | | | | On | .29 |
| | Average: | | | | Off | .12 |
| | | | | | On | .38 |
| Home No. 3 | 12/18/84 | 74 | 23 | 4 | Off | .16 |
| | | | | | On | .42 |
| | 1/08/85 | 70 | 21 | 5 | Off | .13 |
| | | | | | On | .38 |
| | 1/23/85 | 72 | 25 | 15 | Off | .15 |
| | | | | | On | .37 |
| | 4/01/85 | 69 | 32 | 15 | Off | .12 |
| | | | | | On | .50 |
| | Average: | | | | Off | .32 |
| | | | | | On | .51 |

## LIST OF FIGURES

Figure A1. Ventilation rates in the West test room as predicted with Equations (A1) and (A2) in the appendix. (ML87 5469)

Figure A2. Ventilation rates in the East test room with the exhaust fan off and on, as predicted with Equations (A3), (A4), (A5), and (A6) in the appendix. (ML87 5468)

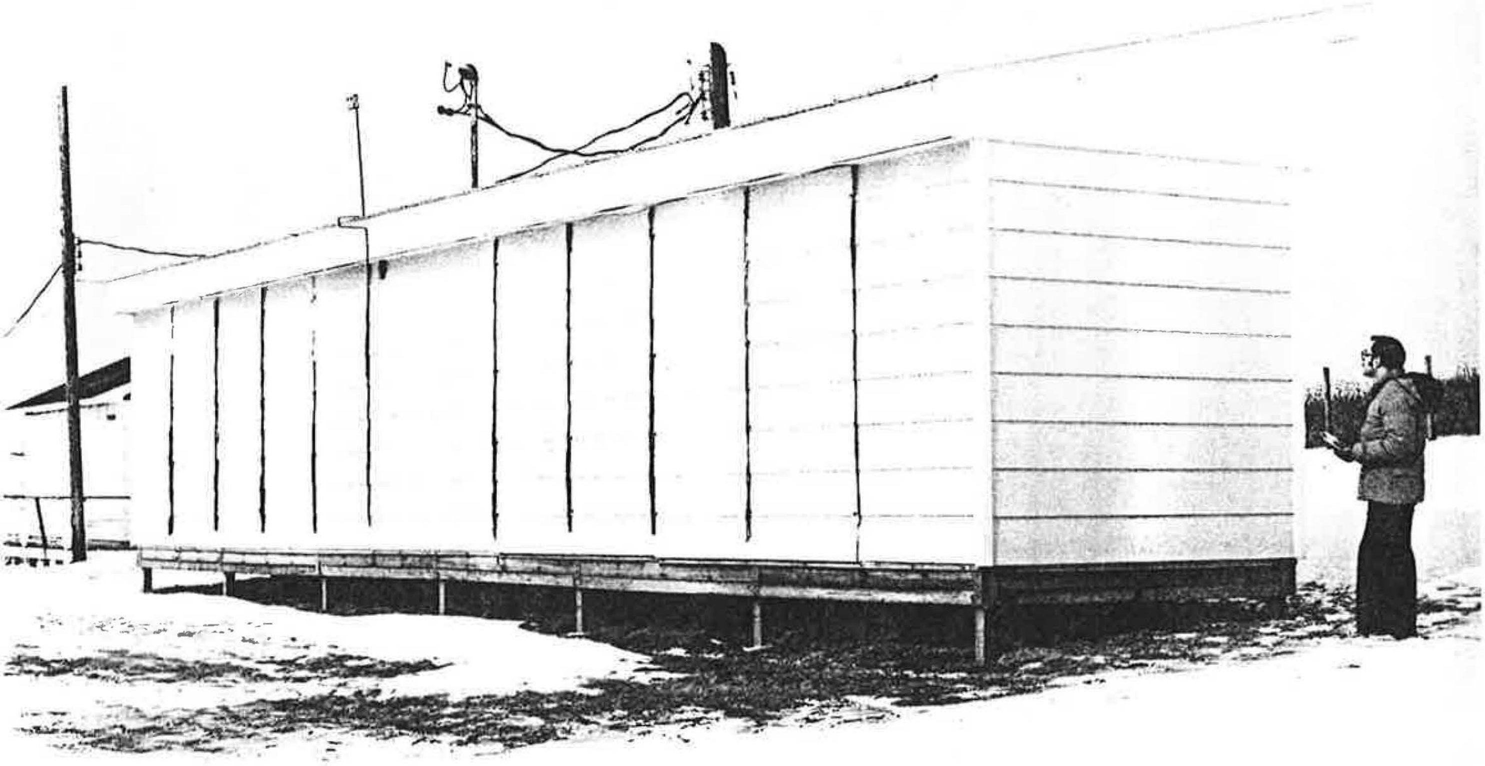

Figure 1. The test building at Valley View near Madison, Wisconsin.

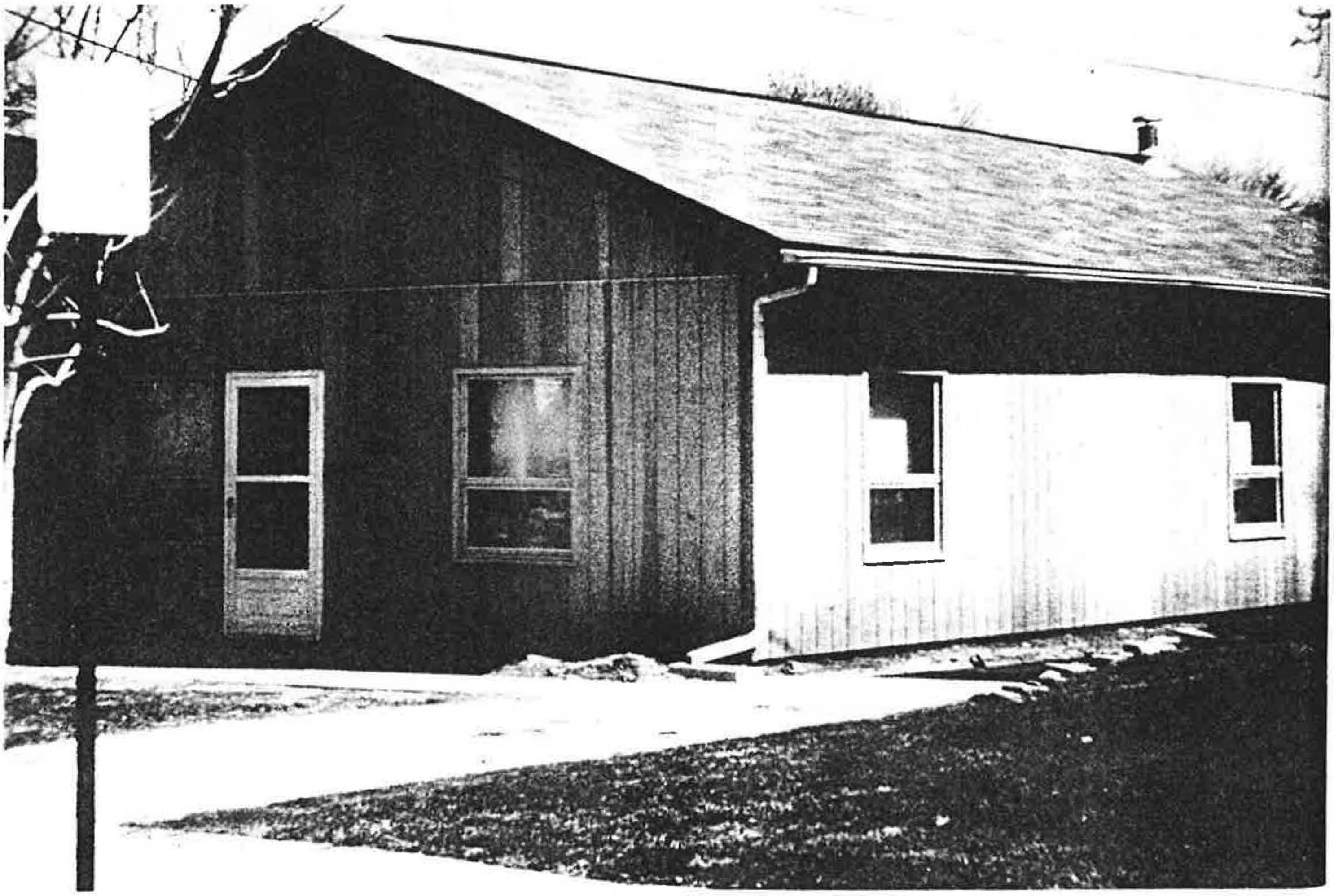

Figure 2. One of the three occupied homes after extensive energy efficiency improvements.

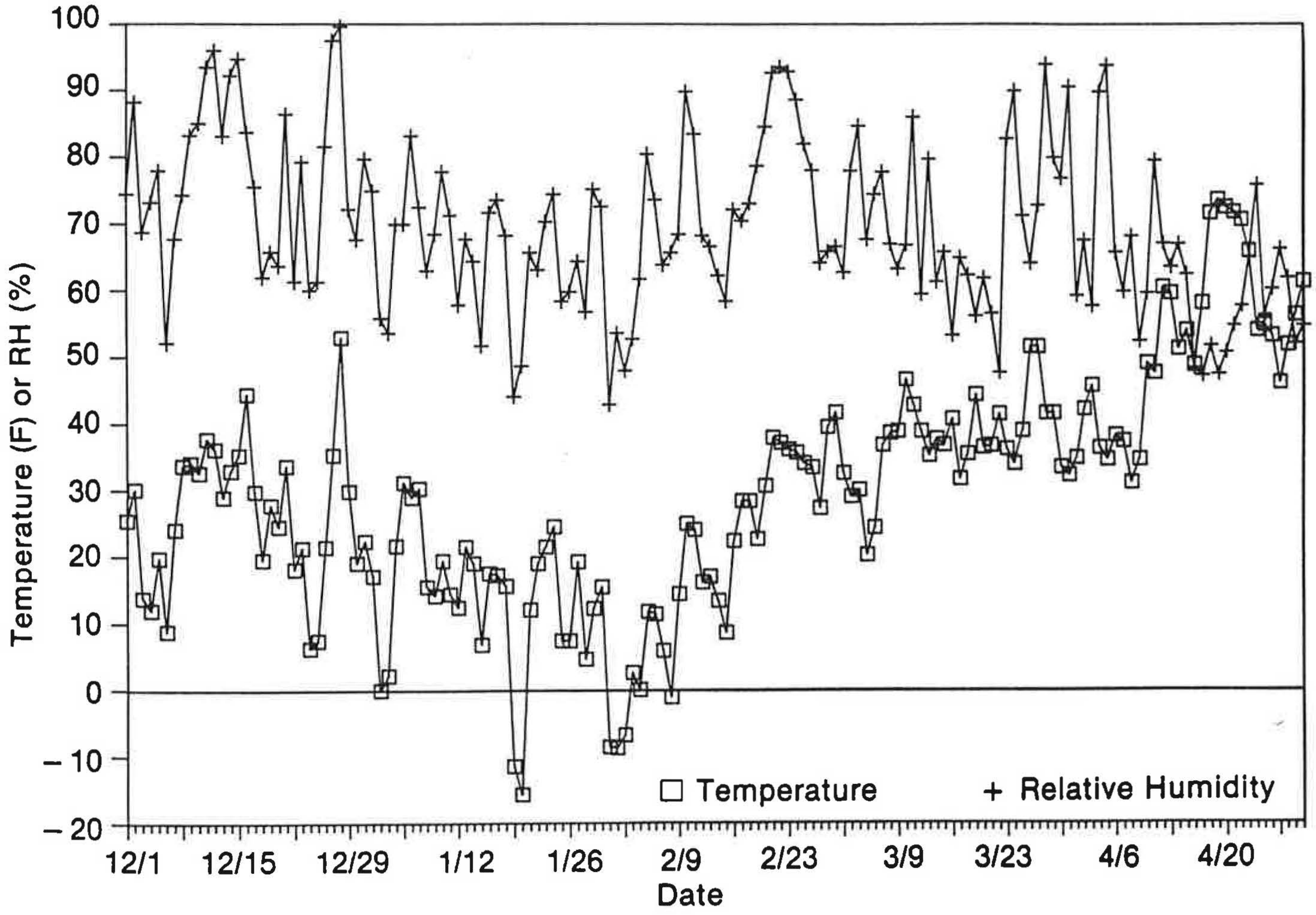

Figure 3. Daily average outdoor temperature and relative humidity for the period 12/1/84-4/30/85 in Madison, Wisconsin.

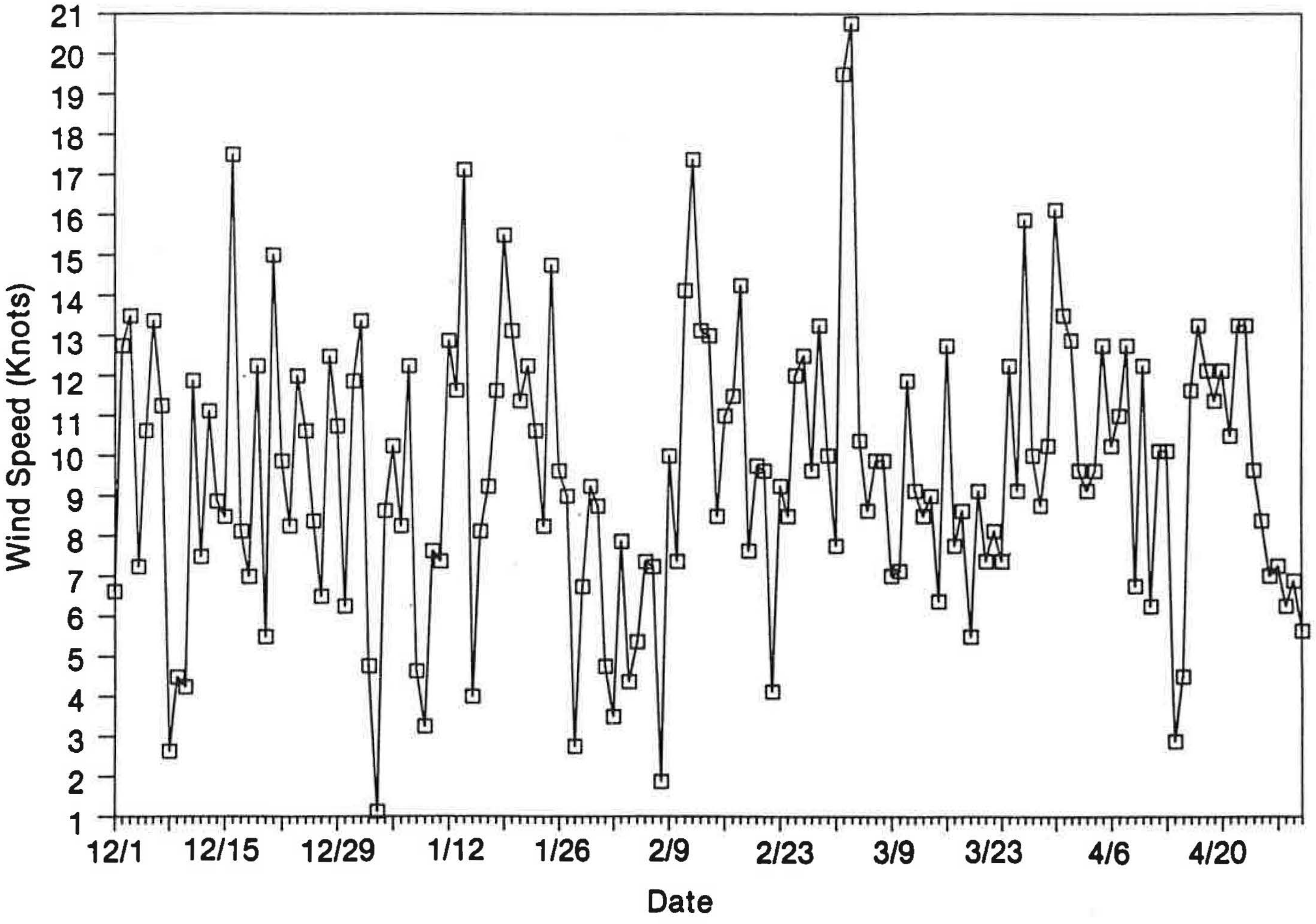

Figure 4. Daily average wind speed for the period 12/1/84-4/30/85 in Madison, Wisconsin.

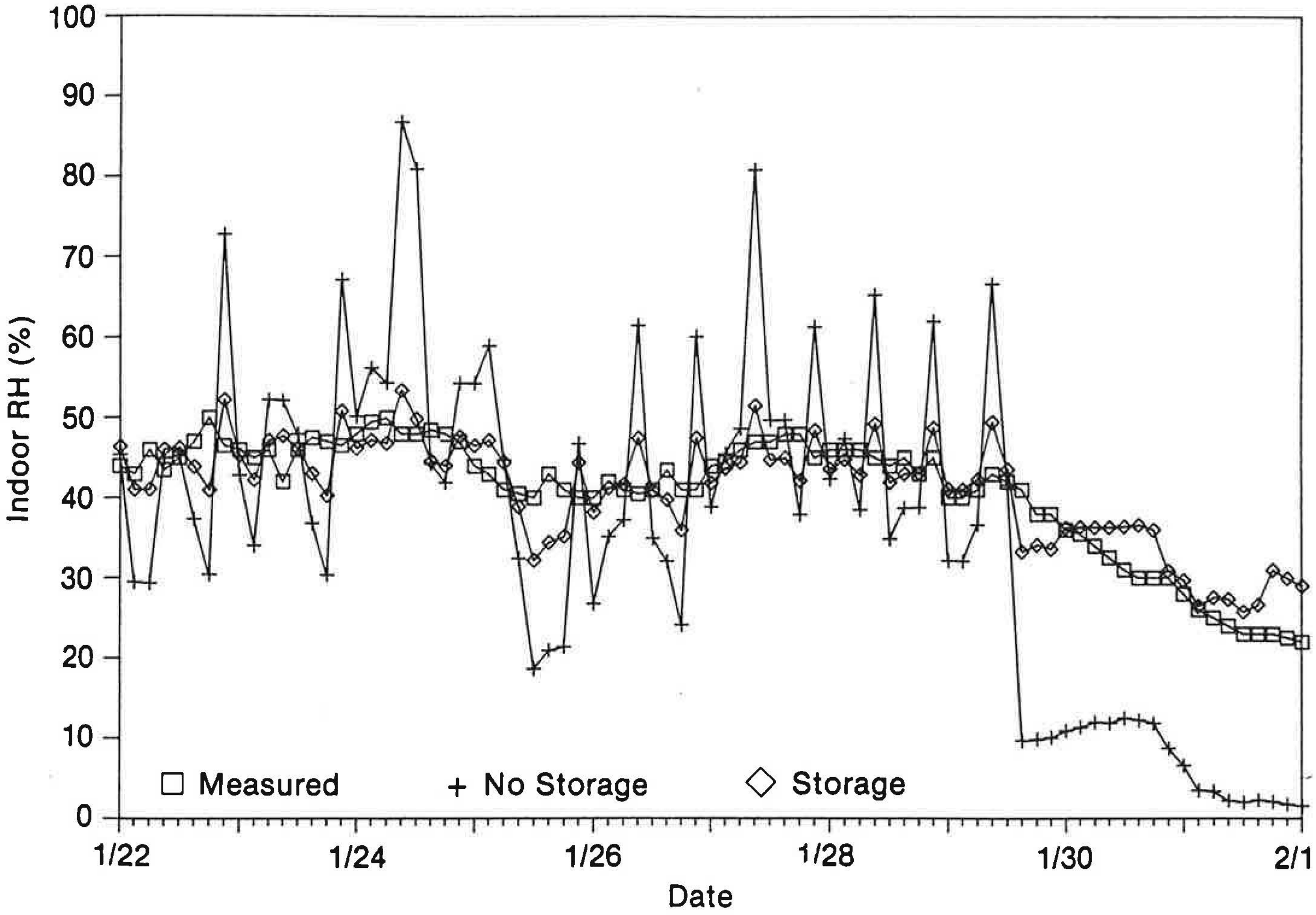

Figure 5. Comparison of measured indoor relative humidity in the West test room with calculated results with and without moisture storage, 1/22/85-2/1/85.

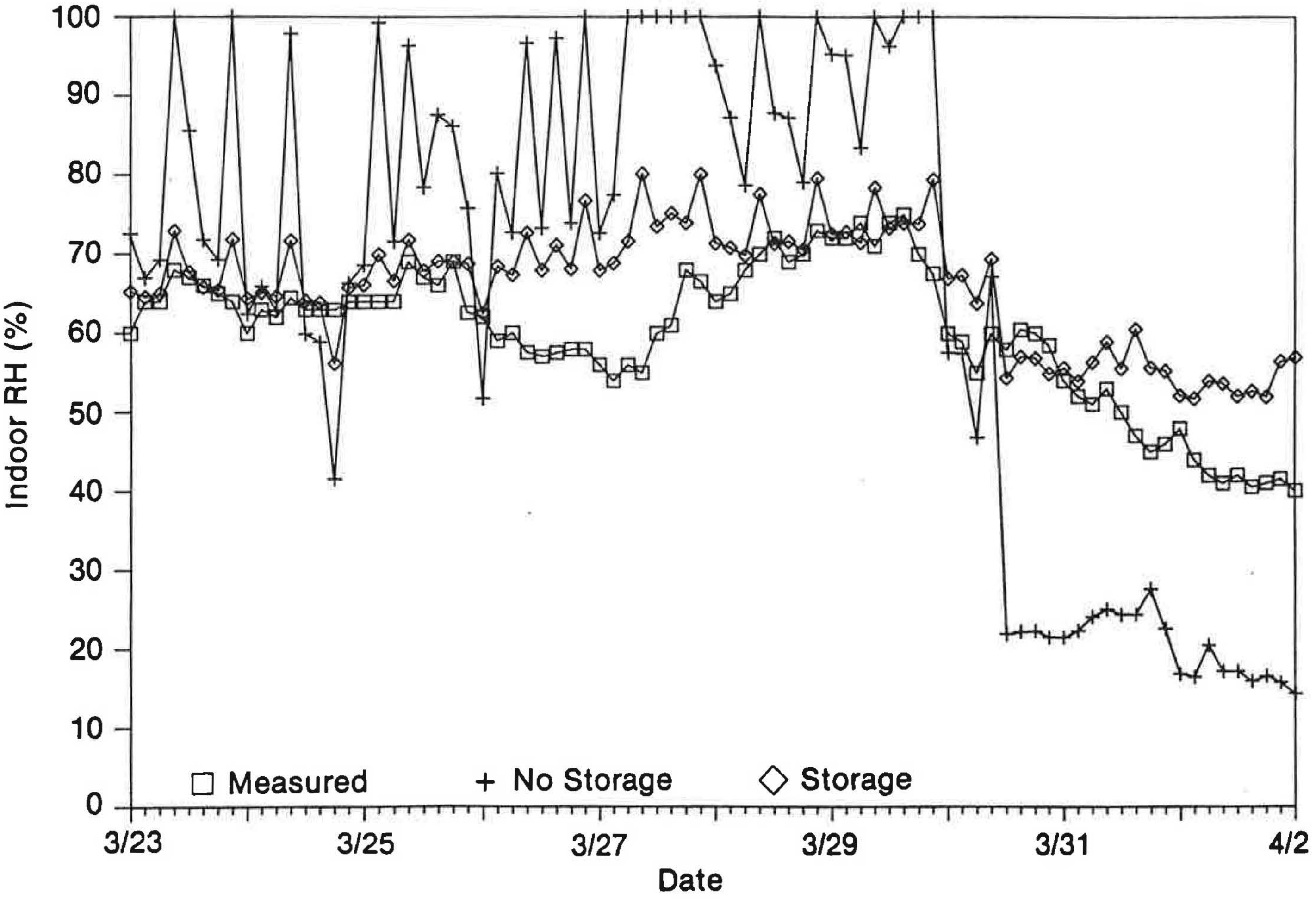

Figure 6. Comparison of measured indoor relative humidity in the West test room with calculated results with and without moisture storage, 3/23/85-4/2/85.

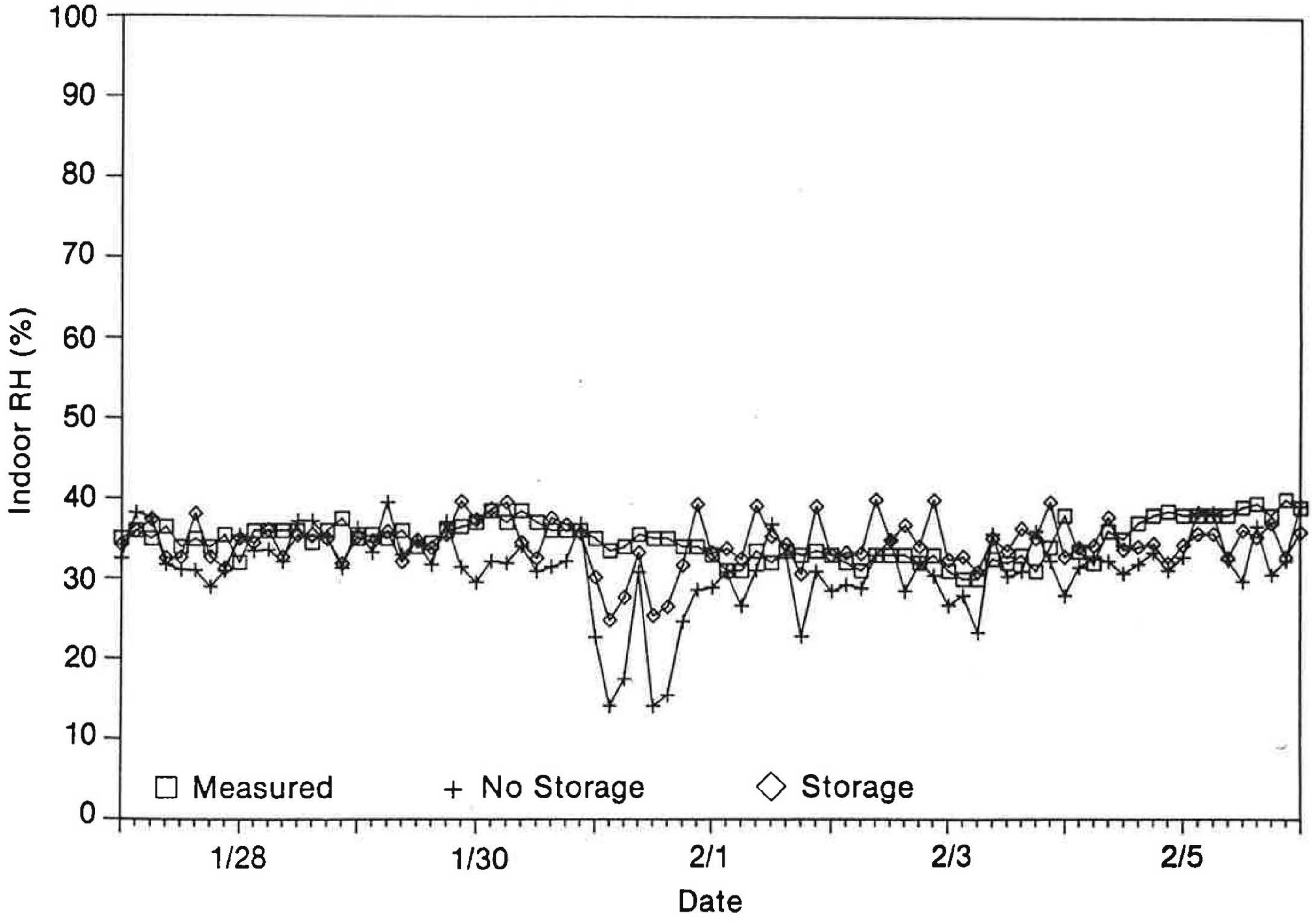

Figure 7. Comparison of measured indoor relative humidity in the East test room with calculated results with and without moisture storage, 1/27/85-2/6/85.

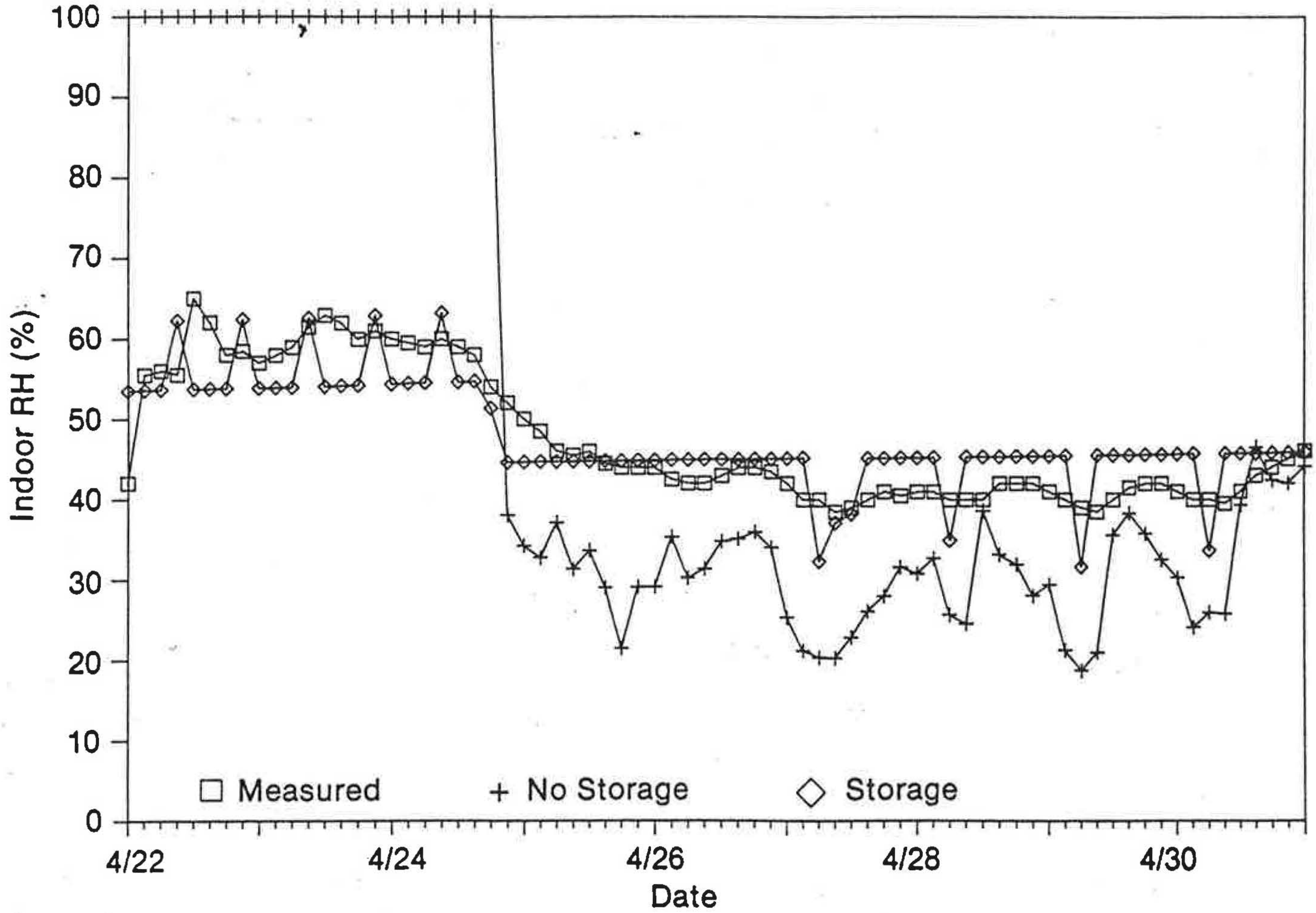

Figure 8. Comparison of measured indoor relative humidity in the East test room with calculated results with and without moisture storage, 4/22/85-5/1/85.

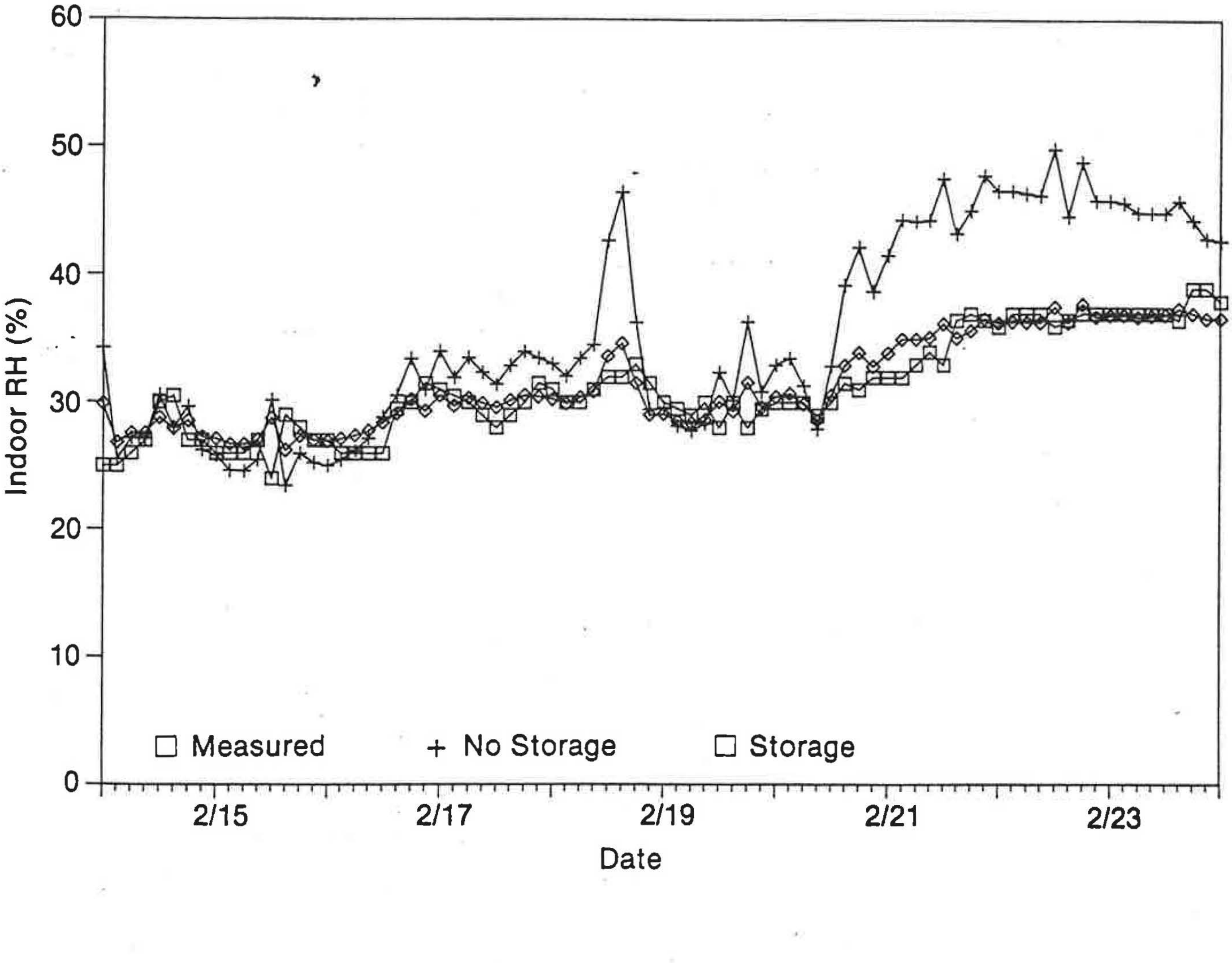

Figure 9. Comparison of measured indoor relative humidity in home No. 2 with calculated results with and without moisture storage, 2/14/85-2/24/85.

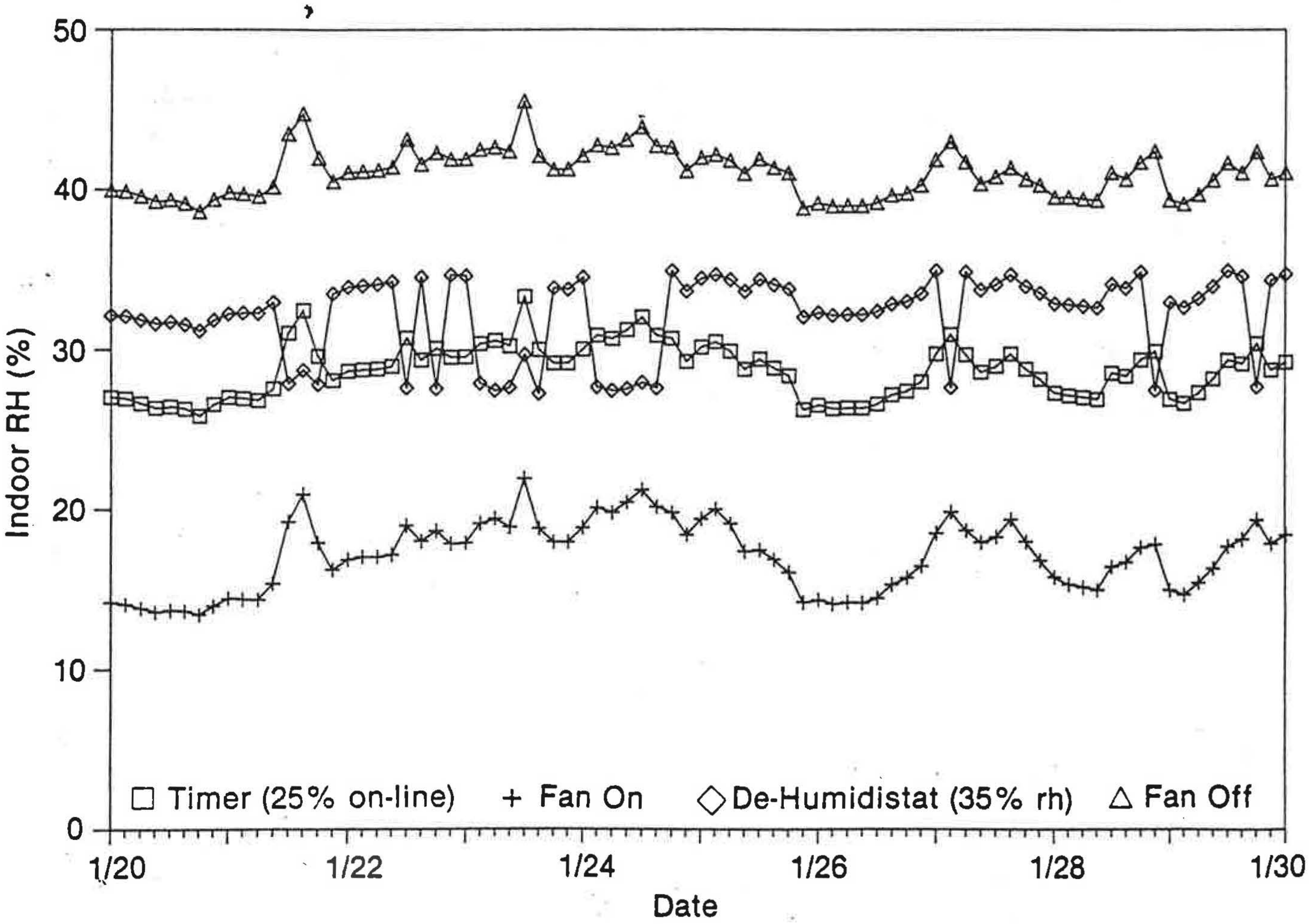

Figure 10. Indoor humidity in home No. 2 as calculated assuming alternative controls on the heat exchanger.

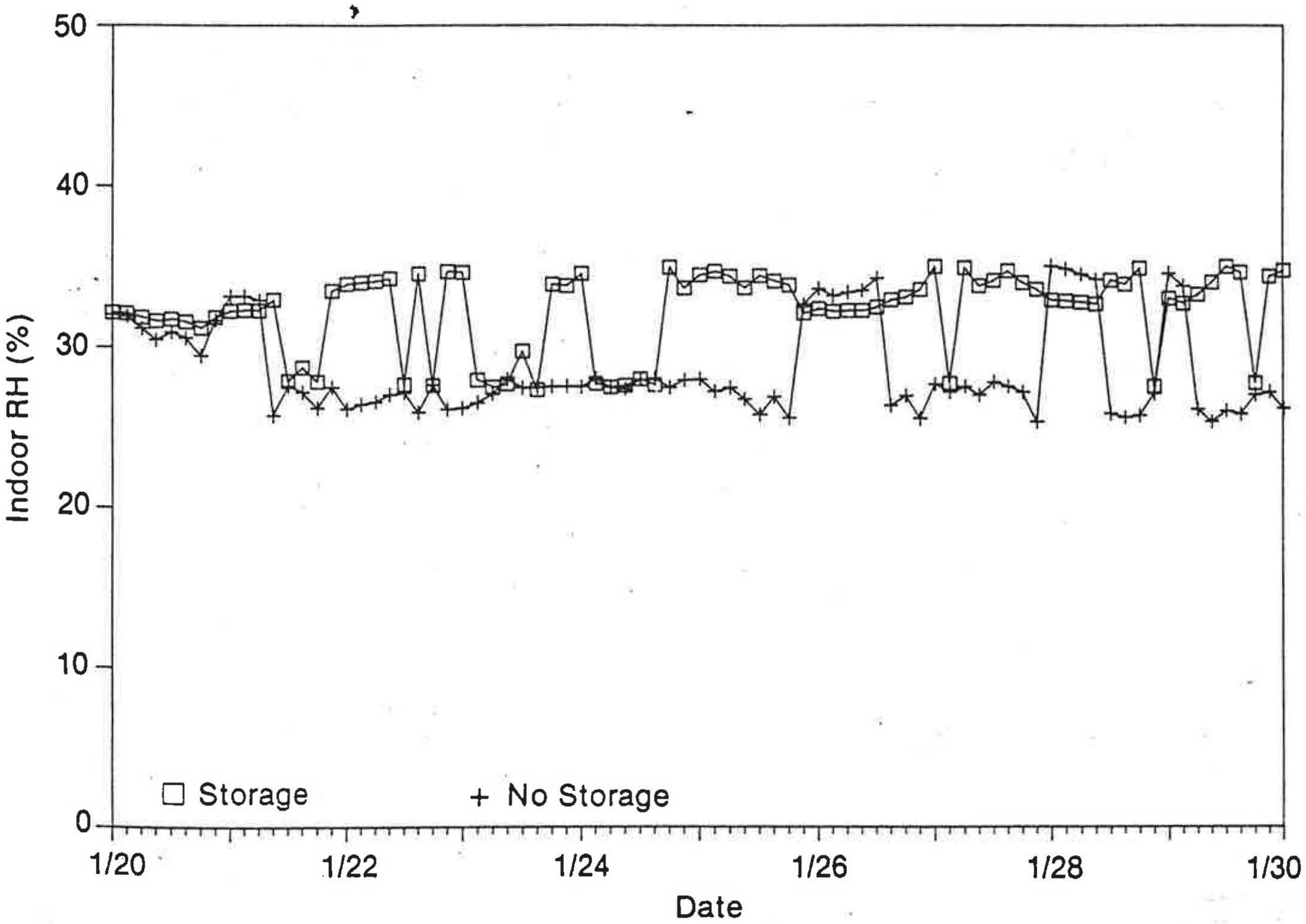

Figure 11. Indoor humidity in home No. 2 as calculated with and without moisture storage and with a dehumidistat control on the heat exchanger.

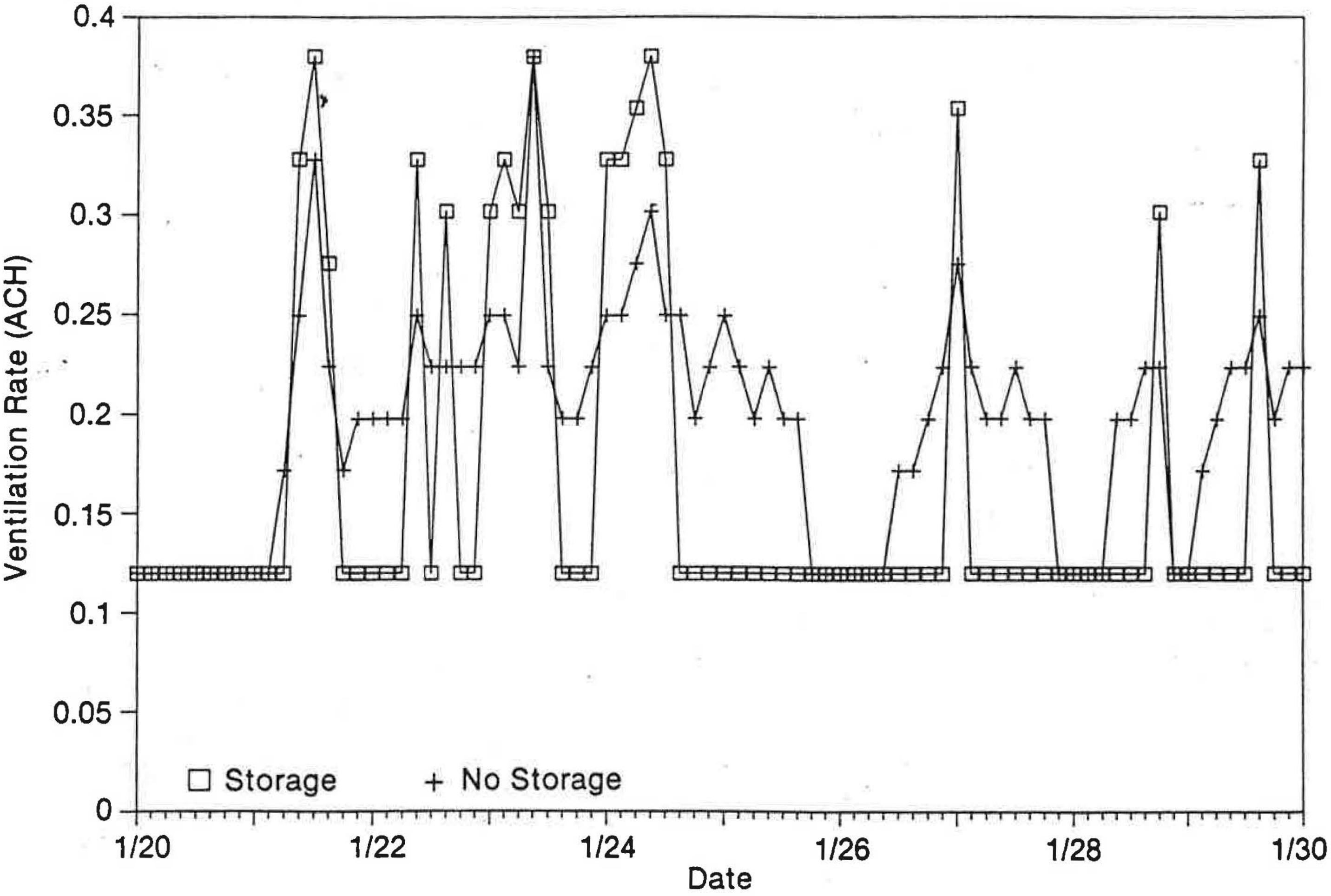

Figure 12. Ventilation rate in home No. 2 as calculated with and without moisture storage and with a dehumidistat control on the heat exchanger.

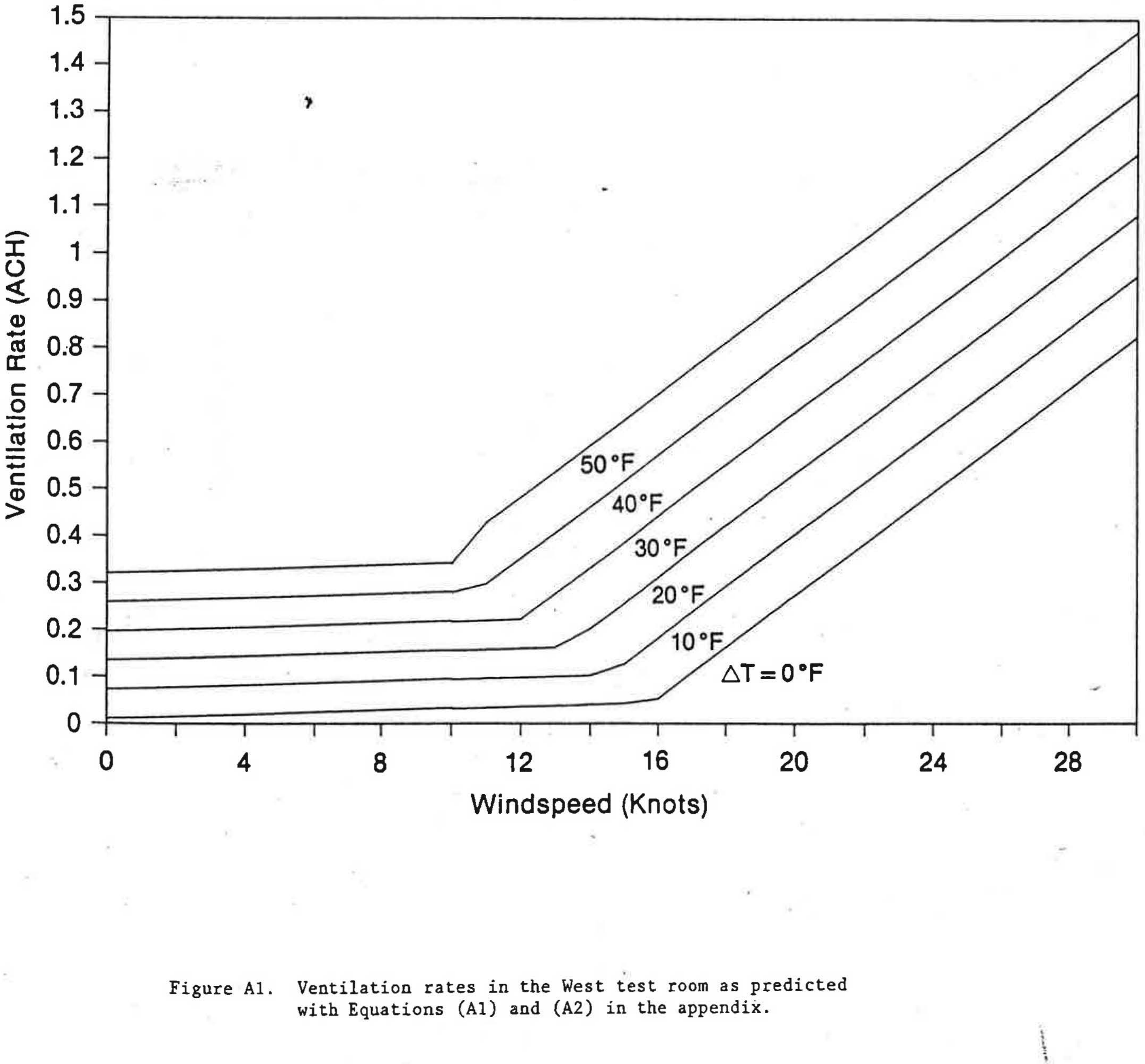

Figure A1. Ventilation rates in the West test room as predicted with Equations (A1) and (A2) in the appendix.