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Whole-building Moisture Experiments and Data Analysis

Task 1 Final Report

Authors

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Original Publication

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NOTICE

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SOLAR BUILDINGS RESEARCH AND DEVELOPMENT PROGRAM
CONTEXT STATEMENT

In keeping with the national energy policy goal of fostering an adequate supply of energy at a reasonable cost, the United States Department of Energy (DOE) supports a variety of programs to promote a balanced and mixed energy resource system. The mission of the DOE Solar Buildings Research and Development Program is to support this goal, by providing for the development of solar technology alternatives for the buildings sector. It is the goal of the Program to establish a proven technology base to allow industry to develop solar products and designs for buildings that are economically competitive and can contribute significantly to building energy supplies nationally. Toward this end, the program sponsors research activities related to increasing the efficiency, reducing the cost, and improving the long term durability of passive and active solar systems for building water and space heating, cooling, and daylighting applications. These activities are conducted in four major areas: Advanced Passive Solar Materials Research, Collector Technology Research, Cooling Systems Research, and Systems Analysis and Applications Research.

Advanced Passive Solar materials Research -- This activity area includes work on new aperture materials for controlling solar heat gains, and for enhancing the use of daylight for building interior lighting purposes. It also encompasses work on low-cost thermal storage materials that have high thermal storage capacity and can be integrated with conventional building elements, and work on materials and methods to transport thermal energy efficiently between any building exterior surface and the building interior by non-mechanical means.

Collector Technology Research -- This activity area encompasses work on advanced low to medium temperature (up to 180°F useful operating temperature) flat plate collectors for water and space heating applications, and medium to high temperature (up to 400°F useful operating temperature) evacuated tube/concentrating collectors for space heating and cooling applications. The focus is on design innovations using new materials and fabrication techniques.

Cooling Systems Research -- This activity area involves research on high performance dehumidifiers and chillers that can operate efficiently with the variable thermal outputs and delivery temperatures associated with solar collectors. It also includes work on advanced passive cooling techniques.

Systems Analysis and Applications Research -- This activity area encompasses experimental testing analysis, and evaluation of solar heating, cooling, and daylighting systems for residential and nonresidential buildings. This involves system integration studies, the development of design and analysis tools, and the establishment of overall cost, performance, and durability targets for various technology or system options.

This report is an account of research conducted in the DOE Solar Cooling Program concerning whole-building moisture capacitance.

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We would also like to express our appreciation to our landlord at Rangewood Villas, James Hunt, for his tolerance of the significant alterations we made on his townhouse, and for his commitment to energy-efficient building design.

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ABSTRACT

For four months (August - November) in 1987 whole-building moisture capacitance experiments were done on a townhouse in Cocoa, Florida. The experiments were designed to:

1. Observe the response of a building to imposed moisture flux

2. Determine the moisture storage capacity of the building and furnishings

3. Evaluate simple models designed to predict the response of room air humidity ratio to pulses of moisture

4. Assess two innovative approaches of cooling (off-peak cooling and DESRAD).

The results of the tests indicate that moisture storage in the furnishings is much greater than moisture storage in the air. The bare building has a total moisture storage capacity (over the range of 50 to 75 percent relative humidity) of eight times as much as could be stored by the air mass alone. When 345 kg of grade 59 silica gel was added to the building, the storage capacity increased to 20 times that of the building air mass.

A simple model predicting room humidity ratio response is proposed. It is called the effective air mass moisture capacity (E_m) model. This model has two forms, the 1-room or 2-room model. Comparisons with measured data show that the 1-room model underestimates the amplitude and phase lag of the room humidity.

The 2-room E_m model provides a much improved match of the amplitude and time lag of the room humidity. For five days of the bare building sinusoidal experiments the average prediction error is 3.5 percent for the 2-room model and 8.0 percent for the 1-room model.

EXECUTIVE SUMMARY

For four months (August - November) in 1987 whole-building moisture capacitance experiments were done on a townhouse in Cocoa, Florida. The experiments were designed to:

1. Observe the response of a building to imposed moisture flux
2. Determine the moisture storage capacity of the building and furnishings
3. Evaluate simple models designed to predict the response of room air humidity ratio to pulses of moisture
4. Assess the ability of two innovative approaches of cooling (off-peak cooling and DESRAD*) to store coolness and dryness in the building during periods when air conditioning (AC) is turned off.

The building was configured in three ways:

1. Low moisture and low thermal capacity
2. Low moisture and high thermal capacity
3. High moisture and high thermal capacity.

Four different types of tests were performed:

1. Sinusoidal pulses of moisture at fixed dry-bulb temperature
2. Step-change of RH between 55 and 70 percent at fixed dry-bulb temperatures
3. Off-peak cooling -- AC is turned off and building "floats" from 2:00 P.M. to 7:00 P.M. AC precools the building from 8:00 A.M. to 2:00 P.M.
4. DESRAD -- AC is turned off and the building "floats" from 8:00 A.M. to 11:00 P.M. AC precools the building from 11:00 P.M to 8:00 A.M.

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* The desiccant enhanced nocturnal radiation concept incorporates desiccant drying and cooling of the space during the night and regeneration of the desiccant using solar radiation during the day.

The results indicate that moisture storage in the furnishings is much greater than moisture storage in the air. It appears that the bare building has a total moisture storage capacity (over the range of 50 to 75 percent relative humidity) of eight times as much as could be stored by the air mass alone. When 345 kg of grade 59 silica gel was added to the building, the apparent storage capacity increased to 20 times that of the building air mass.

A distinction is made between total and effective moisture storage capacity. When the exposure period is 12 hours, the effective storage is only about 50 percent of the total capacity, whereas after three or four days (when the building appears to be approaching equilibrium with the air) the effective capacity approaches the total capacity. The shorter the exposure time, the smaller the effective capacity.

A simple model predicting room humidity ratio response is proposed. It is called the effective air mass moisture capacity (E_m) model. This model has two forms, the 1-room or 2-room model. Both models represent the building/furnishings as an expanded mass of air. E_m is a multiplier by which the actual air volume is expanded to represent the moisture storage potential of the combined air and building/furnishings. In the 1-room model the actual room air and the air representing the building/furnishings are lumped together and are considered completely mixed. Comparisons with measured data show that the 1-room model underestimates the amplitude and phase lag of the humidity ratio response because it assumes that the moisture immediately mixes with the expanded air volume. There is also about a one-hour time lag in predicting the peak humidity ratio for the sinusoidal experiments.

The 2-room E_m model separates the building/furnishings "air" mass and the actual room air mass into two zones. Moisture coupling between the zones is simulated using an airflow rate. All imposed moisture occurs in the small room (the actual room air). This approach provides a much improved match of the amplitude and time lag of the room humidity ratio responses. For five days of the bare building sinusoidal experiments the average prediction error is 3.5 percent for the 2-room model and 8.0 percent for the 1-room model.

The off-peak and DESRAD experiments were conducted in the later part of the season and the amount of data collected were not extensive (14 good days of data for off-peak, six days for DESRAD). As a result the data are not conclusive regarding the usefulness of extra moisture capacitance. It also appeared that the coupling to the air was weak and the temperature excursions larger than that acceptable for complete comfort. Further experiments are planned in the summer of 1988 to obtain further data on these strategies.

I. INTRODUCTION

The behavior of moisture in buildings has not been widely investigated. In almost all building models moisture is treated as if it exists only in the room air. As long as the air conditioner (AC) system is on constantly at a fixed thermostat setpoint, this assumption does not lead to major modeling errors. However, when the AC is off, the windows are open, or when an innovative cooling strategy is being used, errors in the prediction of room humidity, AC moisture removal and AC energy use occur.

The problem of moisture storage in building and furnishing materials is somewhat analogous to heat storage in the building. If room temperatures fluctuate or if there is variation in the heating flux (e.g., passive solar gain), then the building thermal mass is of great importance in predicting room temperatures and energy use. In the case of a passively heated solar home accurate modeling would be impossible without first characterizing the thermal storage effects of the building.

Likewise, innovative approaches to cooling and dehumidification require an understanding of moisture storage capacity. Two innovative approaches are studied in these experiments; off-peak cooling and the desiccant enhanced nocturnal radiation concept (DESRAD)(Ref. 1,2). Off-peak cooling is designed to shed air-conditioning load from the peak demand period of the electric utility, from about 2:00 to 7:00 P.M. For this five hour period the AC is turned off and the temperature and humidity are permitted to float. This approach relies upon the thermal and moisture storage capacity of the building and furnishings to maintain the room temperature and humidity conditions within comfort limits. For this cooling approach it is essential to be able to characterize the moisture storage capacity and moisture adsorption/desorption rates of the building/furnishings. Similar considerations apply to the DESRAD concept.

In order to assess the moisture storage capacity of a whole building a series of experiments were carried out during the period of August through November 1987. A two-story townhouse (Rangewood Villas) in Cocoa, Florida was used for these experiments. The building was tightened from about .35 to .15 air changes per hour, and a computerized control system was installed to allow independent control of indoor moisture generation, indoor moisture removal, indoor dry-bulb temperature, and indoor dewpoint temperature.

The objectives of these experiments were:

1. To observe the behavior of the building air in response to various imposed moisture fluxes,
2. To assess the total moisture capacitance of the building and its furnishings,
3. To assess the ability of simple moisture capacitance models to predict the room humidity ratio, and
4. To evaluate the capability of building thermal and moisture storage to maintain comfort conditions through "floating" periods when the space conditioning equipment is turned off.

To achieve these objectives, four types of moisture pulses were imposed on the building:

1. Sinusoidal (24 hour and 12 hour frequencies)
2. Step-change of RH between 55 and 70 percent (at 25.6°C and 27.2°C)
3. Off-peak cooling
4. DESRAD cooling

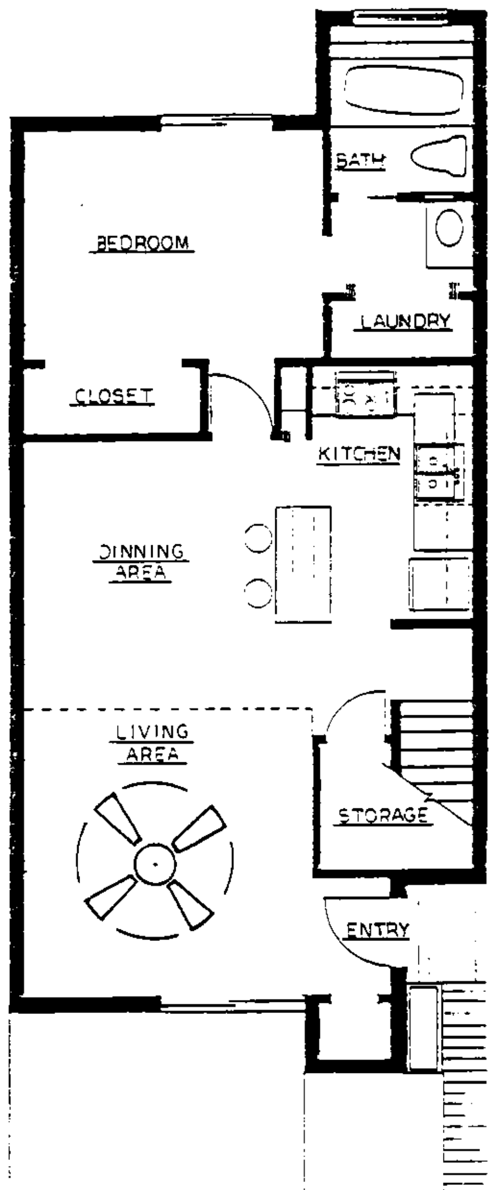
The sinusoidal experiments allowed observation of the amplitude and time lag of room RH with respect to the imposed moisture flux. The step-change experiments were designed to enable evaluation of the moisture capacity of the furnishings. Off-peak and DESRAD experiments were run to evaluate whether the buildings and furnishings can store sufficient dryness and coolness to maintain comfort during extended periods when no space conditioning equipment is used.

II. BUILDING

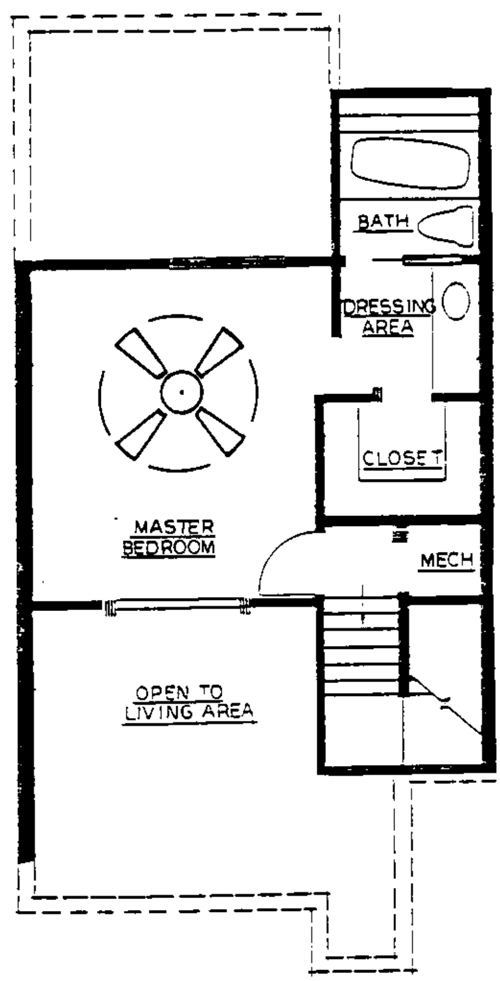
Whole-building moisture capacitance tests were performed in a two-story townhouse, Rangewood Villas, in Cocoa, Florida. The townhouse is located at 28.4 °N latitude and 80.6°W longitude about half way down the Florida peninsula ten miles inland from the Atlantic Ocean. The townhouse is adjacent to undeveloped land covered by tropical vegetation. The buildings were designed to be energy conserving by use of insulation, radiant barriers, double-pane windows, and good shading of windows.

There are four units in each building. Each unit has approximately 1200 ft^2 of conditioned floor area on two stories. The second floor is open to the living room below and has 355 ft^2 in a bedroom, bathroom, vanity room, and two closets (Figure 1). Ceilings are cathedral design in the living room and master bedroom (upstairs). The other rooms have eight foot ceilings. Above the master bedroom dressing area is an attic space where the air-conditioning air handler and second-story duct work are normally located. (For this experiment, however, the air handler and entire duct work have been relocated within the conditioned space.)

The first floor has 820 ft^2 in a bathroom, vanity room, washer/dryer closet, bedroom, kitchen, and large combined living room/dining room area (Figure 1). The cathedral ceiling in the living room rises upward directly to the open air space of the upstairs bedroom. Because of the open air design there is considerable potential for thermal stratification of air. This does not often occur because the air conditioner keeps the air well mixed. During this experiment the living room and upstairs ceiling fans were kept on continuously to maintain good mixing.



First floor



Second floor

Figure 1. Floor plan for Rangewood Villas townhouse.

Since this building was used to evaluate moisture storage capacity of a whole building, it will be useful to describe the interior surface materials of the building. Table 1 gives the surface areas of various materials in the buildings.

Material Description	Finish	Total Area (m^2)
Gypsum	flat latex paint	366
Nylon carpet	sculptured	86
Linoleum		22
Doors (hollow-core)	semi-gloss paint	15
Closet doors (louvered)	semi-gloss paint	16
Closet doors (hollow-core)	semi-gloss paint	6.5
Closet shelves (particle board)	semi-gloss paint	13
Cedar window sills	stained	1.4
Kitchen cabinets/counter (particle board)	vinyl clad	11
Stair bannister and railing	varnished pine	7.4

Table 1. Exposed surface area of major materials inside Rangewood Villas townhouse.

The space conditioning system is a York Model E2CP018A018 heat pump which has an 18,000 Btu/hr rating (cooling). It is coupled with a N2AHD10A06A air handler unit (AHU) which has a 1000 CFM rated blower (0.4 IWG) and an oversized 24,000 Btu/hr coil (G1HC024). Several changes were made to the space conditioning system to prepare for these experiments. The AHU was placed in the upstairs bedroom and a new duct system was located completely within the conditioned spaces. This was done to minimize air handler induced infiltration, which had been observed in the past [3]. The air-conditioning system was disconnected from the thermostat and an IBM PC portable computer performed the task of controlling the air-conditioner compressor, the blower, and the electric terminal strip resistance heater as needed. The IBM also controls the humidifier. The heat pump heating mode was disconnected because the air conditioner, which acts as both a cooler and a dehumidifier, had to sometimes run simultaneously with heating (reheat dehumidification).

The building was tightened to reduce infiltration of outside air. Previously the building had an average infiltration rate of about .35 air changes per hour (ACH) as measured by SF_6 tracer gas tests [3]. Tightening was performed by caulking attic and wall penetrations, taping plastic sheets over all windows, and sealing the dryer and kitchen vent stacks. These measures lowered infiltration to an average of about .15 ACH under typical summer conditions. By minimizing the flow of outdoor air into the building, indoor conditions were easier to control and potential errors in measuring the influx of ambient moisture were reduced. The building infiltration rate was continuously monitored using a Miran 101 SF_6 infrared monitor.

III. EXPERIMENTAL MEASUREMENT EQUIPMENT

Ambient Conditions

An outdoor weather station was installed to monitor ambient conditions at the site. The barometric pressure transducer failed so this parameter was obtained from Florida Solar Energy Center measurements taken 10 miles away. The recorded parameters are listed in Table 2.

Number of Measurements	Parameter	Instrument Type
2	dry-bulb temperature	thermocouples
2	dewpoint temperature	General Eastern Dew-10
2	solar radiation (horiz)	Eppley PSP
1	wind speed	cup anemometer
1	wind direction	vane
1	sky radiation	Eppley PIR
1	rain	tipping bucket
1	roof surface temperature	thermocouple
3	ground temperatures	thermocouple

Table 2. Ambient conditions monitored at Rangewood Villas.

The air dry-bulb and dewpoint temperatures were shielded and aspirated (north thermocouple was naturally aspirated). These were recorded both in the front yard (south) and the back yard (north).

Indoor Space Conditions

Room air dry-bulb temperature was recorded by radiation-shielded, aspirated T-type thermocouples in the living room, downstairs bedroom, upstairs bedroom, and the attic. Thermocouples were also placed in three one-gallon plastic jugs of water located in the living room, downstairs bedroom, and upstairs bedroom, by which we were able to assess the thermal storage capacity of the 1000 gallon jugs of water. The air dewpoint was monitored in the living room and upstairs bedroom, by modified General Eastern DEW-10 and Hygro-M1 chilled mirror hygrometers, respectively. Small capacity air pumps and sample cells were used to move ~.4 cubic feet per hour of air past both types of chilled mirror hygrometers. A discussion of calibration of the dry-bulb and dewpoint temperature probes is given later in this section.

In order to properly control space conditions and to be able to monitor the moisture removal rate of the air conditioner (AC), a number of temperature measurements are made on the air-handler unit (Figure 2). Dry-bulb temperatures before the coil, after the coil, and after the terminal reheat strip are recorded. The dewpoint temperature of the air stream before the coil and after the coil are also recorded. The dry-bulb and dewpoint temperatures before the coil and after the coil are recorded in two separate ways; 1) when the AC compressor and blower are both on, and 2) when the blower is on and the AC compressor is off. If both the compressor and blower are off, the temperatures are not recorded. The run-time for the compressor and blower together and the blower only are also recorded. In addition, the condensate from the coil is measured by both a positive displacement pump and a tipping bucket. The positive displacement pump is a Fluid Metering, Inc. lab pump, model QV1CKC with a built-in Hall Effect switch. By means of the Hall Effect switch the Campbell Scientific CR7 datalogger can record the number of pump strokes, and thus the volume of condensate flow. The pump is turned on by a water sensor switch located in a small reservoir in which the condensate collects. As a double check of the pump, the water is pumped into a Texas Electronics Model 525 tipping bucket. The tipping action of the bucket causes a closure of a reed switch which the datalogger counts. There were intermittent problems with the water level switch which caused the pump to stay on (pumping air) and consequently indicating too much condensate.

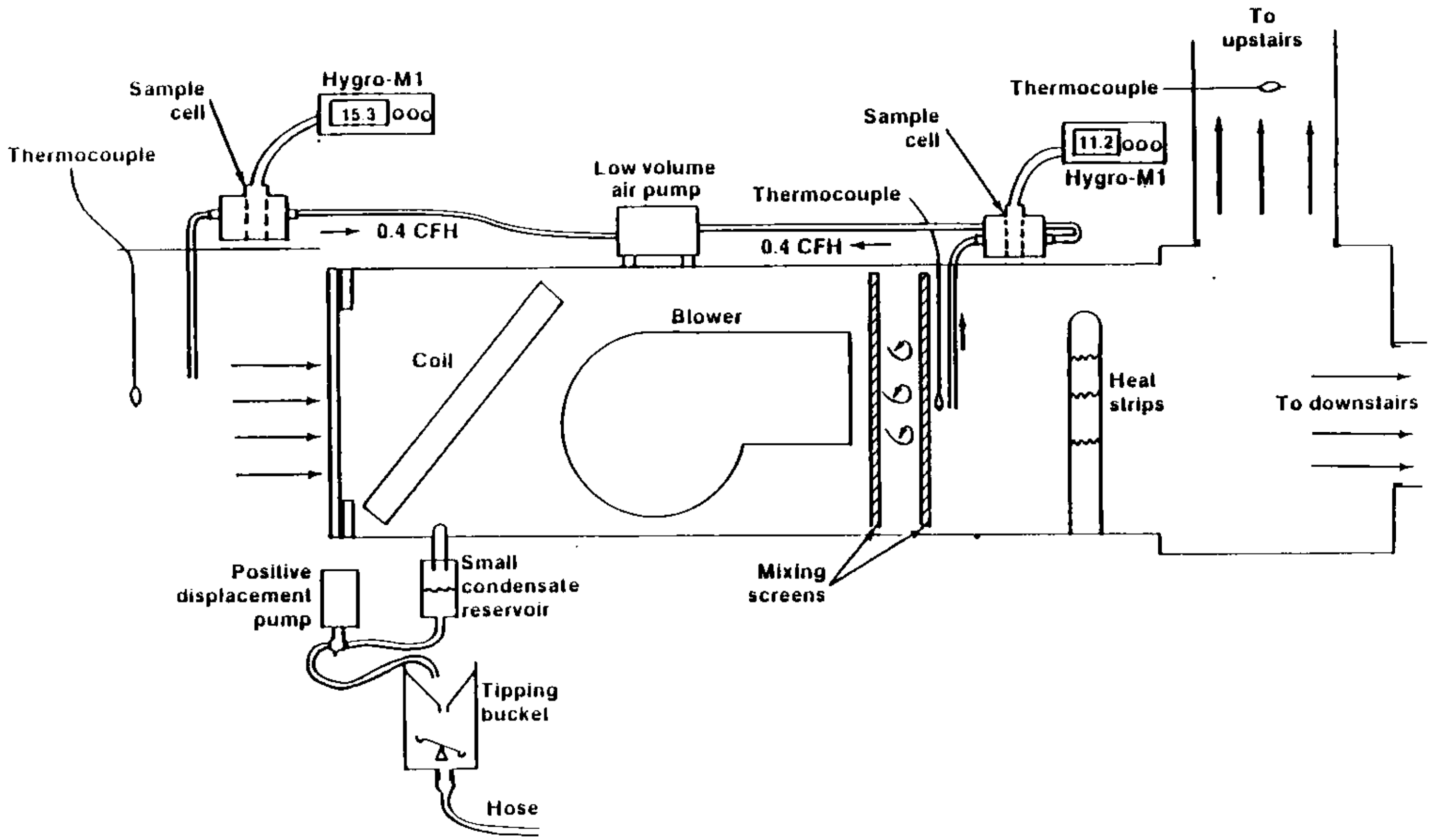


Figure 2. Dry-bulb temperature, dewpoint temperature, and condensate measurement equipment on the air-conditioner air handler.

The tipping bucket performed correctly throughout the tests, and no condensate data were lost.

Electricity use was metered for the whole building and submetered for the AC compressor, blower and heater element combined, and for the internal load. The electrical energy use of the humidifier was also separately monitored.

A humidifier was designed and built to inject moisture into the building. Its design is illustrated in Figure 3. An air compressor provides high pressure air to a manually controllable Binks atomizer spray nozzle which then draws distilled water from a small reservoir. The reservoir is kept full by a positive displacement pump, similar to that used for condensate measurement, and the number of pump strokes is recorded by the Campbell datalogger. The fine mist from the nozzle is blown up into the cathedral ceiling area by approximately 200 CFM stream of air produced by a blower. Heat generated by the compressor, pump, blower, and three wire-wound 100 Ω resistors (installed specifically to provide extra heat) assists in the evaporation of the mist. The humidifier is turned on and off by the IBM control program.

Some portion of the mist particles did not fully evaporate in the air and was observed settling on surfaces. However, even at highest moisture injection rates and at highest relative humidities we did not observe any accumulation of moisture. Any water particles which did settle on surfaces had sufficient time to evaporate prior to the next time period. Throughout the experiments the humidifier performed well to produce the desired dewpoints and sine pulses of humidification.

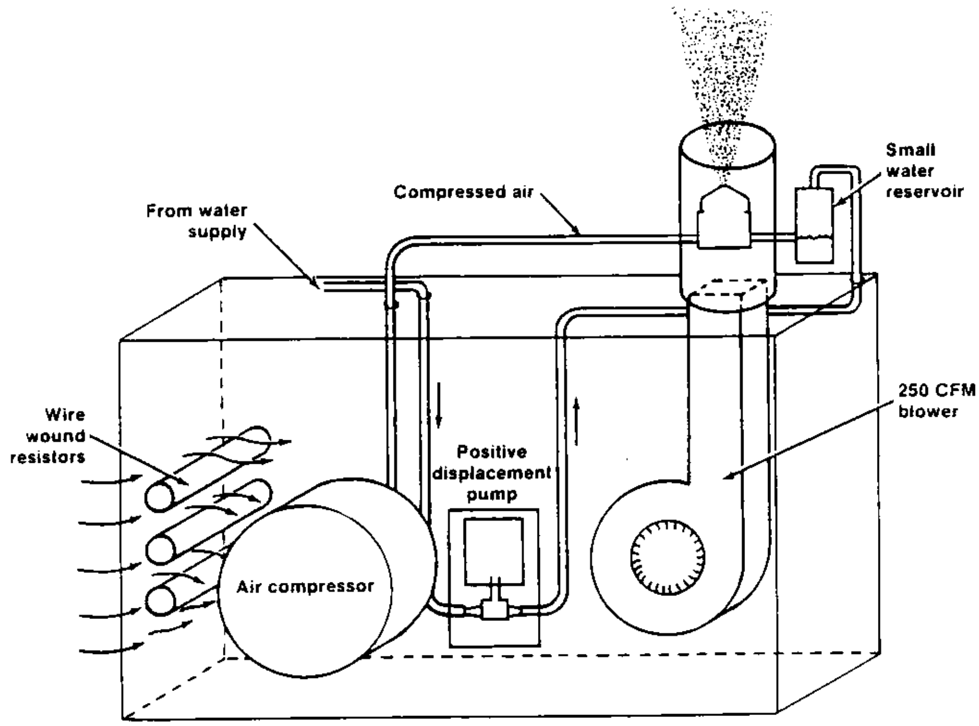


Figure 3. Humidifier design uses air compressor, Binks atomizer spray nozzle, positive displacement pump, 200 CFM blower, and resistance heater (600W)

Monitoring of the building infiltration rate is performed by a Miran 101 specific vapor analyzer made by Foxboro Company. It measures sulfur hexaflouride (SF_6) concentration in the range of 0-5 PPM and delivers a continuous analog signal from 0 to 1.0 volts in proportion to the concentration. An internal air pump draws a continuous stream of room air through a filter at a rate of 30 l/min into the detection chamber. It operates on the principle of infrared absorption in the specific wavelength of

10.7 microns. From the decay rate in the concentration of SF_6 in the room the infiltration rate of the room air is calculated by

$$ACH = \frac{60}{\#\ min} * \ln \left[\frac{C_{start}}{C_{final}}\right]$$

where

ACH is air changes per hour

min is the time interval in minutes

C_{start} is the SF_6 concentration at the start of the time interval

C_{final} is the SF_6 concentration at the end of the time interval.

When the datalogger senses that the concentration drops to 1.0 PPM it sends a 5V signal to a relay that opens a 120V solenoid valve on the SF_6 bottle for five seconds to bring the SF_6 concentration back to about five PPM. This operation has worked very smoothly throughout the tests with the exception of experiments with changing room dry-bulb temperatures — the off-peak and DESRAD tests. It was found that the Miran 101 is quite sensitive to changes in room temperature and therefore, during the "floating" periods (when dry-bulb room temperature was allowed to float upward) the infiltration rate is underestimated. During off-peak and DESRAD experiments the infiltration rate can be approximated by a wind speed correlation, but the degree of accuracy is reduced. The fit between wind speed and the infiltration rate is shown in Figure 4.

Calibration of Instrumentation

All of the instrumentation was calibrated or checked prior to the initiation of the experiments. The positive displacement pumps for the condensate and the humidifier were calibrated by pumping into a graduated cylinder. The tests were repeated several times and the pump stroke count accumulated by the

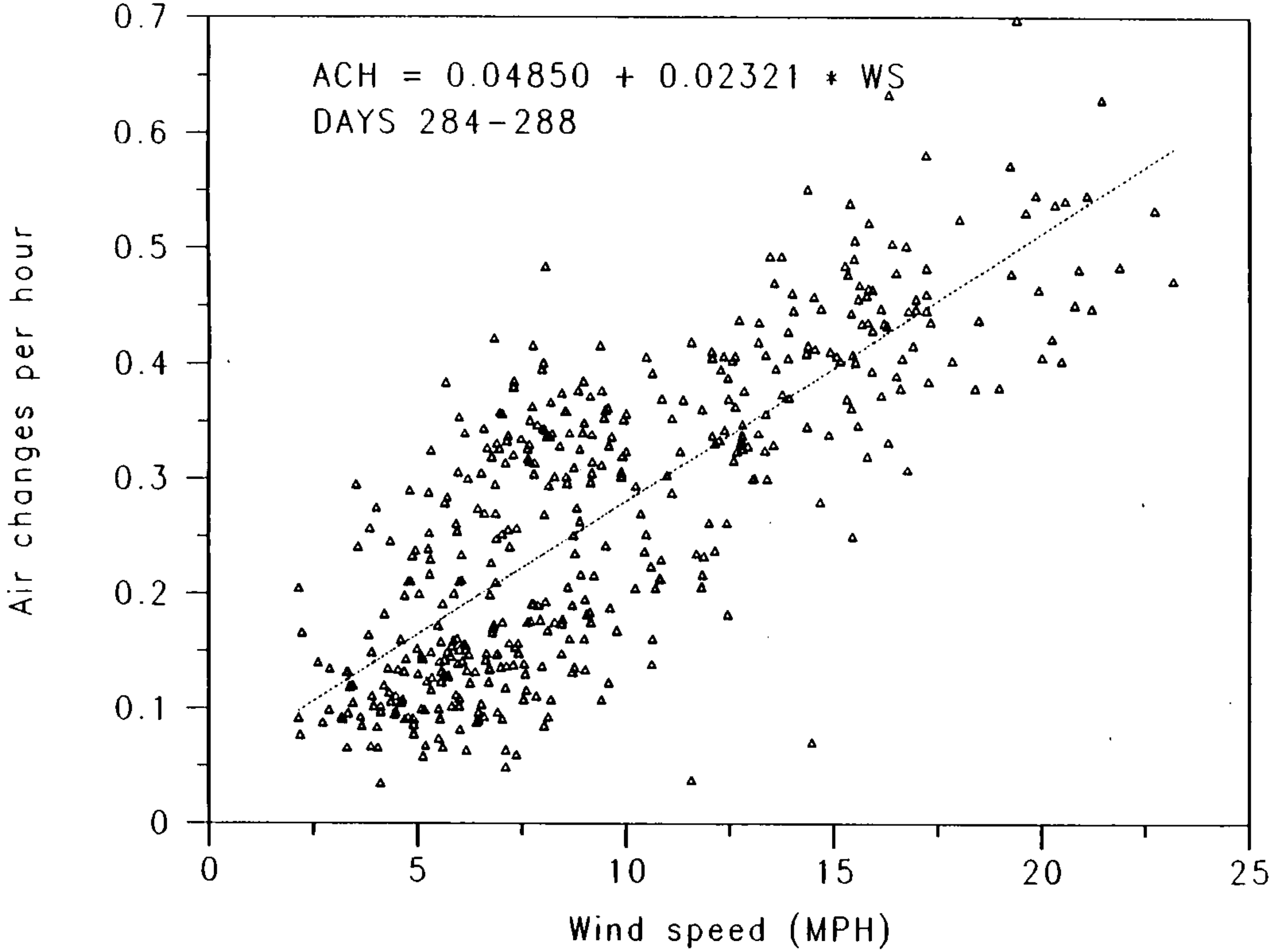


Figure 4. Correlation of infiltration rate (from SF_6) and wind speed at Rangewood Villas.

datalogger was compared to measured volume. It was found that the stroke volume varied with different pump stroke rates, so that each pump had to be calibrated at the specific rate at which it would operate (the pumps are variable speed). The tipping bucket measuring the condensate was then calibrated against the condensate pump. The rain gauge tipping bucket was calibrated by repeatedly pouring known quantities of water at a slow rate into the unit. The humidifier pump, condensate pump, and condensate tipping bucket were rechecked one month into the experiments (8/31/87) and were found to be 0.9 percent too low, 2.0 percent too low, and 0.5 percent too low, respectively. This indicates that their accuracy remained quite stable over time.

The hygrometers were cross calibrated. The two General Eastern Hygro-M1 chilled mirror hygrometers were used for the standard. They have a rated accuracy of $\pm 0.2^{o}C$. In side-by-side comparison while drawing the same stream of air through them, the Hygro-M1s agreed to within $0.009^{o}C$ on average with an average residual standard duration of $0.015^{o}C$ (see Figure 5). The three DEW-10s used in the experiments were calibrated side-by-side against the Hygro-M1s.

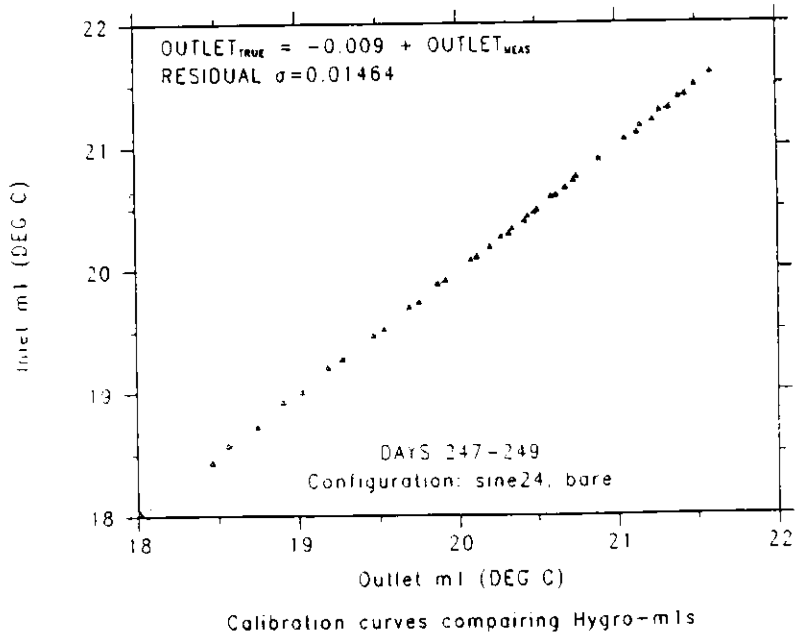


Figure 5. Calibration fit for two HYGRO-M1 chilled mirror hygrometers.

The Miran 101 specific vapor analyzer (SF_6 detector) was checked against two calibration gases, 3.1 and 10.7 PPM, and were calibrated to this standard. (It was found to be quite accurate before calibration.) The Miran 101 has a significant zero drift and it was found that zeroing was required once a week. Toward the end of the experiments it was discovered that the Miran is quite sensitive to temperature. A rise in temperature causes a rise in the SF_6 concentration readings, and vice versa. Since most of the experiments maintained a constant room dry-bulb temperature, most of the infiltration data is good. However, during the off-peak and DESRAD experiments in which the room dry-bulb temperature is allowed to float for 5 hours and 15 hours, respectively, the infiltration rate has to be approximated from wind speed correlations.

The electric meters were calibrated against a Magtrol, Model 4612 power analyzer which has a rated accuracy of $\pm$.35% +.2% of full scale. First one of the building electric meters was calibrated with the Magtrol, and then one-by-one the other meters were calibrated against this one. Toward the end of the experiments, the blower/heater and compressor meters failed intermittently. Where needed, the AC compressor energy use data can be obtained quite accurately by correlation with compressor run time (see Figure 6). Blower/heater energy use cannot be as readily obtained because we have no record of how much time the heater came on. This data was not required for the experiments.

The Eppley Precision Spectral Pyronometers were calibrated in April 1987 at FSEC in accordance with ASTM E941 procedures and referenced to FSECs absolute cavity radiometer.

The cup anemometer was calibrated by comparison to a Solomat hot wire probe which has averaging capabilities.

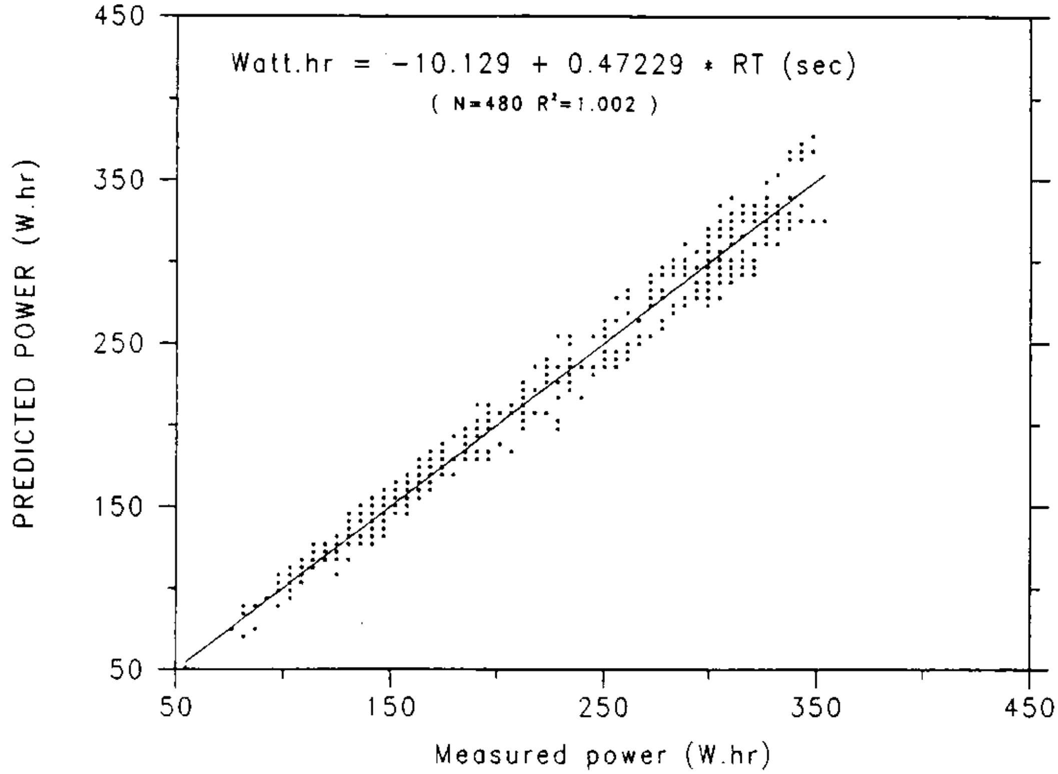


Figure 6. Prediction of compressor energy use from compressor on-time.

Temperature probe accuracies were checked in water baths. The RTD which provides dry-bulb temperature into the AC coil for the IBM control was calibrated in an ice bath and a 20.1°C water bath. Nine thermocouples were checked in an ice bath and a 19.2°C water bath against a precision thermometer. They were found to have a maximum error of .03°C and required no calibration.

Weekly Maintenance

A number of instruments required regular maintenance. Once a week the mirrors on the five hygrometers were cleaned and the optical feedback loops on the three DEW-10 hygrometers were zeroed. The Miran 101 was zeroed once a week using outdoor air brought in through a tube. The contacts on the water switches which controlled the condensate and humidifiers positive displacement pumps were cleaned with a wire brush once a week. The air filter on the air handler was changed weekly.

Air Handler Air Flow Rate

A number of different approaches were taken to determine the air flow rate of the AC air handler unit (listed at 1000 CFM). A Solomat hot wire anemometer was used to measure the area-weighted average velocity of the supply outlets. The sum of the supply outlets was 980 CFM. At the return, the Solomat measured 868 CFM. Using a Balometer, a flow rate of 795 CFM was obtained. By comparing the measured condensate removed by the AC with the change in dewpoint across the coil, and correcting for the .009°C difference in the two Hygro M1s, velocities which varied from 830 to 910 CFM during various experiments were obtained. A correlation of measured versus calculated moisture removal is shown in Figure 7. The accuracy of the condensate measurements was checked at various stages of the experiments so there is good reason to believe the air-handler flow rate derived from the condensate. We have used these flow rates for the analysis.

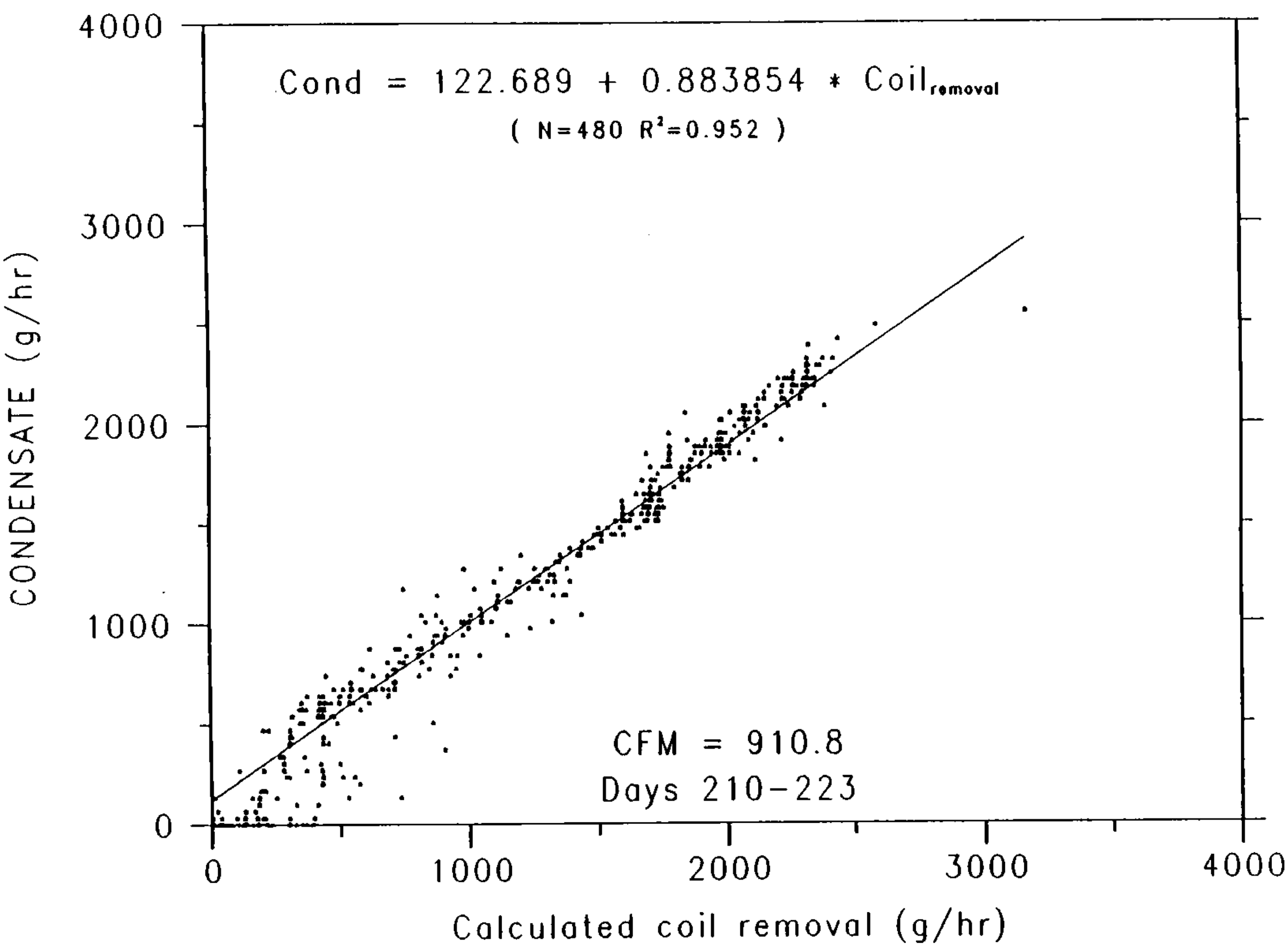


Figure 7. Fit of measured condensate to calculated moisture based on measured humidity ratios into and out of coil.

IV. EXPERIMENT DESIGN AND CONTROL

The objective of these whole-building moisture capacity experiments is to understand the moisture sorption characteristics of buildings and building furnishings in order to be able to:

1. Obtain data for development of moisture models that can account for the moisture capacity of buildings and that can be used in available building simulation models.

2. Assess the impact of various innovative approaches to cooling:

   - Off-peak cooling
   - DESRAD
   - Night ventilation. (No night ventilation tests were done this year.)

Experiment Design

To observe moisture storage capacity the air moisture content was cycled while holding the dry-bulb temperature constant. Several types of cycles were used:

- sinusoidal (24 hour period)
- sinusoidal (12 hour period)
- step change (24 hour period)

The pulses of moisture into the air cause moisture to be driven into and out of the building materials and furnishings. When pulses of moisture are introduced into the building there is a time lag from the time of maximum moisture influx to the time of highest air humidity. This time lag is expected. As we shall observe, higher moisture capacity reduces the time lag.

To generate the sinusoidal pulses we first envisioned pulses of moisture varying in a sine wave fashion from zero to maximum humidification (Figure 8).

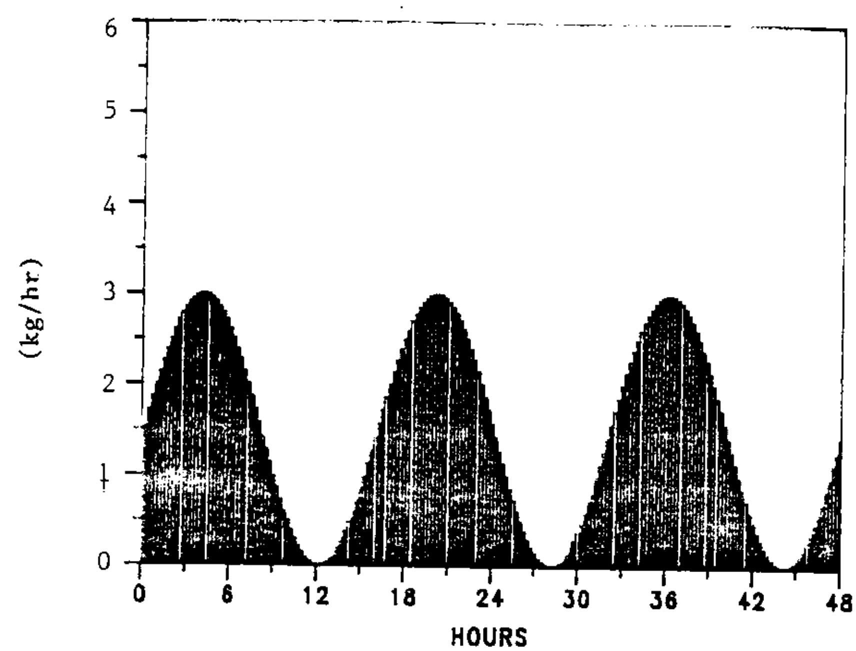


Figure 8. Sinusoidal pulses of moisture generation with the conditioned space

It was realized that this would quickly produce saturation conditions in the space, especially since the ambient dewpoint is so high. It was then considered that pulses of moisture removal could be provided. The building air response would be sinusoidal cycles of dehumidification. The dehumidification would vary from zero to the maximum moisture removal rate. This would have the major advantage that ambient humidity (by infiltration) would be replenishing the moisture removed so that a stable operating range could be established. However, since the building had been tightened to around .15 ACH, it was observed that the influx of ambient moisture would not be nearly as great as our anticipated average dehumidification rate. Consequently the room humidity ratio would rapidly drop to low levels at which the AC (which is our dehumidifier) would no longer have the required moisture removal capacity. The sensible heat ratio of the Rangewood Villas air conditioner is shown in Figure 9. At 13°C dewpoint the AC has one-third the moisture removal capacity as at 21°C dewpoint, and by extrapolation, it does no dehumidification below 10°C dewpoint (this is for hot summer conditions).

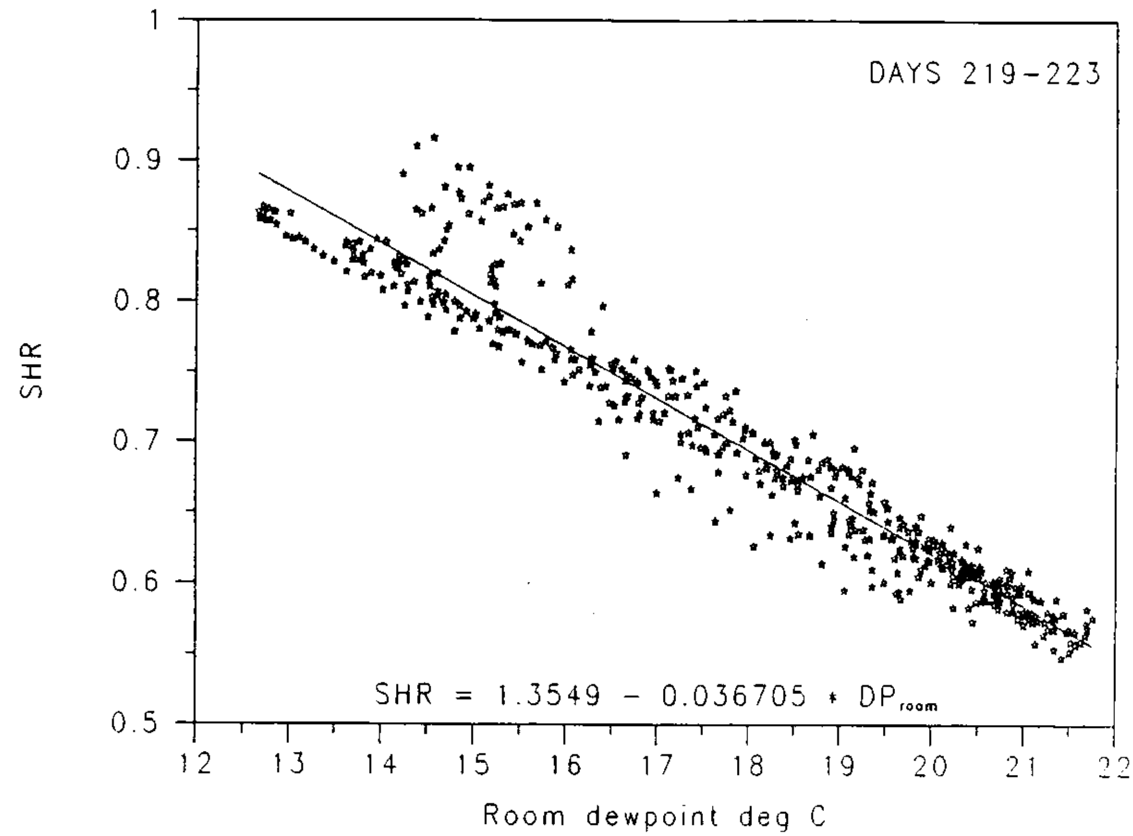


Figure 9. Air-condenser sensible heat ratio versus room DP at Rangewood Villas.

Therefore, an approach which combines humidification and dehumidification was selected (Figure 10). This permitted fine-tuning the net moisture removal/addition rate to match the moisture infiltration from the ambient. Part of the sine wave is moisture input (the peaks) and part is dehumidification (the valleys). This approach has worked well.

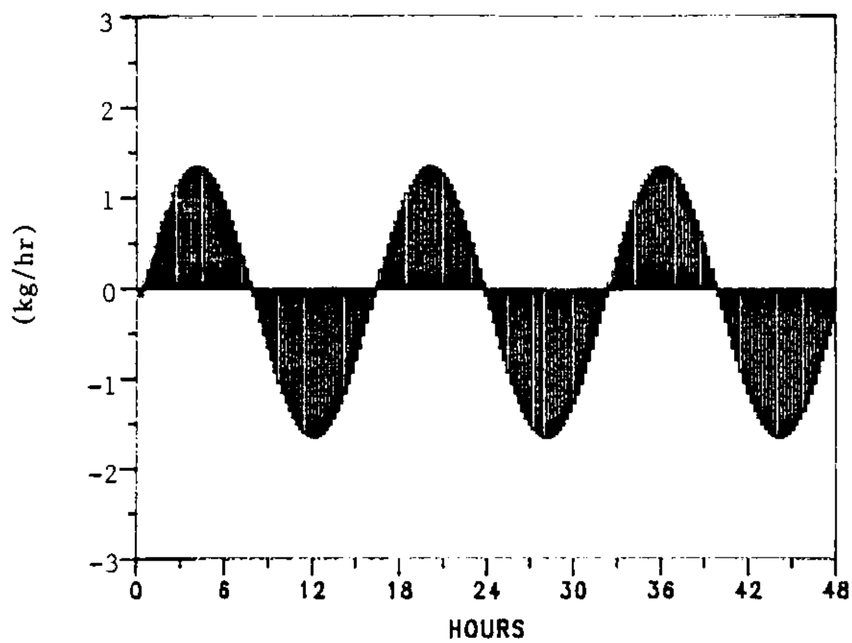


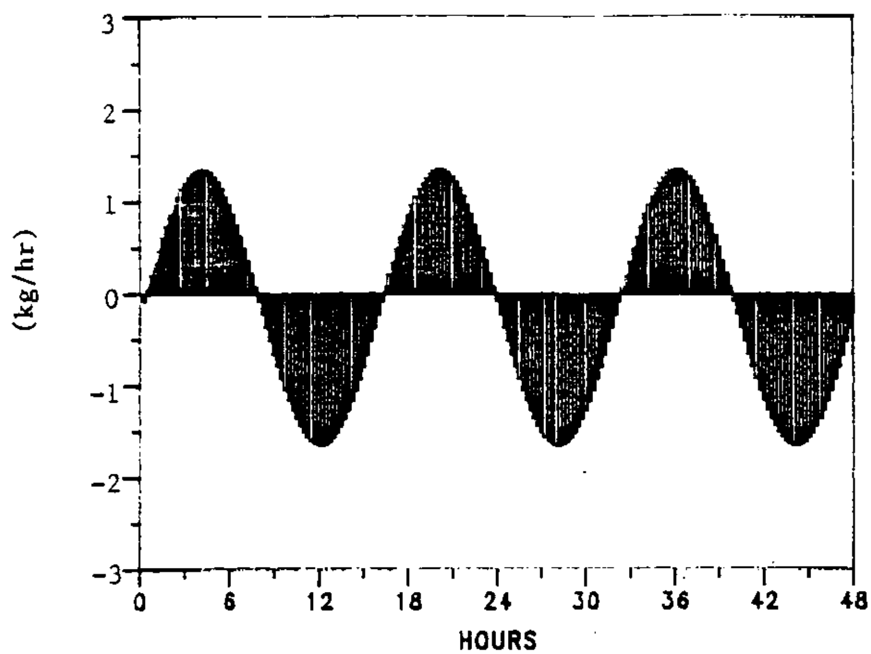
Figure 10. Sinusoidal pulses produced by alternating humidification and dehumidification.

Step-Change Cycles

Step-changes in relative humidity were also used. By stepping the RH from 55 percent during the period from midnight through noon to 70 percent during the period from noon to midnight, we could observe the amount of moisture added or removed and assess the moisture adsorption/desorption capacity of the building/furnishings. These experiments were performed at two different dry-bulb temperatures, 25.3^{o}C (77.5^{o}F) and 27.2^{o}C (81^{o}F).

Building Moisture and Thermal Capacity

The amount of moisture adsorbing materials in the building and the amount of thermal mass was varied. For both moisture and thermal capacity the lowest level was represented by the empty building (including carpet, a table, two chairs and some instrumentation). For high moisture capacity, silica gel was added to the space. A total of 345 kg of grade 59 silica gel was sewn into 68



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The burlap cloth used in the desiccant quilts also has a significant moisture capacity. The approximated 1680 ft^2 of burlap weighs 47 kg. If a moisture isotherm for jute is used to represent burlap, then the moisture storage capacity of the burlap material is 0.10 kg per percent RH over the range from 40 to 80 percent RH. This is 10 percent of the capacity of the desiccant.

Table 3 shows the various configurations of moisture and thermal mass of the building and the experiment type (sinusoidal, step change, off-peak, and DESRAD). The julian days in which good data was obtained are presented in the table. The building configurations can be briefly summarized. "Bare" is the empty building. The "500 gallons" and "1000 gallons" are the empty building with the respective number of 1 gallon water bottles on metal shelves. "Water and quilts" is 1000 gallons of water and 68 desiccant quilts. "Water and quilt +" is the same as the previous arrangement except the quilts are moved away from lying flush on the face of the shelves to being suspended six inches out from the face of the shelves. This is done to increase the exposure to the quilts of the room air. A discussion of the results of these experiments is found in Section V.

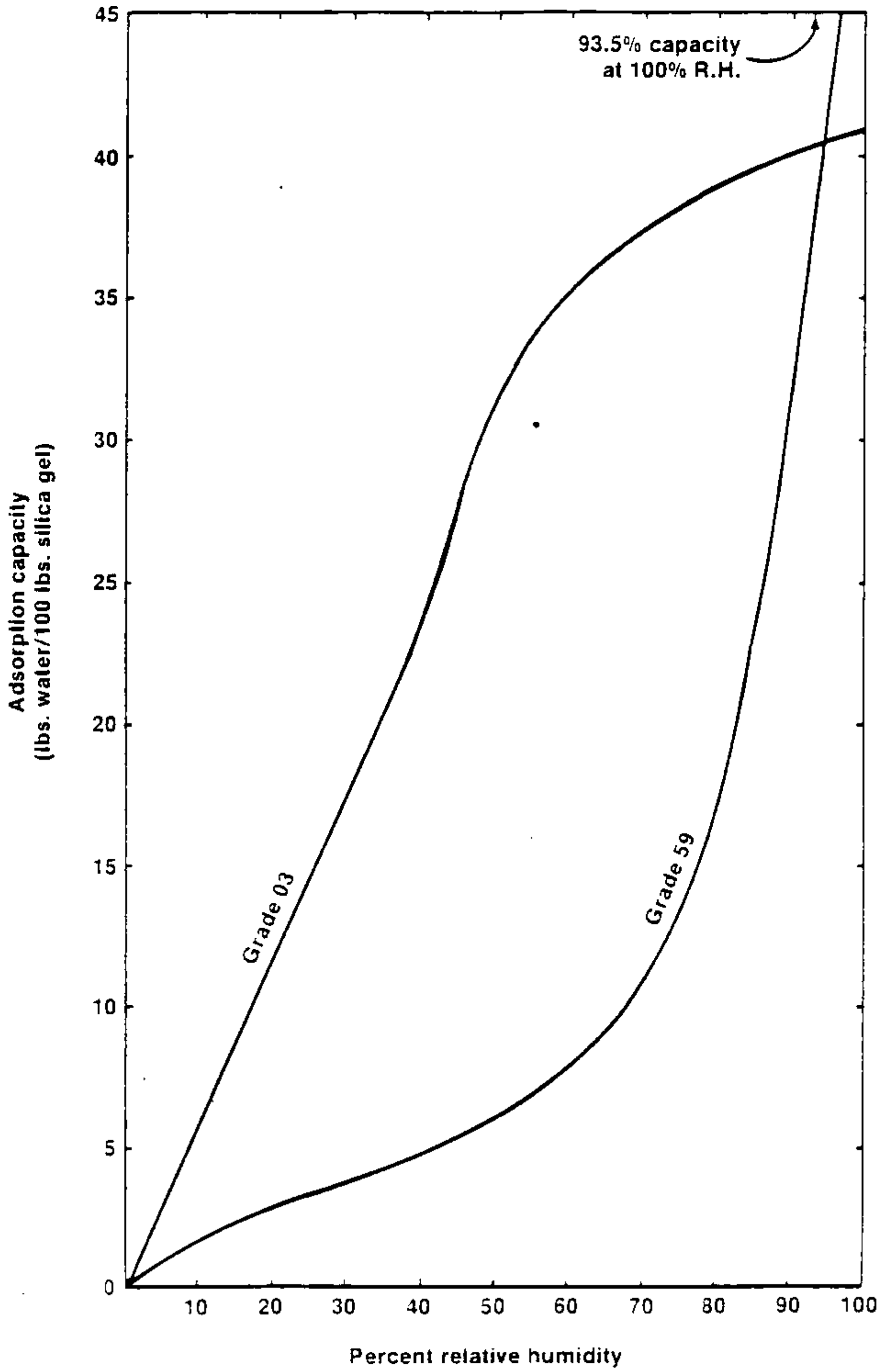


Figure 11. Equilibrium adsorption capacity of silica gel. (Source: W.R. Grace & Co., Davison Chemical Division).

	bare	500 gallons	1000 gallons	water & quilts	water & quilts +
sine wave 24 hr cycle	219 - 223				302 - 306
sine wave 12 hr cycle					308 - 309 212 - 213
step change 55 to 70% RH 25.6° dry-bulb	225 - 229			274 - 277	316 - 317
step change 55 to 70% RH 27.1° dry-bulb	231 236 - 239			279 - 280	
Off-peak	249 - 250	256 - 257	259 - 265	267 - 270	
DESRAD				295 - 296	300 319 - 321

Table 3. Julian days during which good data was obtained for various experiments.

Experiment Control

An IBM PC portable computer was used to provide two types of indoor conditions control:

1. Scheduled addition or removal of moisture
2. Simultaneous control of dry-bulb and dewpoint temperature conditions with the capability of varying the dry-bulb and dewpoint setpoints throughout the day.

The first control mode was designed to be able to provide sinusoidal pulses of moisture. Inputs to the program were the peak humidification amount, the peak dehumidification amount, and the cycle length (typically 24 or 12 hours). The program calculated the quota of humidification or dehumidification which would be required during a given 15 minute period. The IBM would then turn on the humidifier or dehumidifier (the AC unit is the dehumidifier) as needed. The IBM then monitors the amount of moisture injected into and removed from the space by means of the humidifier pump count and the dewpoint drop across the AC coil, respectively. The humidifier or AC is kept on continuously until the quota for that 15-minute period is satisfied. Thus, the humidification or dehumidification occurs during the first part of each 15-minute period.

While the moisture quotas are being satisfied, the room dry-bulb setpoint is being met. This normally means space cooling because of hot summer ambient conditions. This cooling, however, adds complications, because in the process of providing sensible cooling, moisture is also removed from the space. When the moisture quota for a given 15 minute period has been satisfied and space cooling is required, it becomes necessary for the IBM to monitor the amount of moisture removed by the AC and turn on the humidifier to inject the same amount removed by the AC to assure that only the intended moisture quota is delivered. After a number of adjustments to this basic language program both modes of control ran successfully.

Switching control from the IBM was provided by a Metrabyte board with four relays. Five volts was provided to these relays. When they closed they activated other opto isolated relays which switched 120 volts to the humidifiers and 240 volts to the AC compressor, the heat strip, and the AC blower as needed.

The second control mode was designed to meet dry-bulb and dewpoint setpoints for up to 10 separate periods throughout the day. Deadbands for both dry-bulb and dewpoint temperatures are also specified. It was found that constant space conditions generally could be maintained within $\pm$ .5°C of specified values.

This control mode was used for the step change, off-peak, and DESRAD experiments. Dry-bulb and dewpoint control was based on the RTD (air dry-bulb) and a chilled mirror hygrometer at the return grill in the upstairs bedroom. This location adequately represented the house because ceiling fans were left on and the AC blower was on constantly in many of the experiments specifically to enhance mixing.

V. RESULTS

The equipment and experiments were generally trouble-free. The major problems encountered were:

1. The humidifier failed for a portion of one week because of rust in a part which caused clogging of the spray nozzle.

2. Several of the power meters were intermittently inoperative during the later experiments.

3. The water sensor switch on the condensate positive displacement pump failed intermittently by sticking in the "on" position. However, backup data from the tipping bucket was available.

The other equipment components and control elements operated generally without problems. In addition, our data collection, transfer, and storage resulted in less than two days of lost data, none of which was during periods of good data, that is it occurred between experiments or when repairing equipment. Data were transferred to the FSEC Vax 11-750 on a daily basis via telephone modem. The datalogger, a Campbell CR7, has 2.3 days of internal data storage which was very helpful in insuring successful data transfer when problems occurred.

Selection of Cycle Period

Total moisture storage in furnishings is a function of a number of variables including time of exposure. If a house is cycled between 55 and 70 percent RH every 15 minutes, little moisture would have an opportunity to transfer into and out of building materials. Only the very thin outer boundary surface of the furnishings would fluctuate in moisture content, and the deeper levels would reach some equilibrium moisture content. This is analogous to heat storage in building furnishings when the interior air temperature is cycled rapidly. Only a thin surface mass changes temperature so that the effective thermal storage is small. For the moisture storage experiments it was essential to select a cycle period to approximate real cycles of moisture sorption that occur in buildings. A 24 hour cycle was chosen because cooling and dehumidification strategies generally operate on a diurnal cycle. Nighttime ventilation followed by daytime air conditioning has a 24 hour period. The DESRAD strategy has an approximate 13 hour dehumidification period followed by an 11 hour period where humidity comes back into the space by infiltration and internal moisture generation. The off-peak cooling approach provides cooling for about 19 hours and "floats" during five hours. In all these cases the period length is 24 hours and the dehumidification period is sufficiently long to provide for a large moisture sorption capacity. One set of sinusoidal experiments was run with a 12 hour cycle to allow observation of any change in effective storage capacity.

Moisture Capacity of Materials

The moisture capacity of materials at equilibrium is a function of the air relative humidity and dry-bulb temperature. For a material at a given dry-bulb temperature, a curve (sorption isotherm) can be drawn showing equilibrium moisture content versus relative humidity. Curves for the carpet and painted gypsum which make up most of the moisture capacity of the bare building were not available. A curve for nylon is available and may approximate the carpet (Figure 12). Such an isotherm for silica gel #59 is available and is shown in Figure 11. Neither curve is linear. A change in RH from 40 to 55 percent yields a moisture increase of 7.1 kg in 345 kg of silica gel, while an increase from 55 to 70 percent produces a 14.1 kg moisture increase, nearly twice as great.

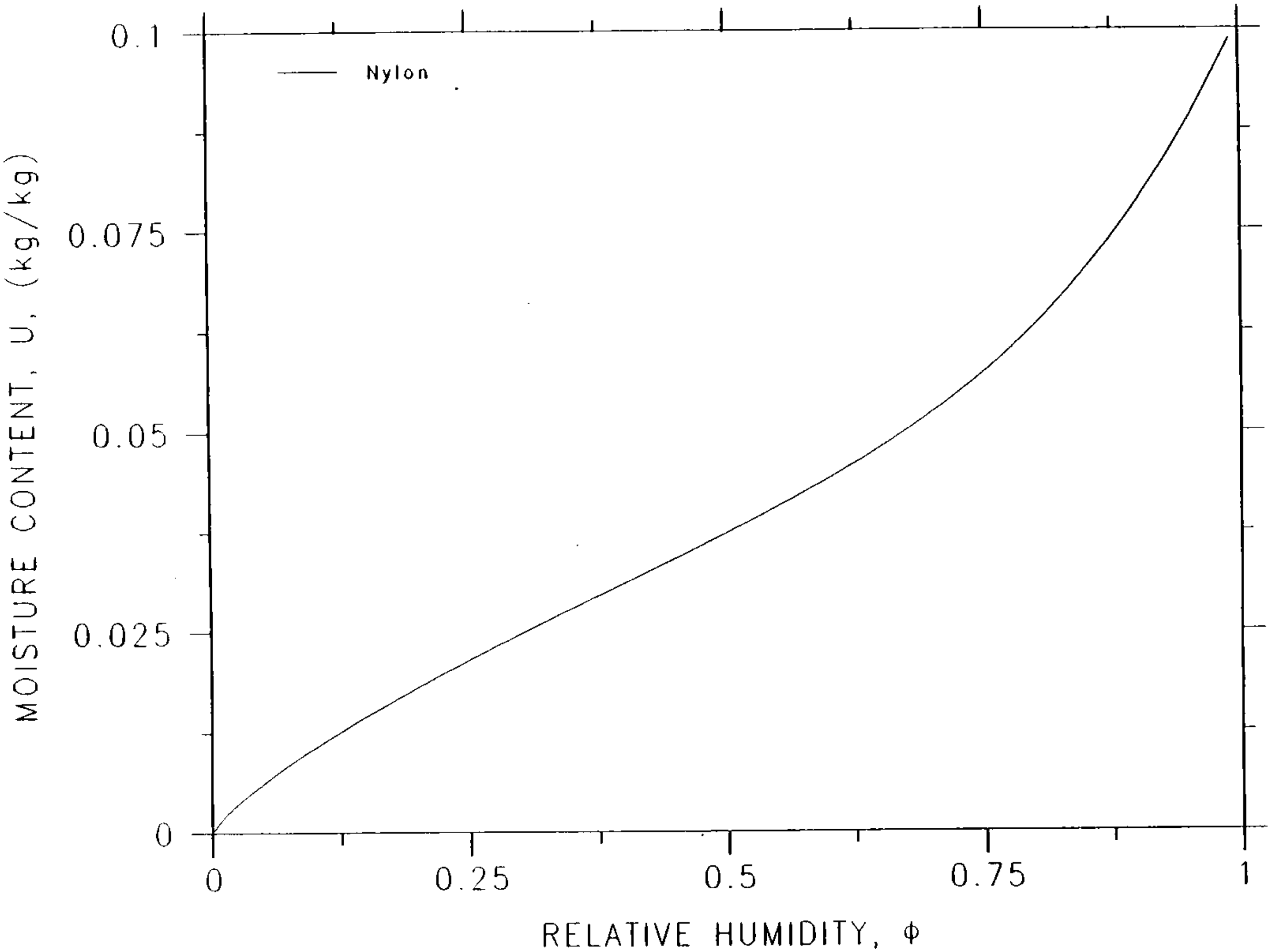
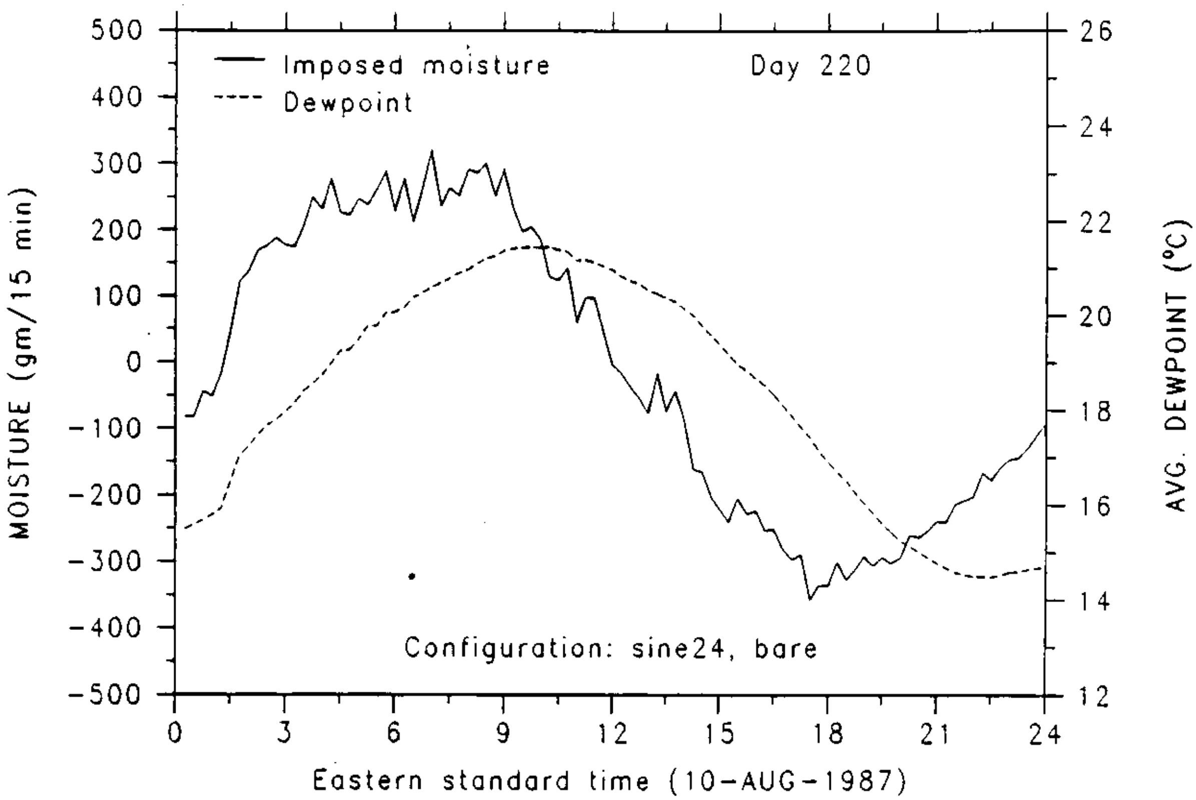


Figure 12. Equilibrium moisture content of nylon. (Source: Reference [4])

Sinusoidal Experiments

The first experiment was sinusoidal pulses of humidification and dehumidification for the bare configuration (low moisture and thermal capacity). Peak humidification and dehumidification rates of 920 and 1600 grams/hour, respectively, produced an oscillating sine wave of RH from 50 to 75 percent (dry-bulb temperature 25.6°C). Figure 13 shows the humidity ratio response (RH response is similar because dry-bulb temperature is constant) to net moisture imposed/removed. The amplitude of the RH response is a function of the moisture capacity and the cycle period. The sine24, bare experiment had a 24 percent RH swing through one cycle. The sine24, quilt + experiment had an amplitude of only 15 percent. The sine12, quilt + had only a 12.5 percent RH response. In each case the magnitude of the moisture pulse was the same.

The high moisture capacity dampens the sine wave of RH response. Does it also have an impact upon the response time of the RH to the pulse? To assess this, it is useful to think about the response of a very low mass building. For example, if the only storage mass was the air, then the humidity ratio should continue to rise as long as the (net) moisture imposition was positive (infiltration is figured into net imposed). The peak dewpoint would occur at the point where the imposed moisture falls to zero. When there is moisture storage in the furnishings, the peak dewpoint occurs earlier. This can be seen in Figure 13. On day 220 (sine24, bare) the peak dewpoint temperature occurs 2.1 hours before the net imposed moisture (IMP_{net} = GEN + INF - AC) drops to zero. On day 303 (sine24, quilt +) the peak dewpoint temperature occurs 1.8 hours before the net imposed moisture drops to zero. It is somewhat surprising that the quilt + configuration does not cause an earlier dewpoint peak, since greater capacity should produce an earlier dewpoint peak.



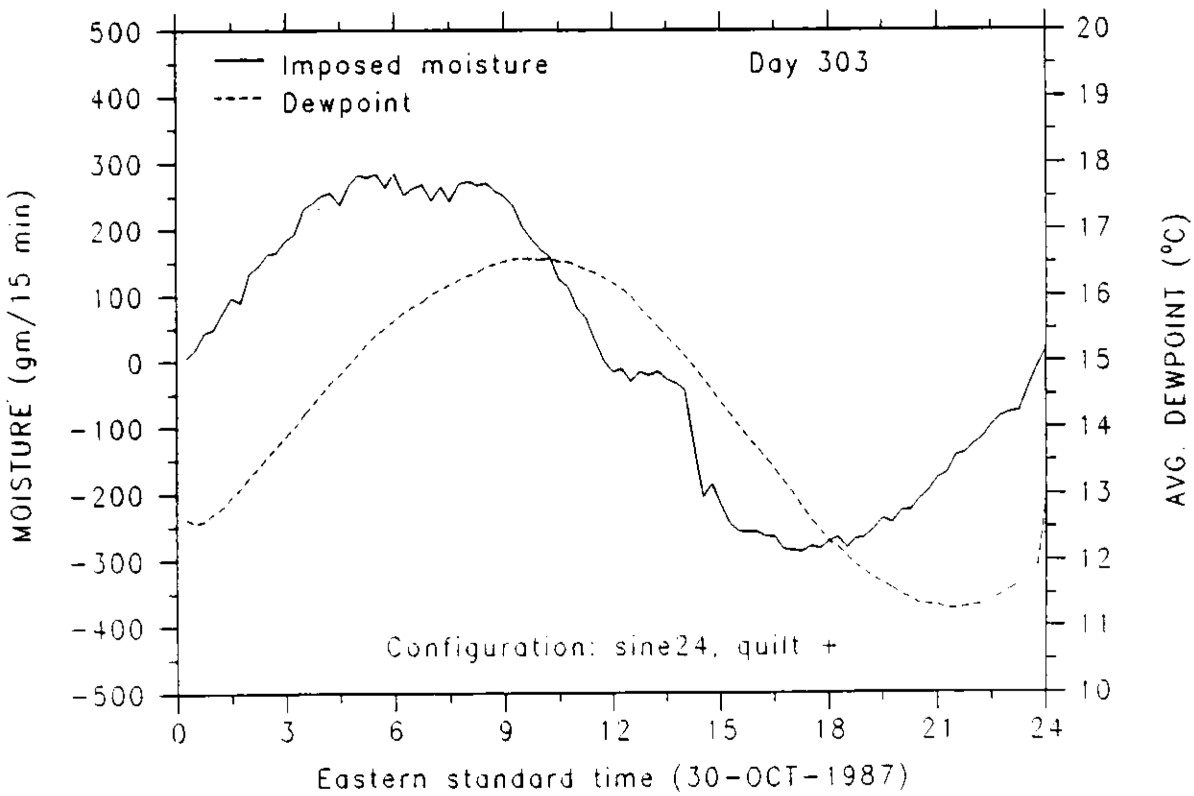
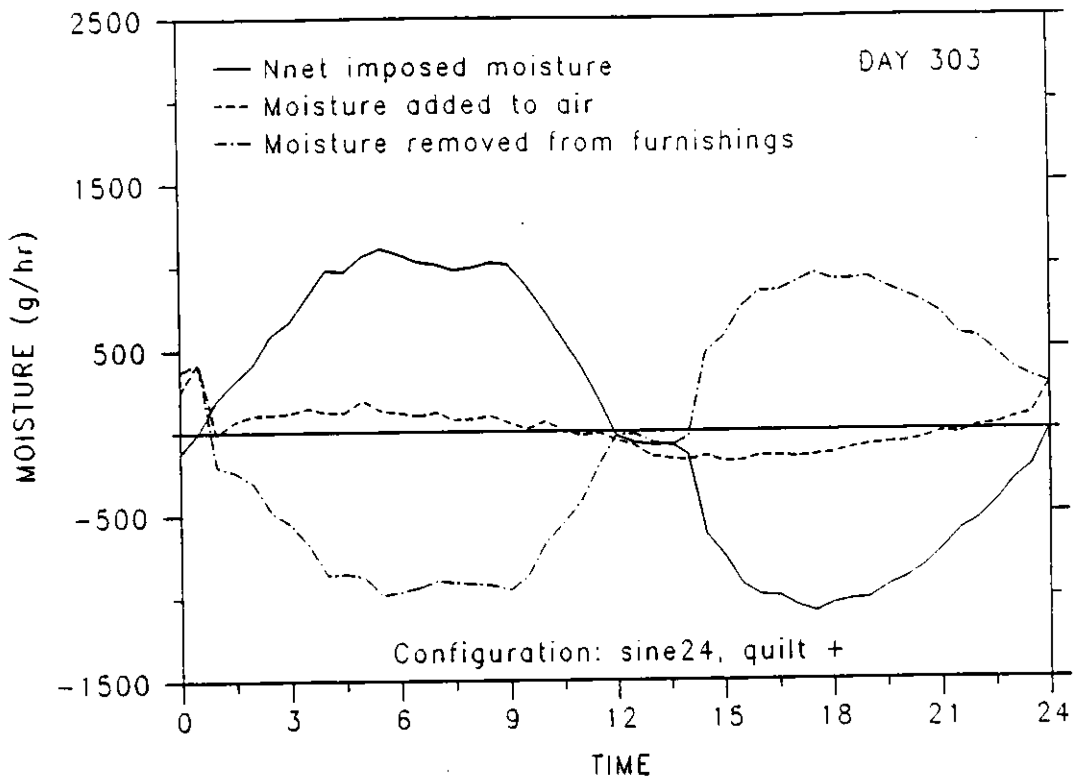


Figure 13. Response of room dewpoint temperature to imposed moisture for low and high moisture capacity configurations.

The reason for the dewpoint peak occurring earlier when moisture storage capacity is available in the furnishings is shown in Figure 14. A breakdown of the imposed moisture going into the air and into the furnishings is shown. (The amount entering the furnishings is determined by subtracting the amount entering the air from the total net imposed moisture flux). Figure 14a shows the moisture entering the air crossing the zero line about 1.5 hours before net imposed moisture reaches zero at midday, and 2.1 hours before net imposed moisture reaches zero at midnight. The dehumidification portion of the cycle is displayed in Figure 14b. At about 9:50 P.M. (21:50) the moisture leaving the furnishings is now greater than the total moisture removal rate, so the air humidity ratio begins to increase. It is the time lag (from the peak flux) adsorption/desorption in the furnishings therefore, that produces the lead time in the peak (or valley) of the dewpoint temperature.

Results from five days of sine24, bare experiments are shown in Figure 15. Five days of sine24, quilt + configuration are presented in Figure 16. The gradual decline of W_r for the bare configuration is the result of slightly more (net) dehumidification than humidification occurring. The humidification of 920 g/hour and dehumidification of 1600 g/hour was chosen to balance the approximate 300 g/hour infiltration. For the quilt + experiment, the peak humidification and dehumidification rates of 1400 and 1200 g/hour, respectively, were chosen because the outdoor dewpoint temperature was 10^{o}C at the beginning of the experiment. However, the daily average dewpoint rose to 20.9^{o}C by the last day (day 306) which caused increased infiltration moisture and a steady rise in W_r over the five day period.



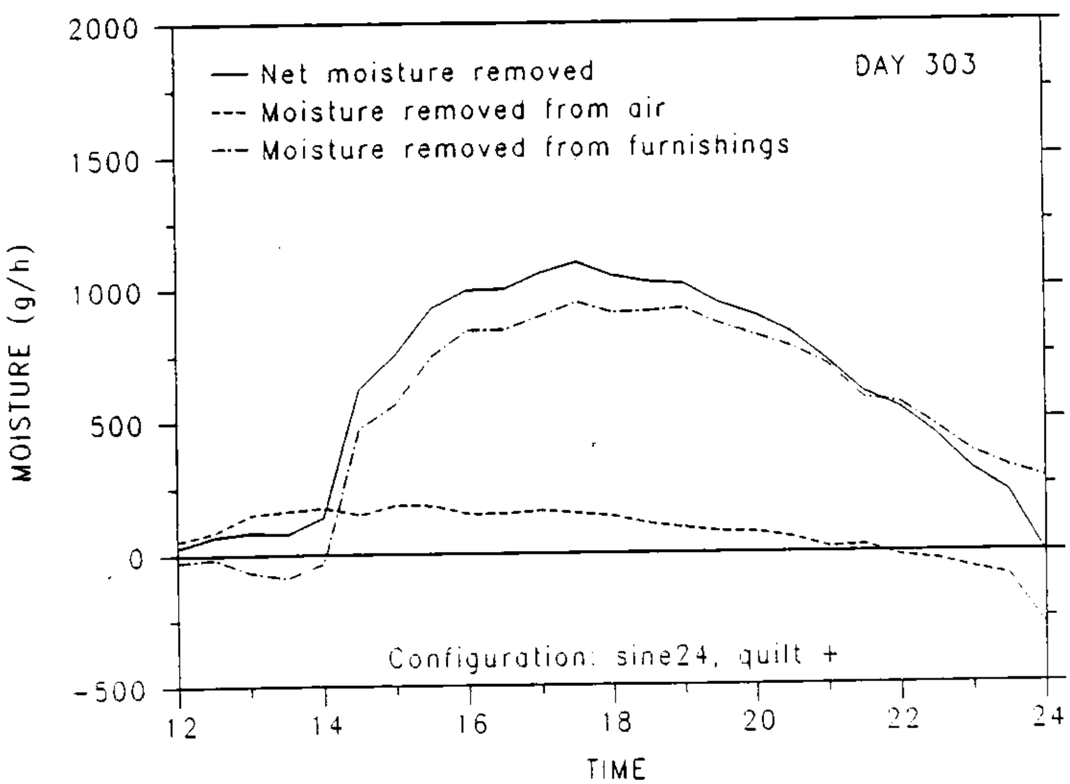


Figure 14. Response of the furnishings and room air to an imposed moisture flux.

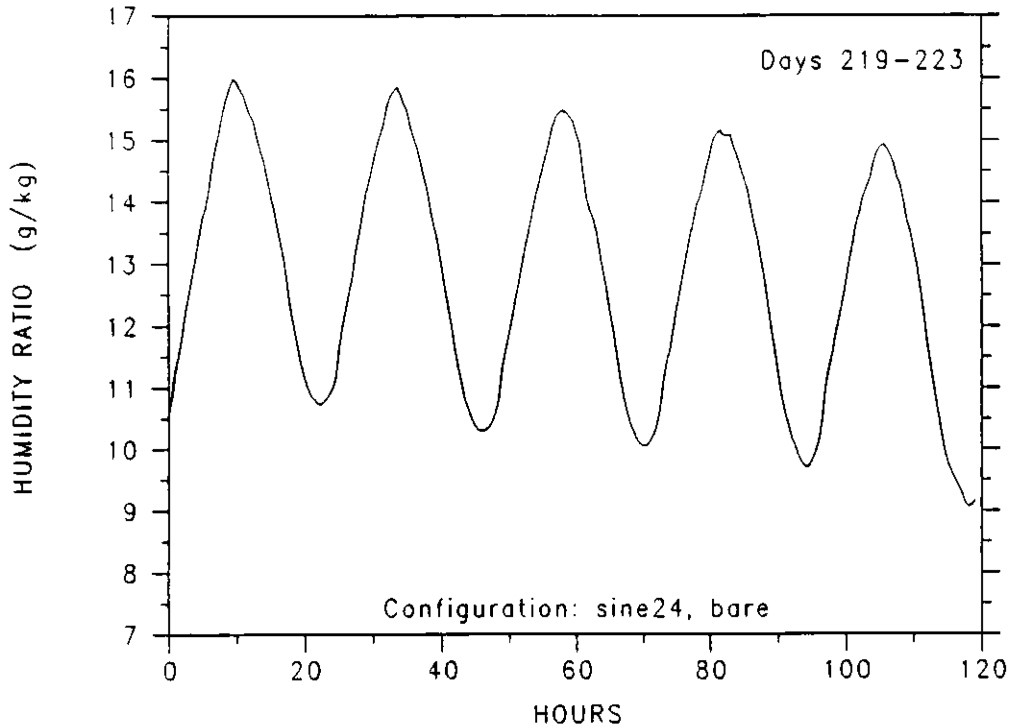


Figure 15. **Measured humidity ratio during five days of sine24, bare experiments.**

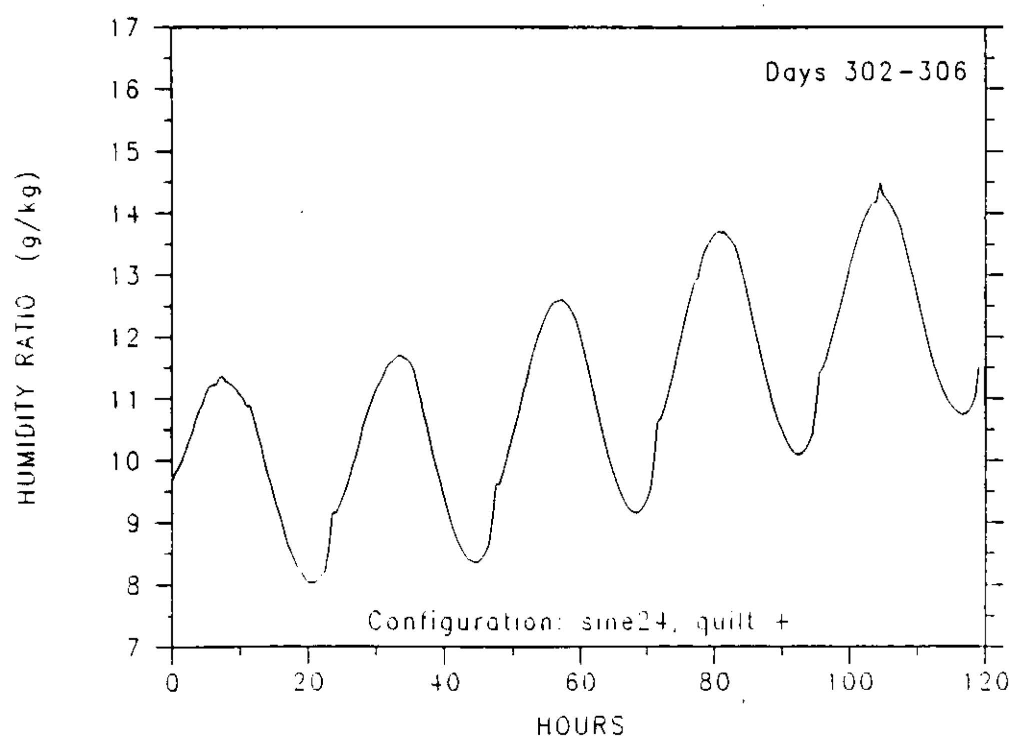


Figure 16. **Measured humidity ratio during five days of sine24, quilt + experiments.**

Step Change

The second type of experiment was a step change pulse. The relative humidity was set at 55 percent from midnight until noon and 70 percent from noon until midnight. A total of nineteen days of step change experiments were done to assess the moisture storage of the furnishings. The net amount of moisture sorbed by the furnishings can be obtained by:

SORB = GEN - AC + INF - AIRSTORE

where

GEN is the internally generated moisture
AC is the air conditioner condensate
INF is infiltration moisture
AIRSTORE is moisture stored in air

where

$$INF = (W_{AMB} - W_{ROOM}) * ACH * AIR\ MASS * TIME$$

For the bare configuration the average moisture added and then removed was 5.6 kg. This was at 25.6°C dry-bulb temperature (55% RH = 15.0°C dewpoint and 70% RH = 20°C dewpoint). Another test was performed at 27.2°C (55% RH = 17.0°C dewpoint and 70% RH = 22°C dewpoint), and the average was 6.3 kg, nearly the same. This quantity is 4.47 times the change in moisture content of the air alone. It is not expected, however, that the moisture storage materials in the building achieve equilibrium in a twelve hour period. In Section VI an evaluation of the E_m model points to a moisture storage capacity of the building and furnishings of about nine times the air capacity.

For the quilt configuration the average moisture added and then removed was 11.3 kg at 25.6°C dry-bulb temperature (step15) and 12.0 kg at 27.2°C dry-bulb temperature (step17). This quantity is 9.0 times the change in moisture content of the air alone. The effective moisture storage of the furnishings (quilt configuration) in a 12 hour exposure is, therefore, nine times the capacity of the air.

A longer-duration test was performed which allows us to assess the effective moisture capacity for a longer exposure time. At the completion of the step17, quilt experiment the RH was set at 70 percent for four days and five hours. During this time a total of 28.5 kg of moisture had to be added to the space (net) to maintain this RH (Figure 17). From this plot the effective moisture capacity (ratio of air + furnishings capacity σ air capacity) for various exposure times can be obtained (Table 4).

Hours	Moisture Added (kg)	Times Air Capacity
6	8.0	5.7
12	12.0	8.5
24	16.0	11.3
48	21.0	14.9
72	24.0	17.0
96	28.5	20.2

Table 4. Cumulative moisture desorption when the building is at near moisture equilibrium with the room at 70 percent RH and the RH is then lowered to 55 percent RH. Building appears to achieve equilibrium with the room air in three days.

After more than four days the furnishings are still adsorbing moisture, and equilibrium with the air has not yet been achieved. It is important to note that the stored moisture in the furnishings did not begin at equilibrium with the air. The changing RH from 55 to 70 percent every 12 hours produced a moisture content somewhere between the equilibrium moisture content at 55 percent RH and 70 percent RH. What this content was is difficult to surmise. Since a 12 hour exposure transfers about 12 kg of moisture, which may be about

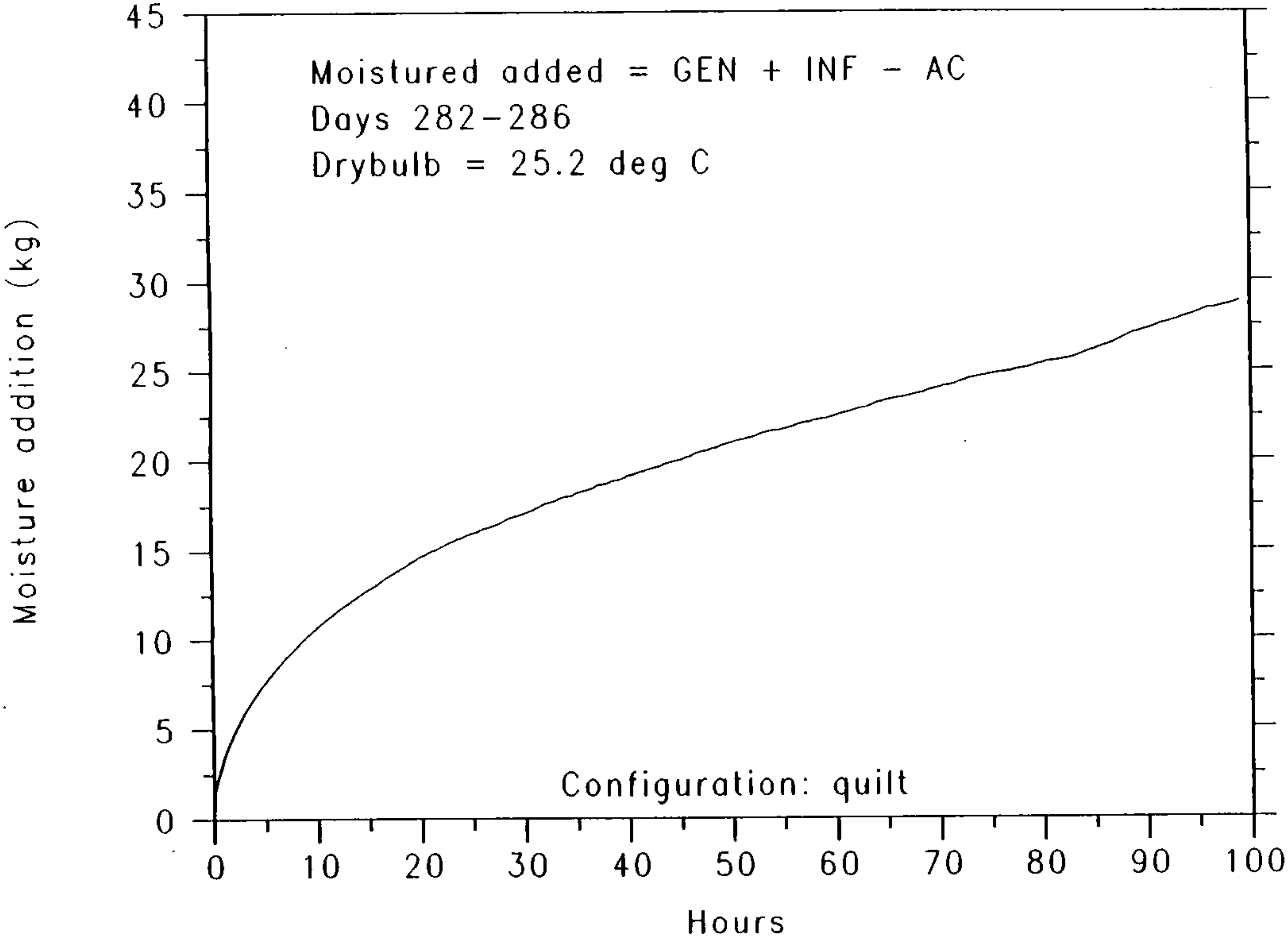


Figure 17. Cumulative moisture input required to bring furnishings to near-equilibrium when room air is set at 70 percent RH when the preceding period was three days of alternating 12 hour periods of 55 and 70 percent RH.

one-third of the total storage capacity from 55 to 70 percent RH, the moisture content may be equal to 60 percent RH equilibrium moisture content (though obviously not in equilibrium).

When this experiment was completed the RH was lowered to 55 percent and held there for four days. The furnishings appear to come to equilibrium with the air after three days (Figure 18). The cumulative moisture removal is 33.6 kg after four days, which is 24.7 times the storage capacity of the air alone. However, since the experiment did not begin at equilibrium, we cannot say that the total capacity is only 24.7 times that of the air. It is more than this, but how much more is unknown.

A significant difference exists in the initial moisture transfer rates of these last two experiments (Figures 17 and 18). While only 12 kg of water were added during the first 12 hours of the adsorption cycle (Figure 17), 23.5 kg were removed in the same length of time during the desorption cycle (Figure 18). A much larger portion of the total storage capacity was used during the dehumidification experiment. The explanation for this is probably the fact that the dehumidification cycle began with the furnishings in near-equilibrium with the air, while the humidification period followed a period of cycling RH and was therefore far from equilibrium. A conclusion can be drawn that the <u>effective</u> moisture capacity of the furnishings for a 12-hour exposure is much greater when the building furnishings are near equilibrium than when they are cycling.

Another check of the moisture capacity can be obtained by an analysis of the moisture capacitance of the silica gel. From the capacitance versus RH curve in Figure 11, the moisture capacity over the range of 55 to 70 percent RH is

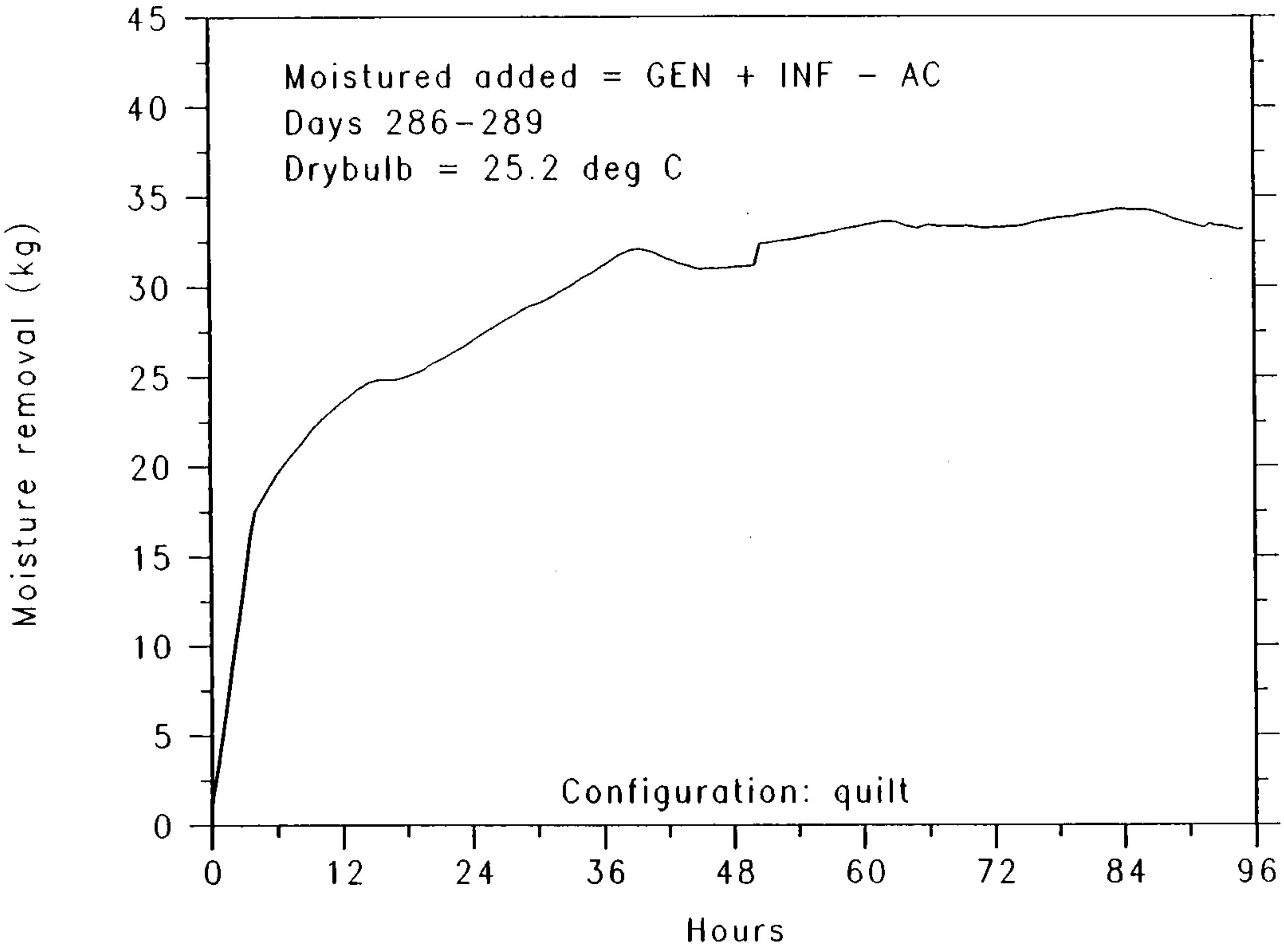


Figure 18. Cumulative moisture removal when the building is at near moisture equilibrium with the room air at 70 percent RH and the RH is then lowered to 55 percent RH. Building appears to achieve equilibrium with the room air in three days.

14.1 kg of water or about 11 times the capacity of air. The burlap in the quilts can store an additional 1.5 kg of moisture. Add to this the estimated capacity of the rest of the furnishings and building (nine times the air), and the moisture storage is about 20 times that for air.

Based on these considerations, it appears that the total moisture capacity of the empty building is about 9 times the air capacity, and the total moisture capacity with the desiccant quilts added is about 20 times the air capacity. Corroboration of these conclusions in also found in Section VI. Evaluation of the simple E_m model points to a storage capacity of the building and furnishings of about 8 times and 18 times the air capacity for the bare and quilt + configurations, respectively.

VI. MOISTURE MODELS

In hot, humid climates like Florida the common means for providing cooling in homes is vapor-compression air conditioning. Because of a desire to reduce cooling energy use and peak demand for the electric utility, alternative approaches to cooling are being considered. An approach as simple as opening windows at night or on cool cloudy summer days is already widely practiced. More innovative approaches which provide cooling at night (DESRAD) or during non-peak cooling periods (off-peak cooling) are being contemplated. In each of these cases there is a significant swing in the humidity within the building. Accurately assessing the impact of these humidity swings requires knowledge about the moisture sorbing capacity of the materials in the building and the moisture transfer rate between the air and materials.

One simple model which we have begun to evaluate is the lumped model. The building and furnishings moisture storage capacity is represented by a hypothetical moisture isotherm. Moisture transfer between the air and furnishings is determined by a moisture transfer coefficient, h_m, and the surface area of the material. Finding an appropriate capacitance curve is an effort we are currently undertaking. The experiment we are currently executing to find capacitance curves for carpet, gypsum, wood, furniture, etc. (see Section VIII for a description of the current experiment) should help toward this end. No further presentation of our efforts with the lumped capacitance model will be made in this report.

A simple model which can account for the response of buildings to the addition or removal of moisture is proposed. The model is called the effective air mass moisture capacity model (E_m). In this approach the building and furnishing moisture storage capacity is represented by expanding the building air volume by a factor, E_m. An E_m of 10.0, for example, means the combined moisture storage capacity of the combined furnishings and the air is 10.0 times the storage capacity of the air alone. For example, from 55 to 70 percent RH (at 25.6°C dry-bulb) air can store .0032 kg of water for each kg of dry air. A building with an E_m of 10.0 can store .0320 kg of water for each kg of dry air in the space.

The moisture capacity versus RH curve for air (at 25.6°C) is quite linear. For each 10 percent rise in RH the moisture change of air is about .0022 kg per kg dry air. This linearity can cause a problem in the E_m model because many materials do not have linear moisture capacitance versus RH curves. Nylon (such as in carpet) is fairly linear over the range of 40 to 80 percent RH (Figure 12). Silica gel, on the other hand, is quite non-linear over this same RH range (Figure 11). To the extent that the important moisture absorbers have non-linear curves the E_m model will produce inaccuracies.

Two versions of the E_m model have been developed; the 1-room and the 2-room model (Figure 19b). Both represent the moisture storage capacity of the furnishings by an expanded volume of air. The 1-room model conceptually lumps the actual room air and the air simulating the furnishings into one, well-mixed "room" of air. Any moisture input to the space is instantaneously mixed throughout the whole volume of air. Thus, there is no variability in the transfer rate of moisture between air and furnishings. The numerical solution is very simple:

$$W_r(t) = W_r(t-1) + IMP/(M_{air} * E_m)$$

where W_r is the room humidity ratio

IMP is the imposed moisture during period (kg)

M_{air} is the mass of the room air (kg)

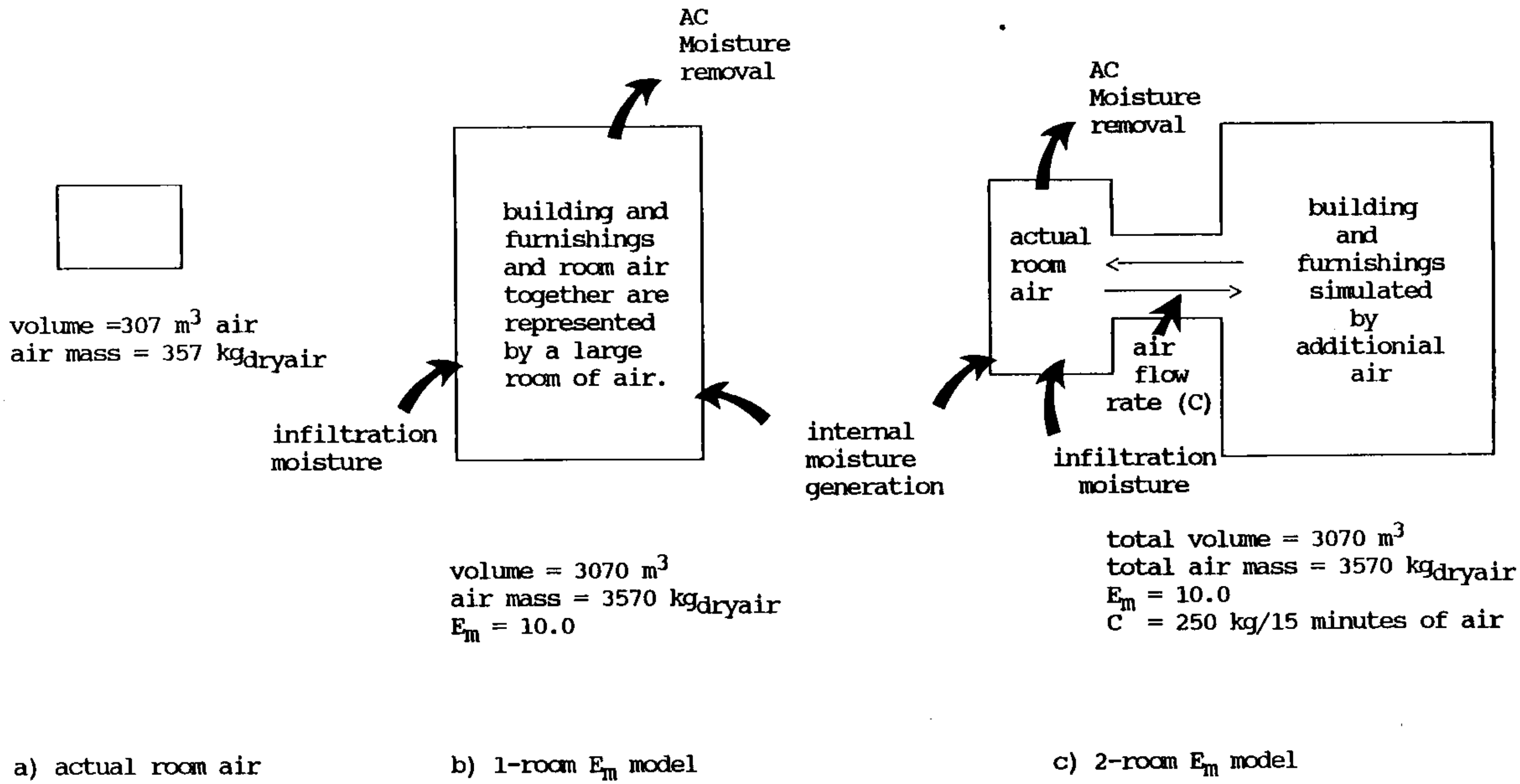


Figure 19. E_m model increases room air volume to simulate moisture storage capacity of building and furnishings.

Suppose 1.0 kg of water is added to the room. The room humidity ratio would increase as follows (assume Wr (t-1) = .0110):

$$W_r(t) = .0110 \frac{kg_{H_2O}}{kg_{dry\ air}} + 1.00\ kg_{\ H_2O}/(357\ kg_{\ dry\ air} * 10.0)$$

$$= .0110 \qquad + .00028$$

$$= .01128$$

The assumption of instantaneous mixing has potential problems. In reality there is a limited transfer rate between air and furnishings so that a flux of moisture raises the air moisture content more rapidly. This higher air moisture content then drives the moisture transfer into the furnishings. Because of this assumption of instantaneous mixing, this causes underprediction of the amplitude of the room moisture response, and causes a time lag in the predicted response relative to the data, as we shall see.

To correct for this problem, a second E_m model is proposed, the 2-room E_m model. It also represents the furnishings by an expanded volume of air, but differs from the 1-room model by placing the furnishings "air" in a separate "room" (Figure 19c). The two "rooms" of air are connected by a "duct" through which a flow of air occurs. The flow rate of the air, C (in kg dry air per hour), determines the moisture transfer rate between the two bodies of air:

$$(W_{room1} - W_{room2}) * C$$

where W_{room}, is the humidity ratio

An example of this calculation is shown.

$$(.0160 - .0150) \frac{kg_{H_2O}}{kg_{dry\ air}} * 250\ kg/hr\ dry\ air = 0.250\ kg\ H_2O$$

How well do the 1-room and 2-room E_m models work at predicting the room humidity ratio? As a first evaluation, one day of sinusoidal experiment was modeled with the 1-room concept. The imposed moisture on the space is known from measured data. The infiltration moisture, the humidifier moisture input, and the AC moisture removal are all measured or calculated from measured conditions. This imposed moisture goes into the air and furnishings, but the amount going into each one is unknown. By varying the value of E_m from 1 to 10 we can assess what furnishings moisture capacity produces the closest fit to the measured room humidity ratio. Figure 20 shows that for E_m = 1 (furnishings have no moisture capacity) the predicted W is too high. At E_m = 5 the predicted air W is very close to the measured W. At E_m = 10 the predicted W is too low. When more than one day is simulated, it can be observed that the humidity ratio drifts higher for E_m = 4 and 6, and is approximately on target for E_m = 8 and 10 (Figure 21). This indicates that the actual total moisture capacity may be higher than E_m = 5.0, and closer to 10.0. When the model overpredicts W_r over a several day period, it indicates that too little cumulative moisture storage is occurring and that the value chosen for E_m is too small.

While E_m = 5.0 produces an amplitude of humidity response which is accurate, a one-hour time lag can be seen between the predicted and actual humidity ratio in Figure 20. This occurs because the moisture transfer rate between the air and furnishings is not instantaneous, as is assumed in the 1-room E_m modeling approach.

Use of the 2-room E_m model for the same five days produces better argument. The one hour time-lag is eliminated and the correct amplitude is achieved. A

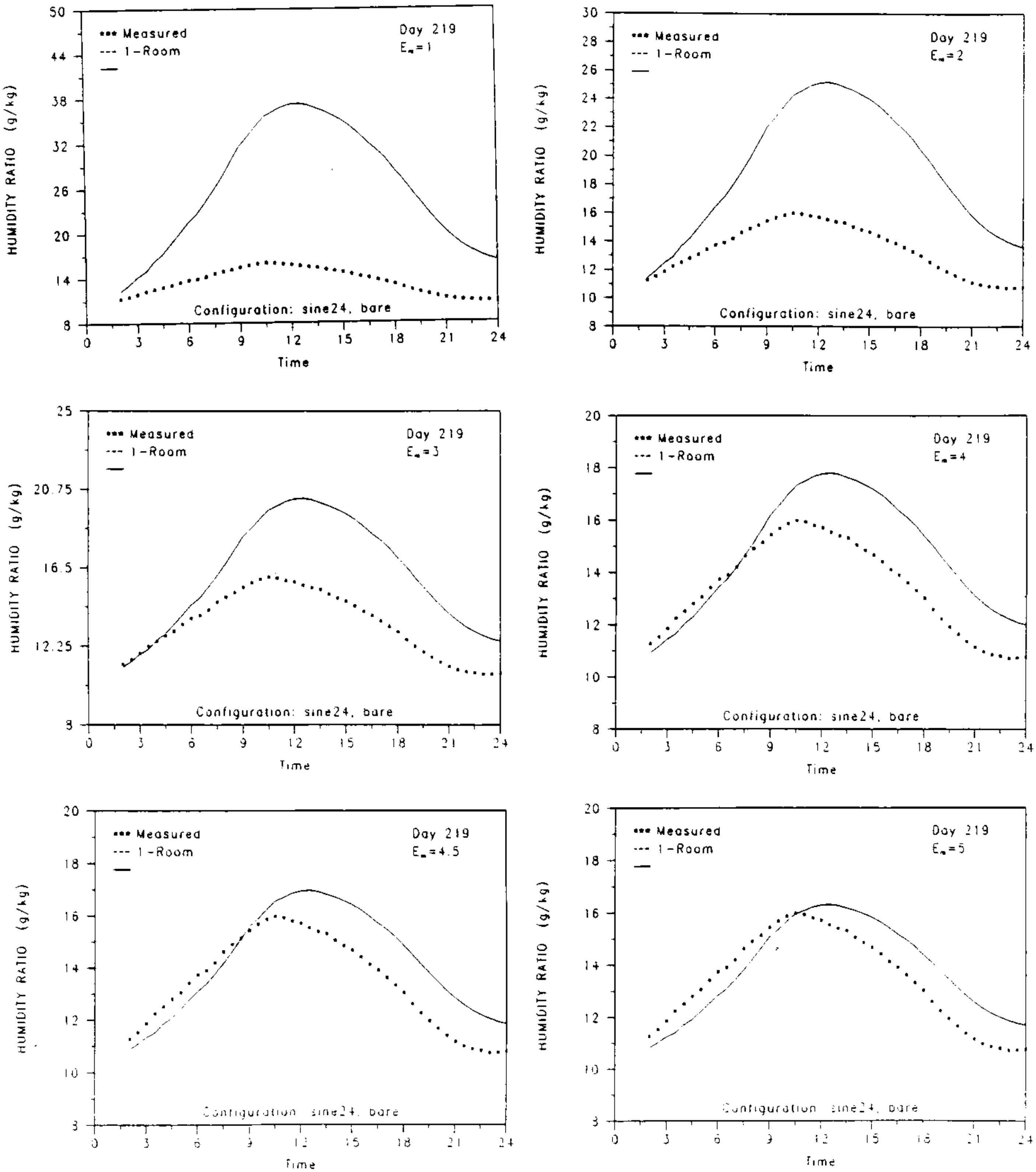


Figure 20. Predicted versus measured humidity ratio for various values of E_m using the 1-room E_m model for sine24, bare experiment.

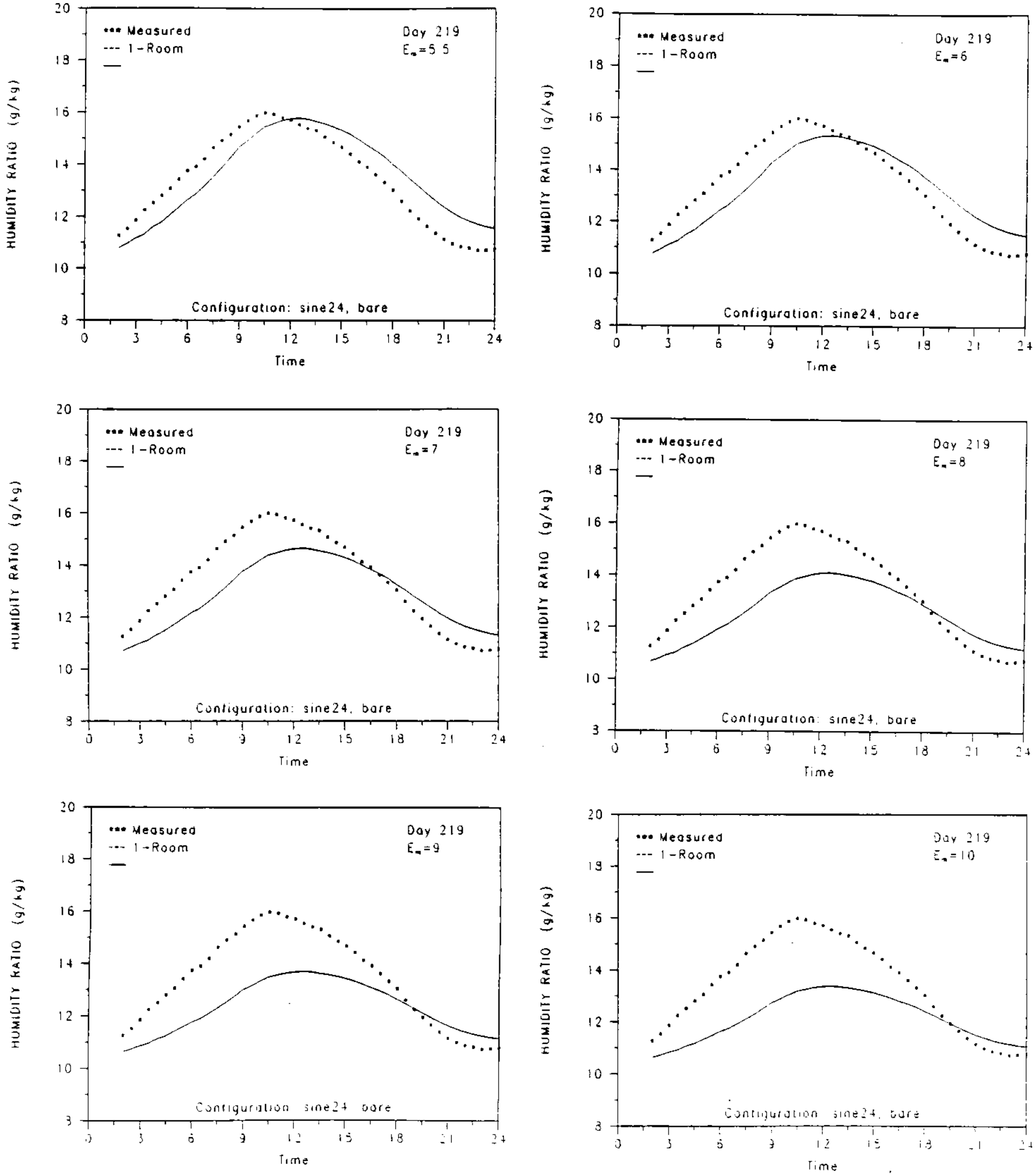


Figure 20. continued

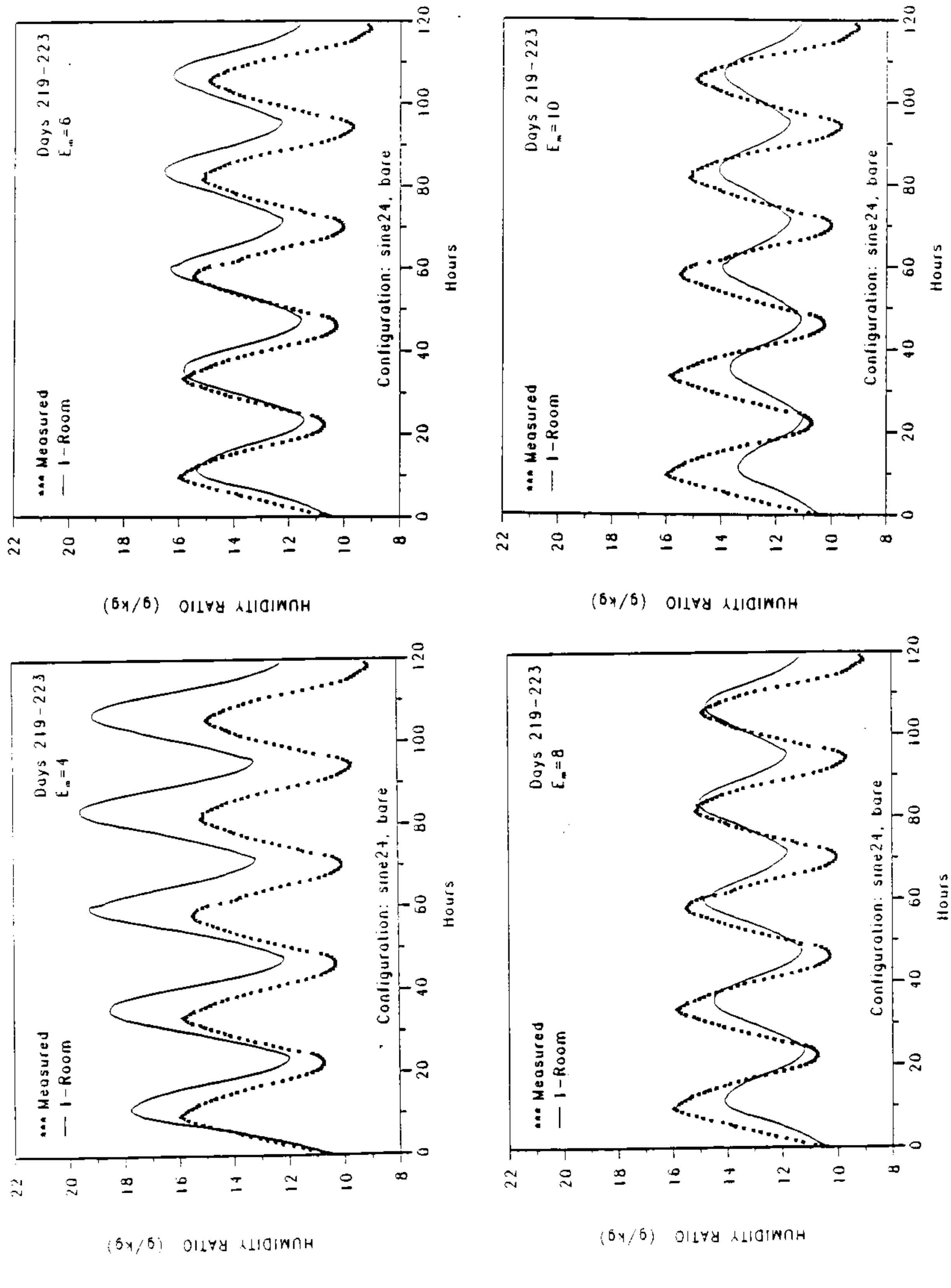


Figure 21. Predicted humidity ratio for a five day period by 1-room E_m model for sine24, bare experiment.

transfer rate, C, of 250 kg/hour airflow and an E_m of 8.0 or 10.0 provides the best match (Figure 22). Another five-day period was modeled for the quilt + configuration. Figure 23 shows that E_m values of 18 to 20 with C = 400 produce the best match. Figure 24 plots average prediction error versus E_m value. It illustrates that the best match of E_m values for the bare and quilt + configurations are 9.0 and 18.0, respectively. These moisture storage capacities are in good agreement with the values discussed in Section V. The average prediction errors for the bare and quilt + configurations are less than 7 percent and 4 percent, respectively.

It was noted in Section V that silica gel has a very non-linear moisture isotherm. The desiccant's capacity from 55 to 70 percent RH is twice as great as from 40 to 55 percent. This appears in the results shown in Figure 23. During the first three days (RH range is 40 to 55 percent) an E_m of 12 provides the best match. However, by the end of five days an E_m of almost 20 fits best (the RH range increases to 55 to 70 percent). Thus, in the case of a very non-linear capacity curve, as with grade 59 silica gel, the linear capacity characteristics of air produces a noticeable prediction inaccuracy.

It is interesting to note that the 1-room model underpredicts the amplitude of the RH response. In Figure 22 (bare configuration) it can be seen that the predicted amplitude of the 1-room model is about the same as the amplitude for the measured data when E_m = 4 and 6. However, when E_m = 10, the predicted amplitude is only 50 percent of the true response. For the quilt + configuration (Figure 23) the 1-room amplitude drops to about 40 percent of the true amplitude when E_m = 18.0. An explanation of this is that the 1-room model brings the total moisture capacity of the furnishings to equilibrium

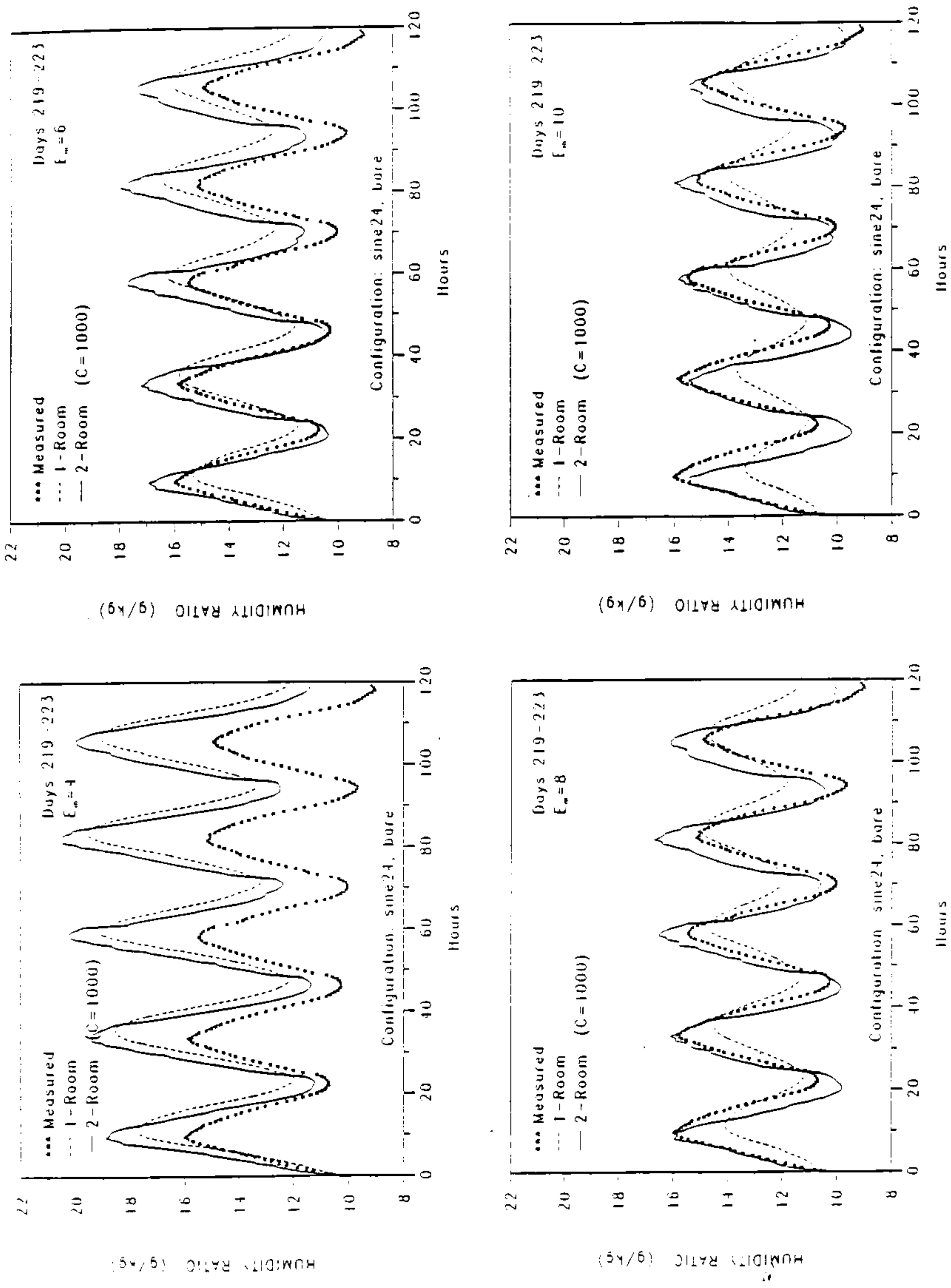


Figure 22. Predicted humidity ratio for a five day period by 1-room and 2-room E_m models for sine24, bare experiment.

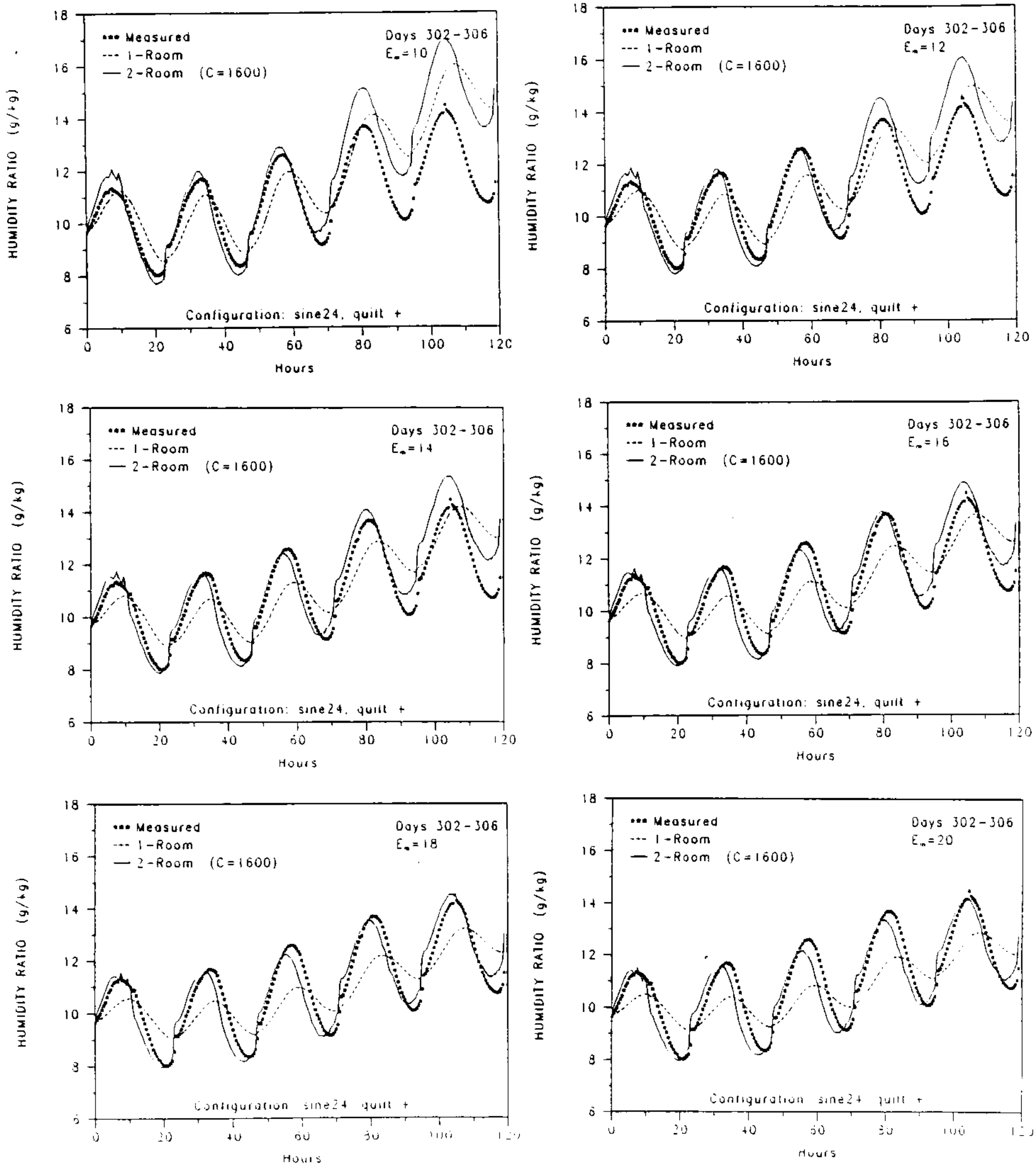


Figure 23. Predicted humidity ratio for a five day period by 1-room and 2-room E_m models for sine24, quilt + experiment.

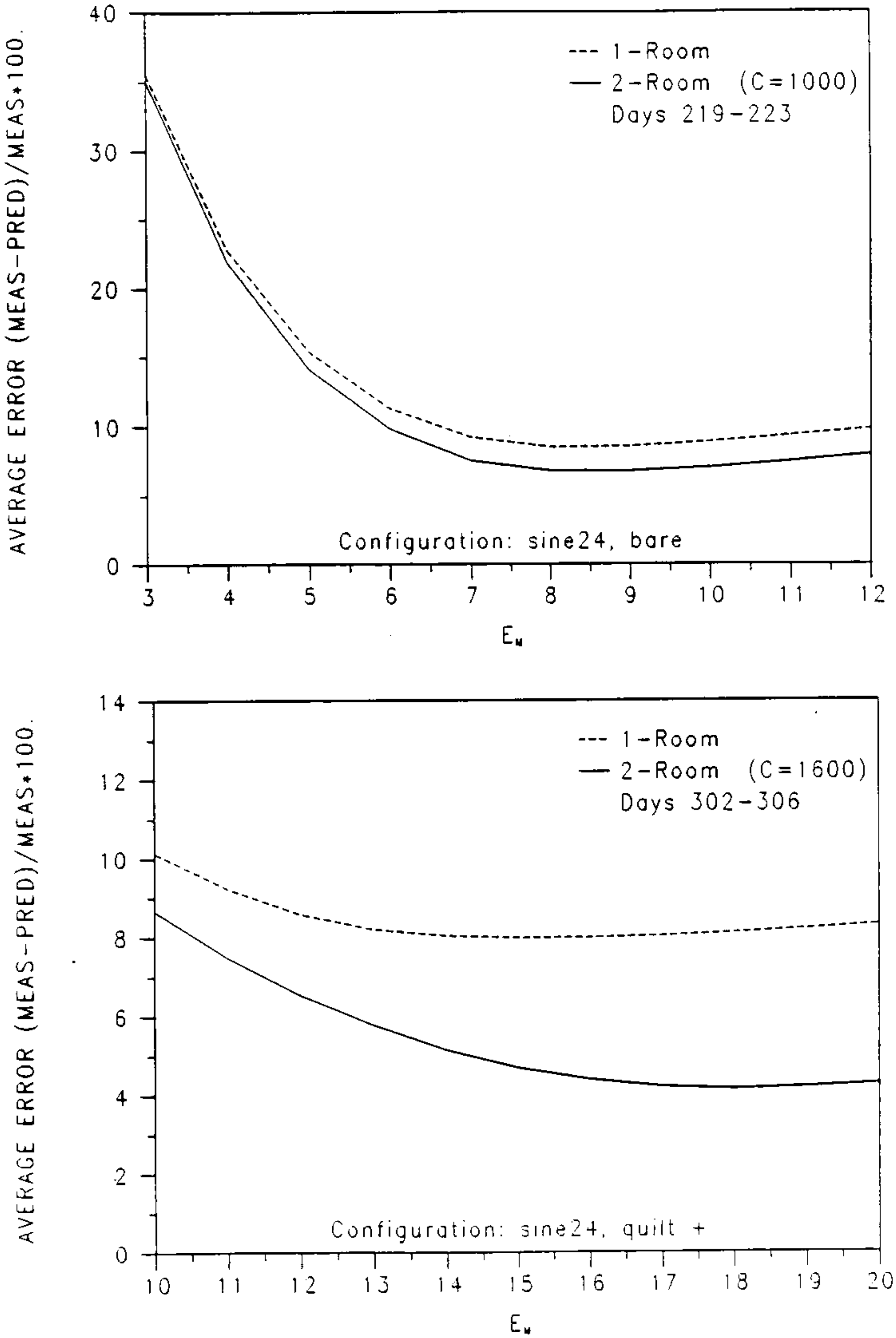


Figure 24. Average prediction error versus E_m value for two different five day periods by the 1-room and 2-room E_m models for a) sine24, bare and (b) sine24, quilt + experiments.

with the air. But this does not match reality. As was noted in Section V less than 50 percent of the total capacity is used when the building is exposed to alternating pulses of moisture on a 24 hour cycle.

How will the 1-room and 2-room models respond when the sinusoidal pulse is reduced from 24 hours to 12 hours? This can be seen in Figure 25. Because of the shorter exposure time the 1-room model amplitude is only 25 to 30 percent of the actual room air response. This corresponds well with results in Table 4 in Section V. The moisture adsorption in a 6 hour exposure (corresponding to one-half of the 12-hour cycle) can be seen to be about 8.0 liters, or about 28 percent of the four-day accumulation. While the 1-room model predicted only 25 to 30 percent of the amplitude of the Rh response, the 2-room model predicted the amplitude quite well and the one- to two-hour time lag was again eliminated.

The moisture transfer factor, C, was chosen by trial and error. Figure 26 shows that the prediction error is not a strong function of the moisture transfer rate assumed. For the bare configuration, from C = 1000 to 2000 kg/hour (airflow) yields average prediction error of only six percent. The best match of humidity ratio amplitude is provided by 1000 kg/hour (Figure 27). For the quilt + configuration C = 1600 to 2200 produces average prediction error of only 4.0 percent, and C = 1600 provides the best match of amplitude.

<u>Step-change Prediction of E_m Model</u>

The 2-room E_m model predicted changes in the room humidity ratio quite closely for the gradual changes experienced in the sinusoidal tests. How does it

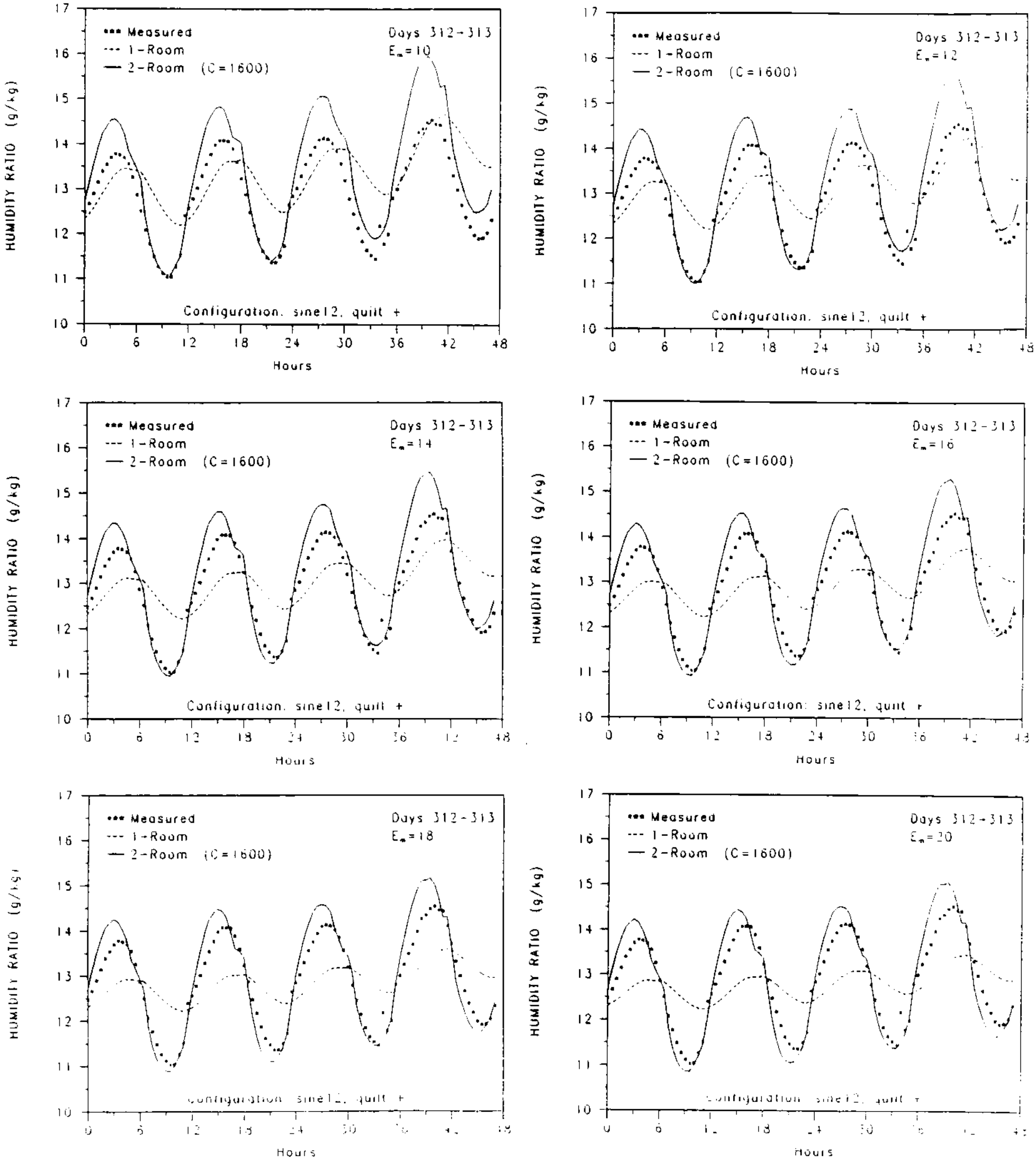
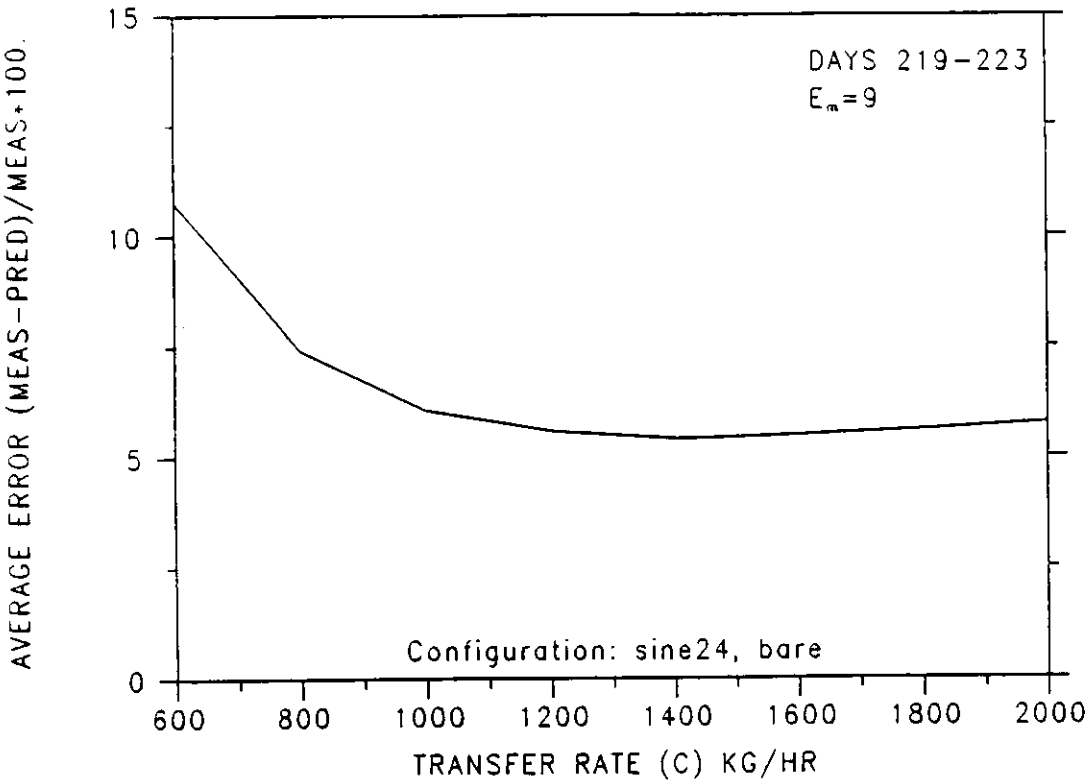


Figure 25. Predicted humidity ratio for a two day period by 1-room and 2-room E_m models for the sine12, quilt + configuration. Sinusoidal period reduced to 12 hours.



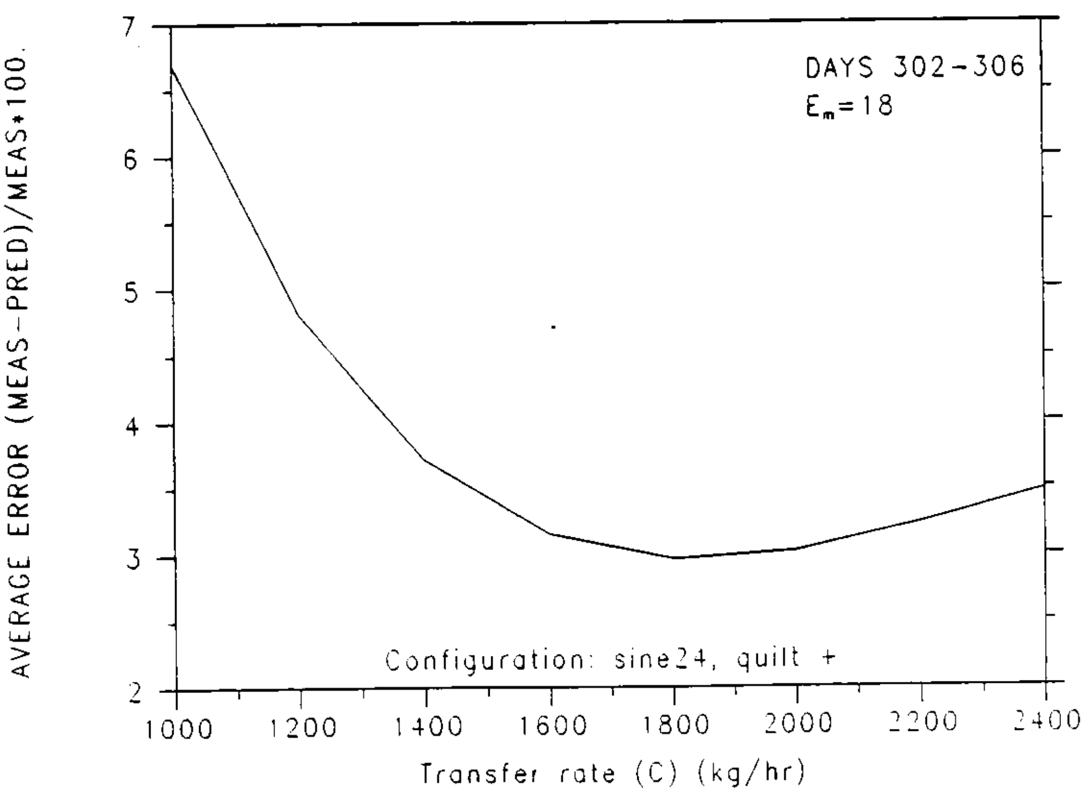


Figure 26. Average prediction error versus C (moisture transfer factor) for the 2-room model for a) sine24, bare and b) sine24, quilt + experiments.

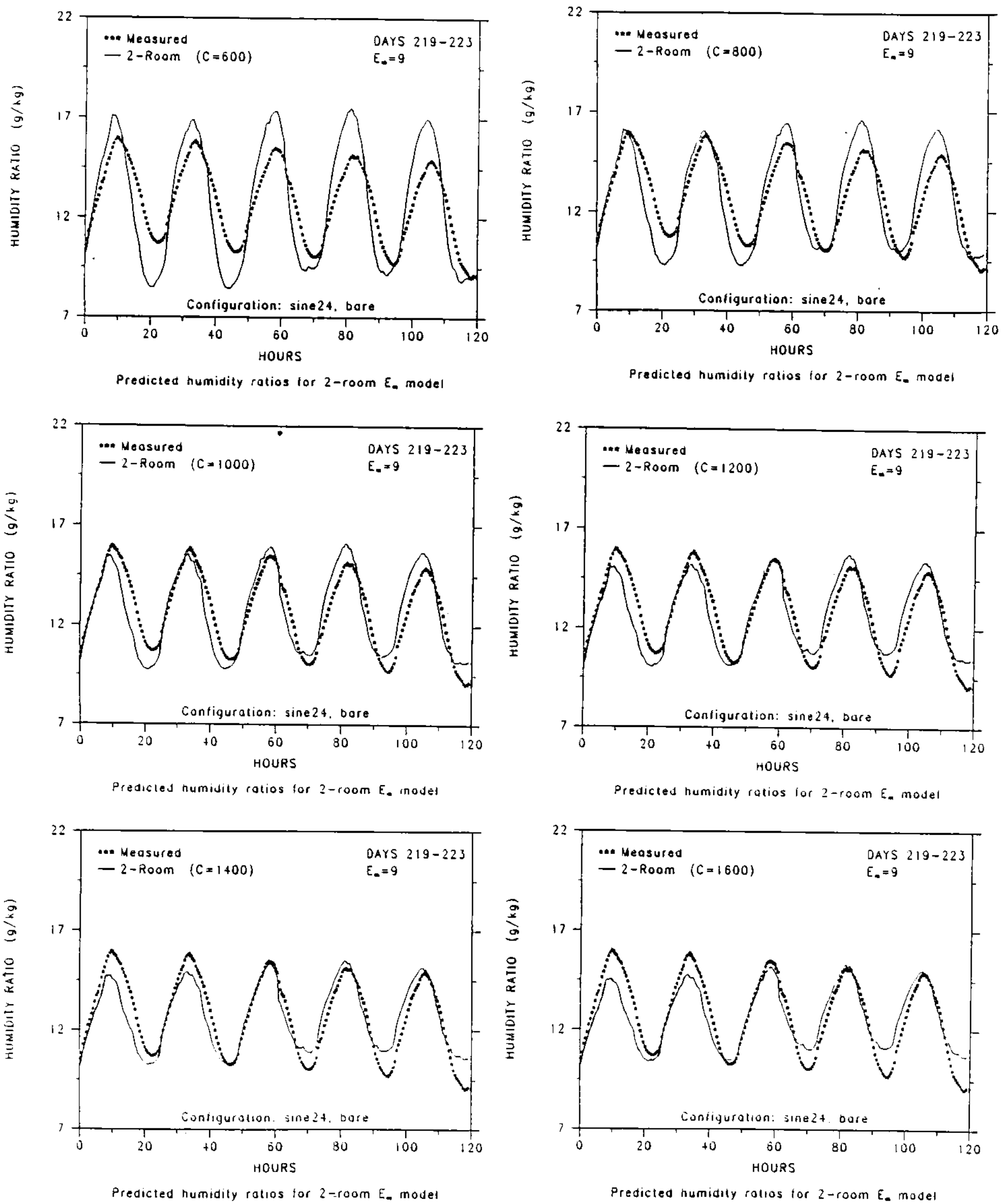


Figure 27. Predicted humidity ratio for the sine24, bare experiment by the 2-room E_m model for various moisture transfer rates (C = 600 to 1600 kg/hr).

responded to a situation of rapid change in humidity ratio, such as the step-change experiments. Figure 28 shows the predicted W_r for various transfer rates for a step from 15 to 20°C dewpoint (55 to 70 percent RH and 25.6° dry-bulb temperature). While the actual dewpoint temperature rises rapidly to 19.5°C in two hours, the 1-room model takes many hours. The 2-room model, however, responds much more quickly, but it seems to overshoot W_r in the first couple hours after the step-change. This suggests that the moisture transfer rate is variable and is much greater at first and then diminishes.

The concept of a variable moisture transfer rate is quite plausible. If we think about the materials that adsorb the moisture, there is a large surface area (carpet fibers and gypsum surface) which can readily receive moisture. After the initial adsorption, additional moisture transfer becomes dependent upon moisture migration deeper within the materials. This internal moisture transfer rate should be much slower. In the case of carpet, the upper carpet fibers may quickly come to equilibrium while the lower fibers, the jute backing, and the carpet pad may receive moisture much more slowly. In the case of the gypsum the outer surface may adsorb moisture rapidly while the internal moisture transfer rate carrying the wave of moisture through the complete gypsum thickness may be much slower. Additionally, the transfer rate to the surface is dependent on $W_r - W_s$ (W_s is surface air humidity ratio) which is initially high. When W_s increases, delta-W decreases. When a variable moisture transfer rate is used ($C = f(W_r - W_f)$ where W_f is the W of the "air" representing the furnishings) the overshoot of the room humidity ratio largely disappears (Figure 29).

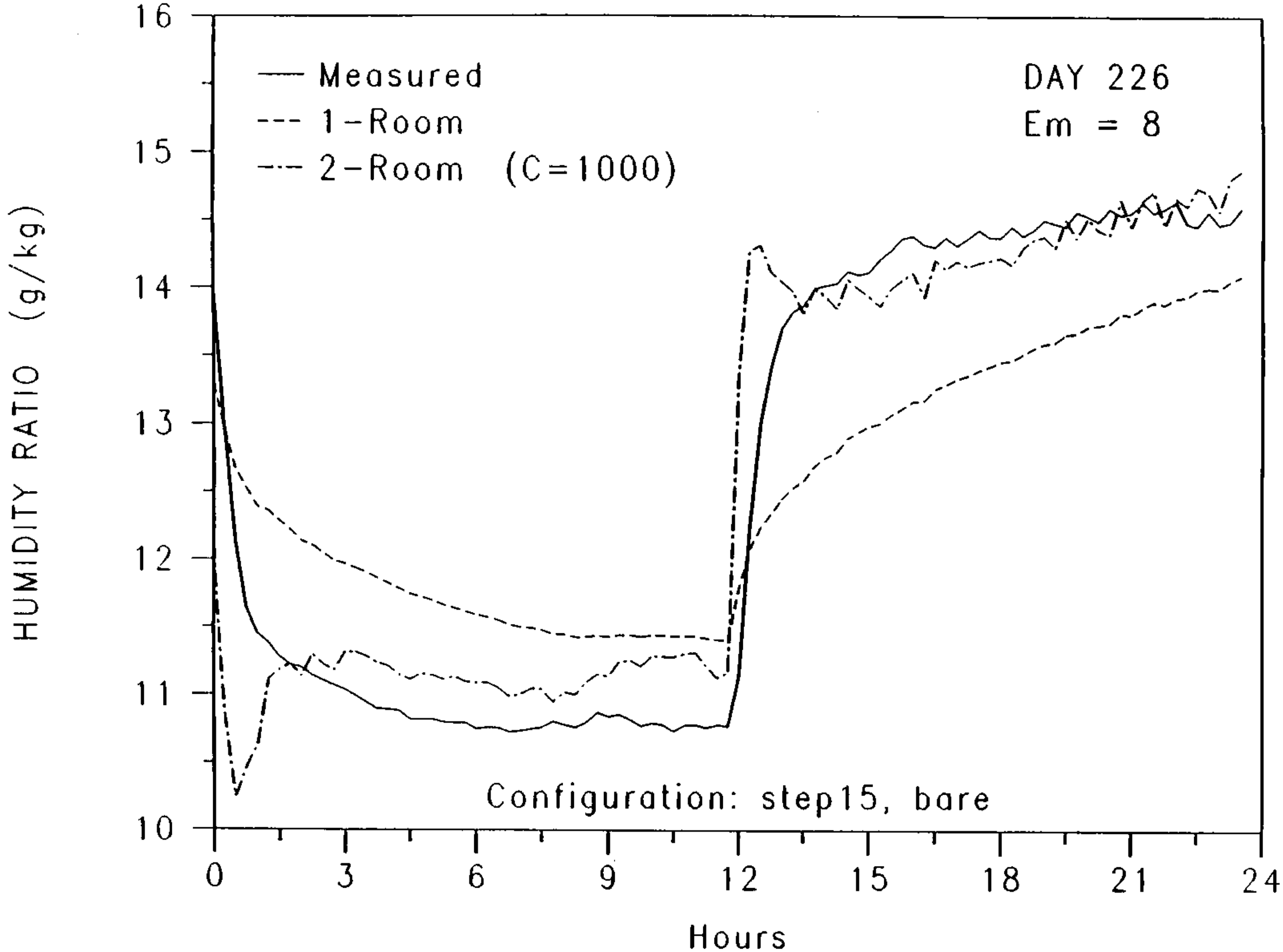


Figure 28. Predicted humidity ratio for one day of step change from 55 to 70 percent RH at 25.6°C for 1-room and 2-room E_m models for step15, bare.

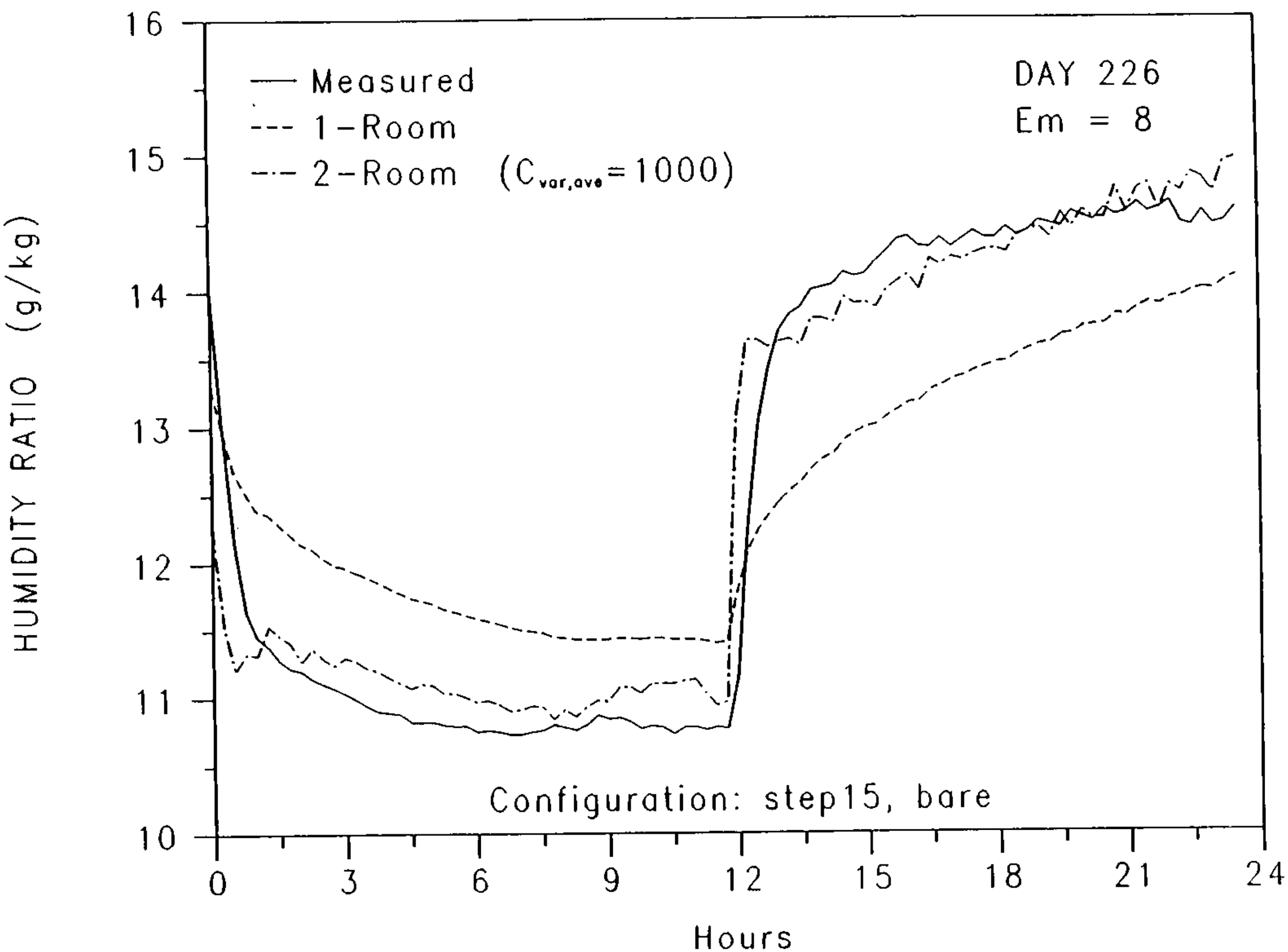


Figure 29. Predicted humidity ratio for one day of step change from 55 to 70 percent RH at 25.6°C for 1-room and 2-room E_m models for step15, bare when moisture transfer rate is a function of moisture flux rate.

The E_m model does not predict sudden RH changes with as much accuracy as the more gradual RH changes of the sinusoidal pulses. When five days of step-change are modeled the minimum prediction error is about six percent for the 2-room model and five percent for the 1-room model. These results are shown in Figure 30 for E_m = 4, 6, 8 and 10.

Off-peak Cooling Prediction

The off-peak cooling concept, as was explained in the introduction, is designed to reduce air-conditioning loads during the peak demand period of the electric utility. In this experiment the AC set points were changed according to the following time-table:

	Dry-bulb setpoint	Relative Humidity					
		"bare"			"quilt"		
		min.	max.	ave.	min.	max	ave.
7:00 P.M. - 8:00 A.M.	25.6°C	61	69	66	63	69	66
8:00 A.M. - 2:00 P.M.	24.0°C	61	64	62	63	66	65
2:00 P.M. - 7:00 P.M.	no AC	65	68	67	67	73	70

During the period from 2:00 P.M. - 7:00 P.M. the air dry-bulb temperature "floats" upward typically to 82°F. E_m model prediction of a day of off-peak cooling is shown in Figure 31. During the afternoon floating period the model under-estimates W_r by as much as 3.0 g/kg. When the peak humidity actually reaches 69 percent, the predicted peak RH is only 57 percent for the 2-room model and 56 percent for the 1-room model. The problem is that during this floating period, only a relatively small amount of imposed moisture produces a large increase in the room air humidity ratio. For example, on September 6, 1987 (J.D. 249) from time 2:00 to 7:00 P.M. the cumulative imposed moisture (from internal generation, infiltration, and evaporation from the AC coil while the AC blower was on) was 4.290 kg. During this period W_r increased

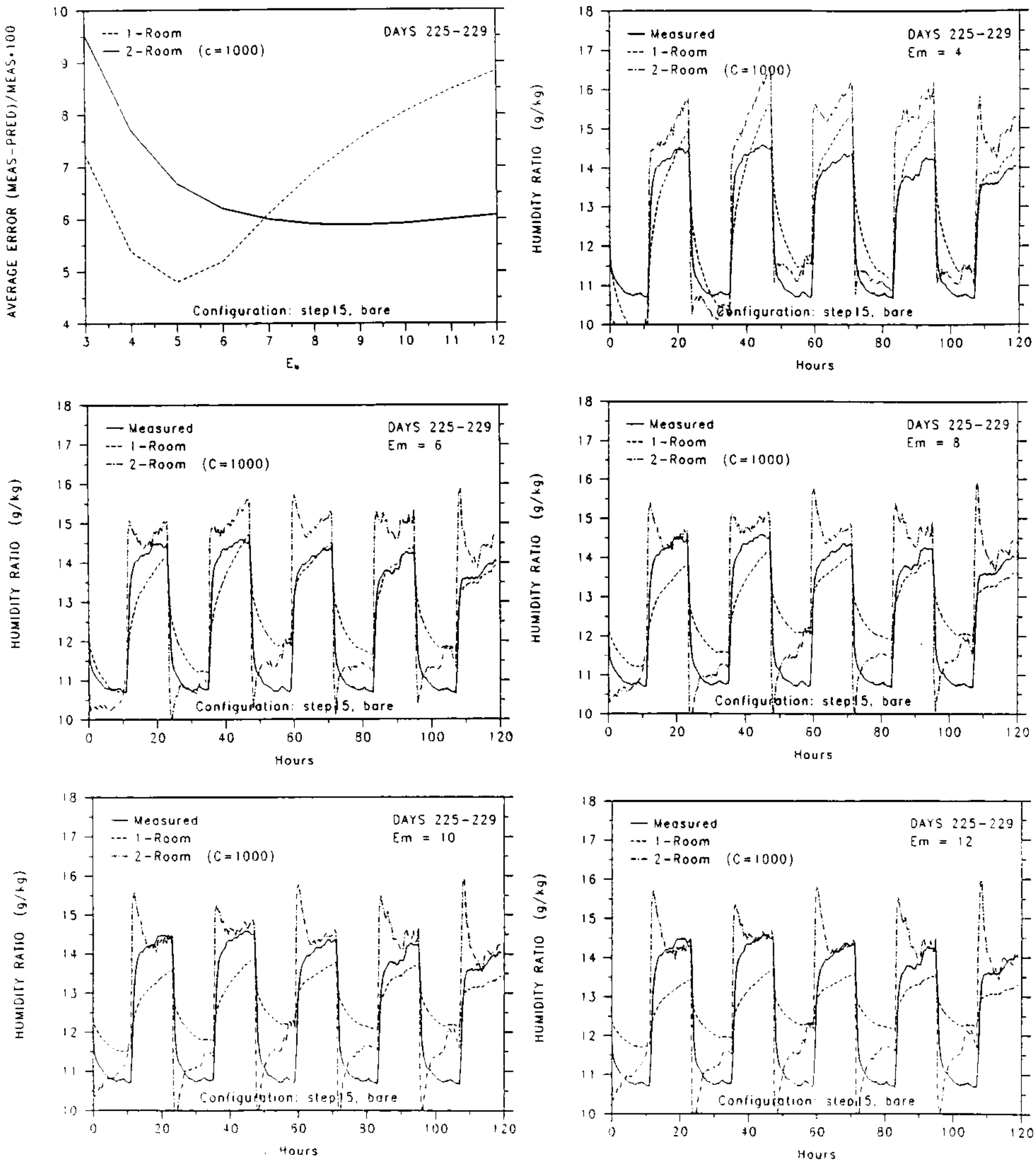


Figure 30. Error analysis and predicted humidity ratio for a five day period of step 15, bare experiment by 1-room and 2-room E_m models.

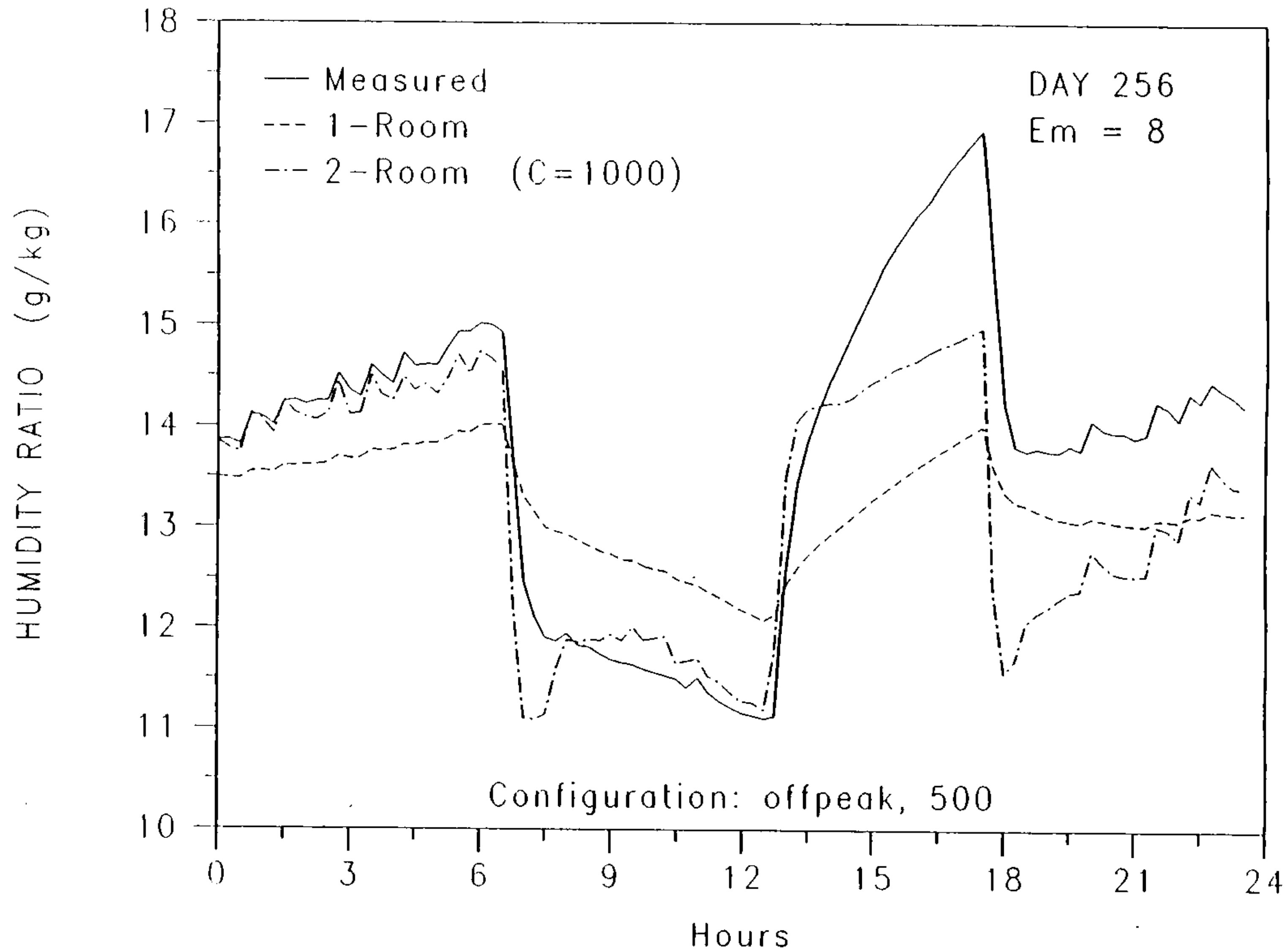


Figure 31. Predicted humidity ratio for one day of off-peak cooling for 1-room and 2-room E_m models for bare configuration.

from 11.50 g/kg to 16.35 g/kg. From this we can calculate that the room air absorbed 1.731 kg of the total 4.290 kg of water, or 40 percent of the imposed moisture. Only 2.559 kg of water went into the furnishings, indicating an E_m of 2.5. If the effective E_m had been about 5.0 (as we have found for the bare configuration when the dry-bulb temperature is constant) the furnishings would have adsorbed 4/5ths of the moisture and the humidity ratio would have risen to only 13.9 g/kg. This is 60 percent RH instead of 69 percent which actually occurred. In summary, the problem is that as the temperature rises the ability of the air to hold moisture increases while the ability of the materials to hold moisture decreases.

What is the cause of this change in the moisture storage capacity of the building/furnishings during periods of rising dry-bulb temperature? The answer lies in the change in RH produced by the rise in dry-bulb temperature. When the AC was turned off at 2:00 P.M. the dry-bulb temperature and RH were 24.0°C (75.0°F) and 61 percent, respectively. The rapid rise in temperature to 27.5°C (81.5°F) would have lowered the RH slightly to 60 percent if only 1/5th of the imposed moisture was stored in the air. Since RH is the determining factor for moisture content of materials, the furnishings (should desorb) at this lowered RH. Thus, the room air RH had to increase to a level where the furnishings could adsorb more moisture. The E_m model could not account for the change in the moisture transfer potential because it uses the difference of humidity ratio between the two rooms (the room air and the furnishings "air") to calculate moisture transfer. To model this floating period correctly, or any period in which the dry-bulb temperature is changing, the E_m model will need to be modified to calculate moisture transfer between air and furnishings based on delta-RH rather than delta-W. These modifications have not been attempted at this time.

Modelling When AC Moisture Removal is Characterized

Modeling of the room humidity ratio, to this point, has been done with measured AC moisture removal. That is, for each 15-minute period we know the dewpoint temperature entering and leaving the coil and the on-time of the AC unit. The actual moisture removal is calculated by:

$$MOIST = (W_{coil,in} - W_{coil,out}) * m * TIME$$

Infiltration moisture has been calculated based on the measured infiltration rate and the <u>measured</u> (rather than predicted) room humidity ratio. Thus, in our modeling we have known everything, all flows of moisture into and out of the space, and the only unknown has been the moisture storage capacity of the building/furnishings. This has been a useful exercise because it showed sensitivity to the variable of moisture storage capacity. The model's prediction of whole-building moisture capacitance agreed well with other assessments made in Section V.

However, when buildings are actually modelled, the measured AC moisture removal is not usually known. It is calculated based on characterization of a specific AC unit. Infiltration, also, is calculated based on characterized infiltration rates (from wind speed and direction) and the predicted room humidity ratio. The importance of this is that when characterized AC moisture removal is employed, and the infiltration moisture calculation is based on the predicted W_r, these two tend to self-correct errors in the predicted W_r produced by an inaccurate moisture capacitance assumption. For example, if moisture capacitance is assumed to be $E_m = 1$ (only the air stores moisture), then predicted W_r will be much too high during a period of positive moisture imposition. The AC model will "see" a very high wet-bulb entering the coil and thus the AC characteristics will remove a larger amount of moisture. Thus, W_r may be predicted fairly closely but the moisture removal by the AC will be overpredicted quite a bit. Likewise, the infiltration moisture influx will be reduced because predicted W_r is high. These two calculations will have the effect of reducing the over-prediction of W_r caused by the inaccurate moisture storage capacity.

So, when AC and infiltration moisture are calculated in this fashion, how important is the moisture storage capacity to the correct prediction of W_r and the moisture removal by the AC? To answer this question, characterization of the AC unit at Rangewood Villas was done. For each experiment period, a correlation of $W_{coil,out}$ versus $W_{coil,in}$ was developed. A typical curve is shown in Figure 32. The results of modeling with this characterization follow.

Modeling the Sinusoidal Experiments

Previously the 2-room E_m model provided excellent prediction accuracy when measured AC and infiltration fluxes were used (call this "everything known"). The average prediction error for five days was as low as seven percent. The 1-room model predicted with as little as nine percent error. When the AC moisture removal is characterized and the infiltration moisture is calculated from $W_{r,predicted}$ (call this "characterized"), then the following changes occur for the 2-room model.

1. the minimum average prediction error declines from 7 to 1.5 percent
2. the E_m providing the best match is somewhat lower, 6 compared to 9 when everything is known.
3. the amplitude of the sinusoidal response is dampened for high E_m values.

Figure 33 shows prediction error and plots for various E_m values for the 2-room model. For smaller E_m values the amplitude of the RH swings is dampened,

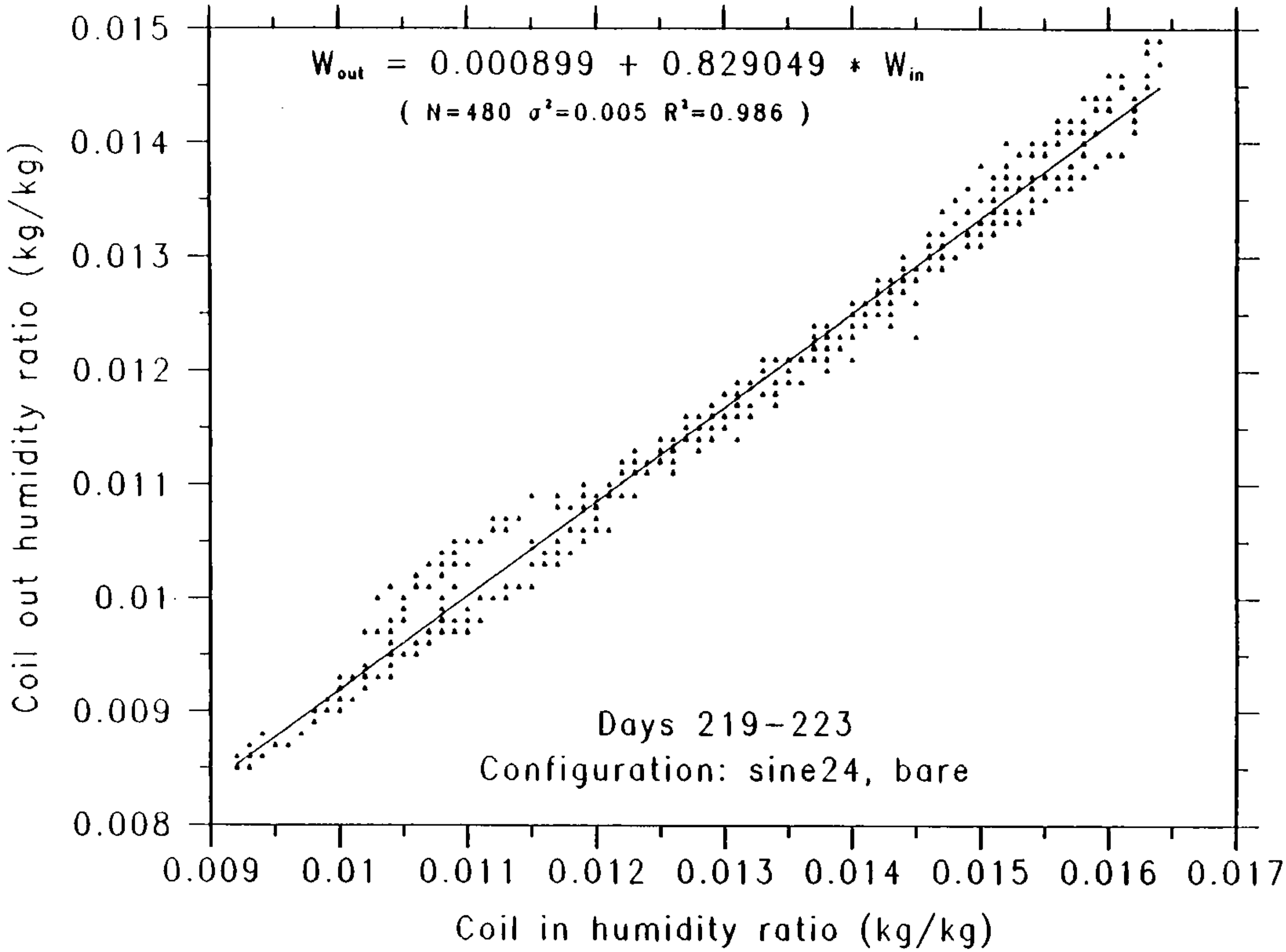


Figure 32. Correlation of humidity ratio into and out of coil for the air conditioner at Rangewood Villas

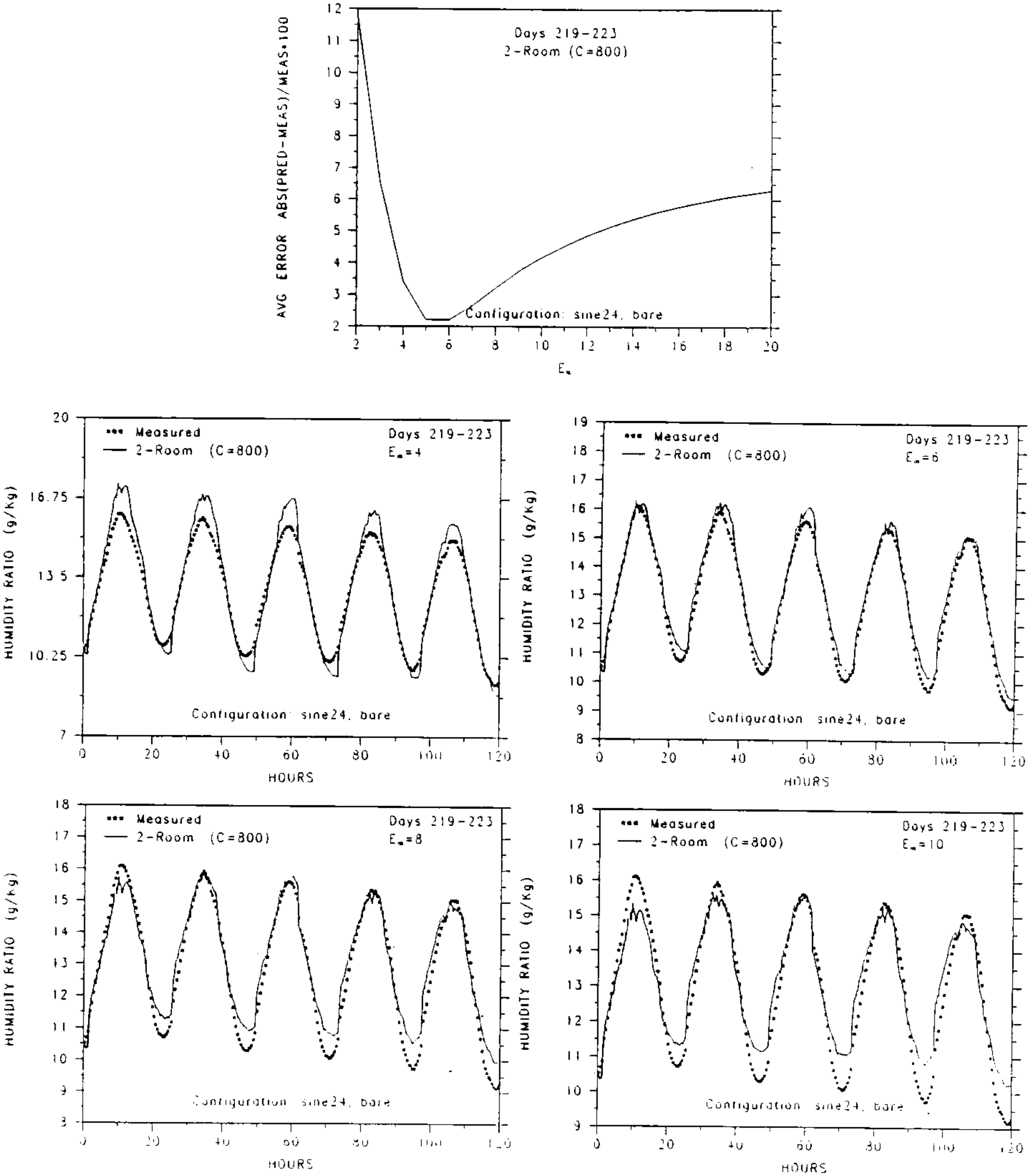


Figure 33. Error analysis and predicted humidity ratio plots for sine24, bare configuration for the 2-room E_m model. AC and infiltration "characterized".

as expected, because of the previously discussed self-correcting nature of the characterized modeling approach. The accuracy of the model is remarkably good, 1.5 percent average error.

Figure 34 shows results for the 1-room model. Previously the 1-room model, with everything known, had an average error of nine percent, and an E_m of nine provided the best fit. Now the average error is reduced to six percent and E_m = 4 or 5 is the best match. The explanation for the difference in Em is that the upward drift of the predicted W_r (Figure 27) when everything is known (caused by underprediction of moisture storage) is eliminated by the self-correcting nature of the "characterized" approach. Inaccuracy in the amplitude of the room humidity ratio response is now the chief source of error. It can be also noted that the time of one or two hours is still present with the 1-room model. This time lag is eliminated in the 2-room model.

Prediction for the high moisture and thermal configuration (quilt +) is shown in Figure 35 (2-room model). The minimum error is five percent for E_m values from 10 to 20, while it was about four percent for everything known. The best match of amplitude of RH(W_r) is E_m = 10, while when everything was known the best match of amplitude was E_m = 14. Again it can be observed that moisture capacitance of Rangewood Villas increases on the last two days, when the RH range increases from 40-55 percent to 55 to 70 percent. The nonlinear isotherm for grade 59 silica gel (Figure 12) is the reason for this. At the higher RH range the capacitance is twice as high as at the lower RH range.

Figure 36 shows the results for the 1-room model. The minimum error is about nine percent, while it was 7.8 percent for everything known. The amplitude

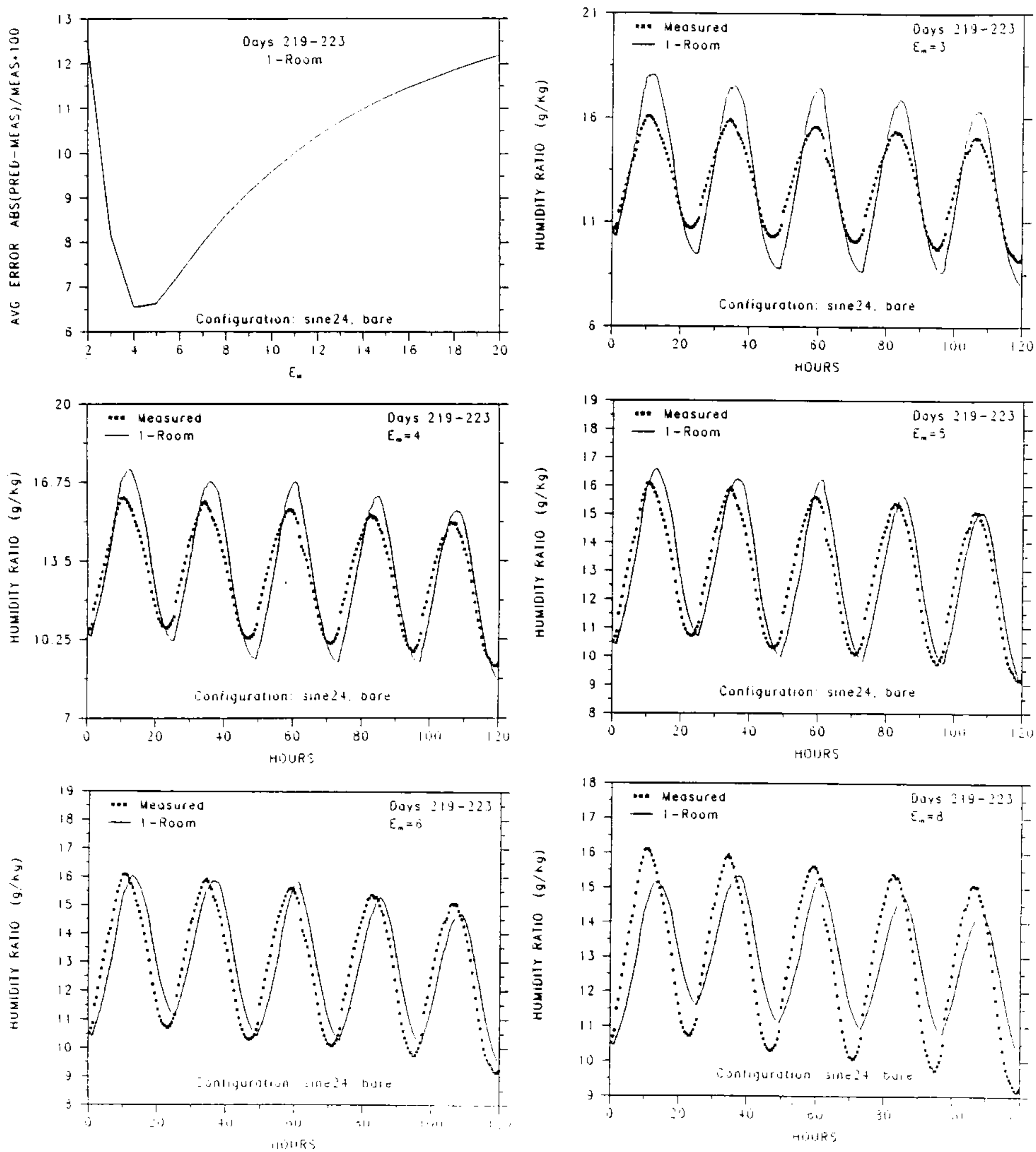


Figure 34. Error analysis and predicted humidity ratio plots for sine24, bare configuration for the 1-room E_m model. AC and infiltration "characterized".

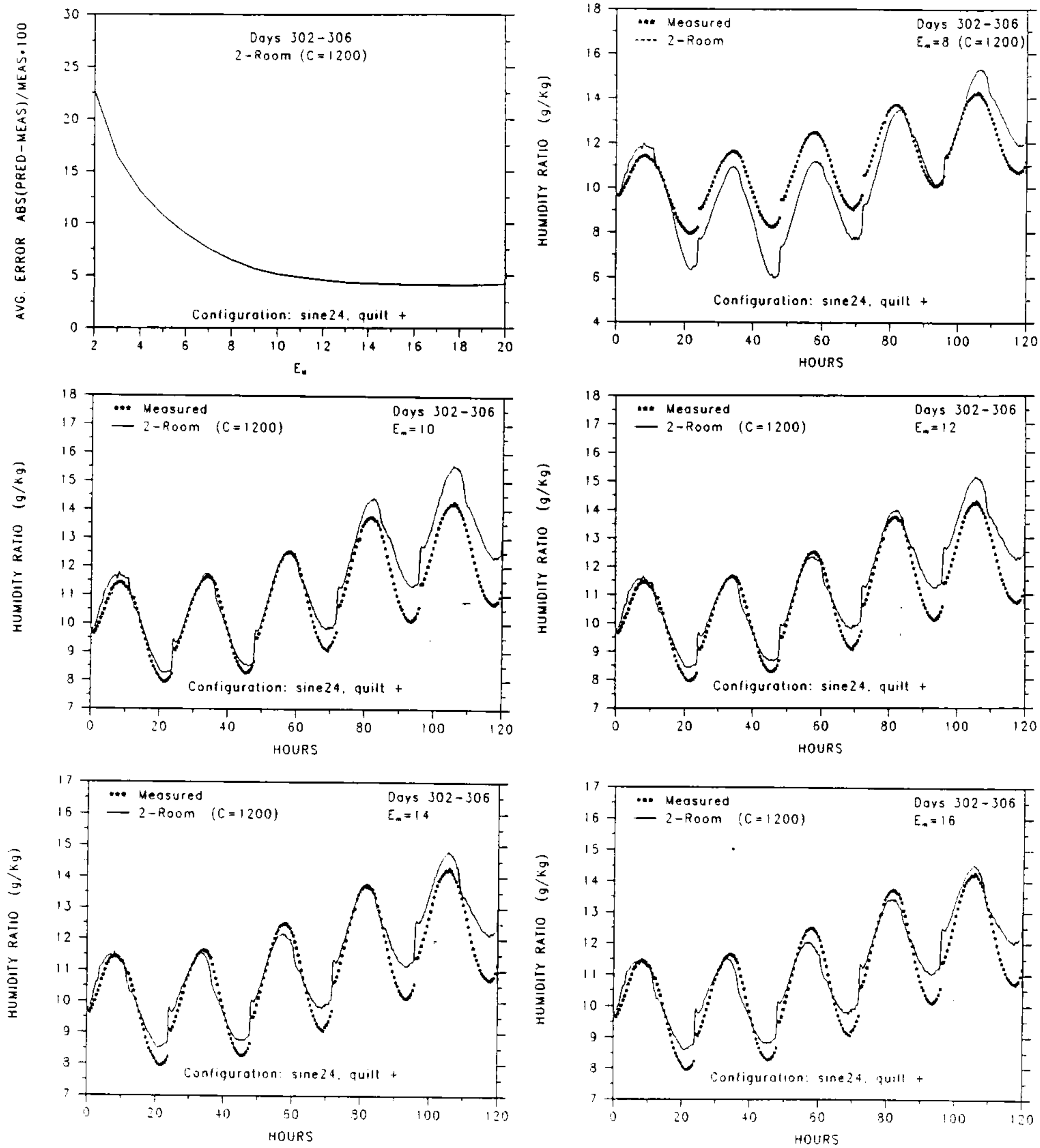


Figure 35. Error analysis and predicted humidity ratio plots for sine24, quilt + configuration for the 2-room E_m model. AC and infiltration "characterized".

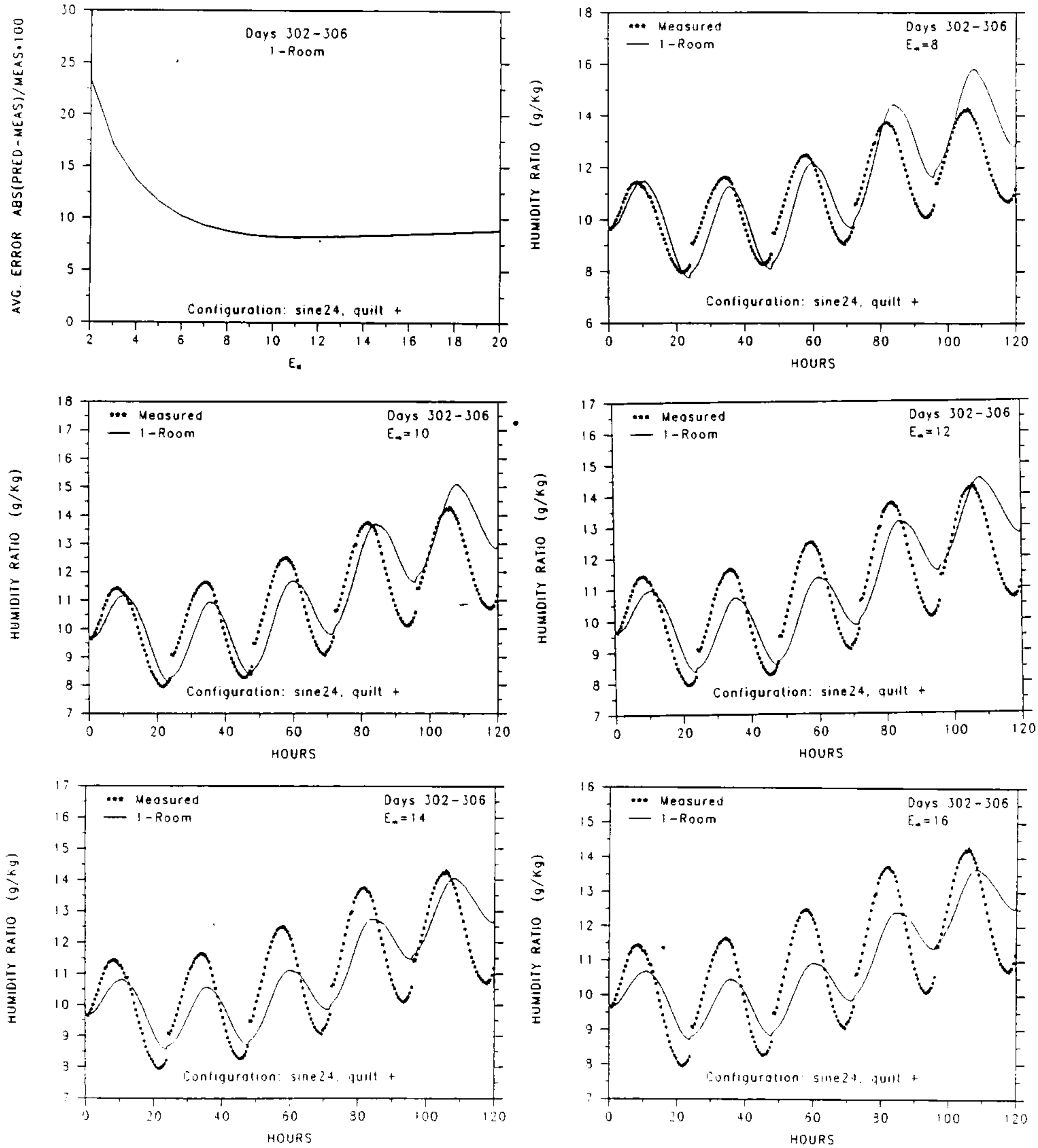


Figure 36. Error analysis and predicted humidity ratio plots for sine24, quilt + configuration for the 1-room E_m model. AC and infiltration "characterized".

response is best for $E_m = 8$. The time lag of one or two hours is still evident. The reason why the error rises for high capacity and drops for low capacity is not known.

The moisture transfer rates used to this point for the 2-room model have been C = 1000 and C = 1600 for the bare and quilt + configurations, respectively. Figure 37 shows that for the bare configuration C = 800 kg/hr produces the least error for $E_m = 6$ and $E_m = 8$. For the quilt + configuration, C = 1000 or C = 1100 produces the least error (Figure 38). For characterization, therefore, the moisture transfer factor, C, is 20 to 35 percent lower. This is not surprising because smaller values of C produce larger RH amplitude, and this counteracts the tendency for the characterized model to dampen the amplitude of RH change.

<u>Modeling the Step Change</u>

Step-change of RH between 55 and 70 percent each 12 hours has proved difficult to predict. When everything was known the least error was 8.5 percent with the 2-room model. When "characterized" the least error is 3.4 percent at an E_m of 5 (Figure 39). The prediction of humidity ratio is quite good, though it underestimates the high W_r for a period of several hours. Unlike the "everything known" approach, it does not overshoot the RH at the first part of each RH change.

The prediction for the 1-room model is shown in Figure 40. The least error is 7.8 percent at $E_m = 4$ and the best match of amplitude is $E_m = 5.0$. However, this model cannot respond to the rapid RH rise because of its assumption of instantaneous moisture transfer into the furnishings.

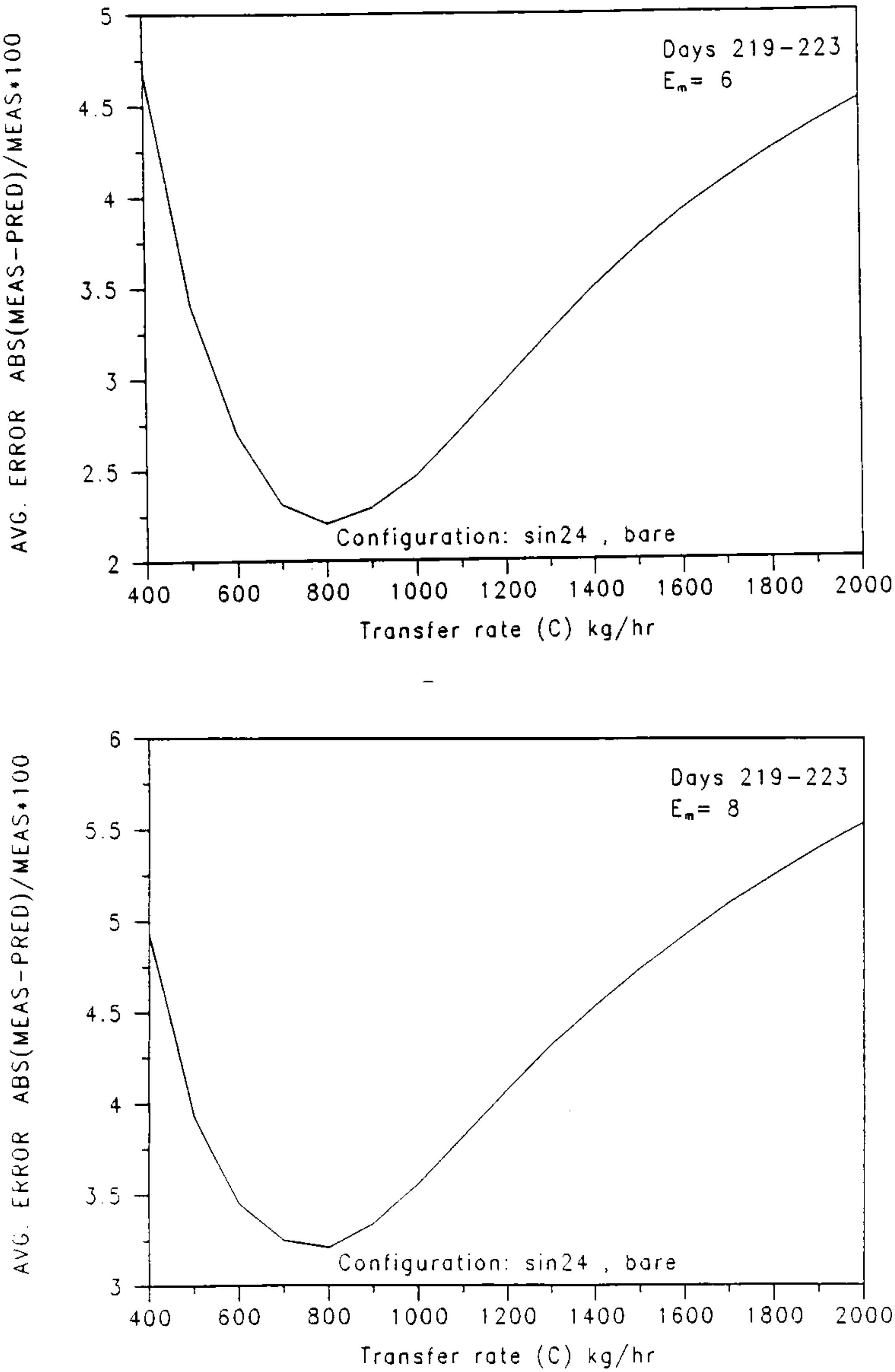


Figure 37. Error analysis for various moisture transfer factors (C) for sine24, bare configuration for the 2-room E_m model. AC and infiltration "characterized".

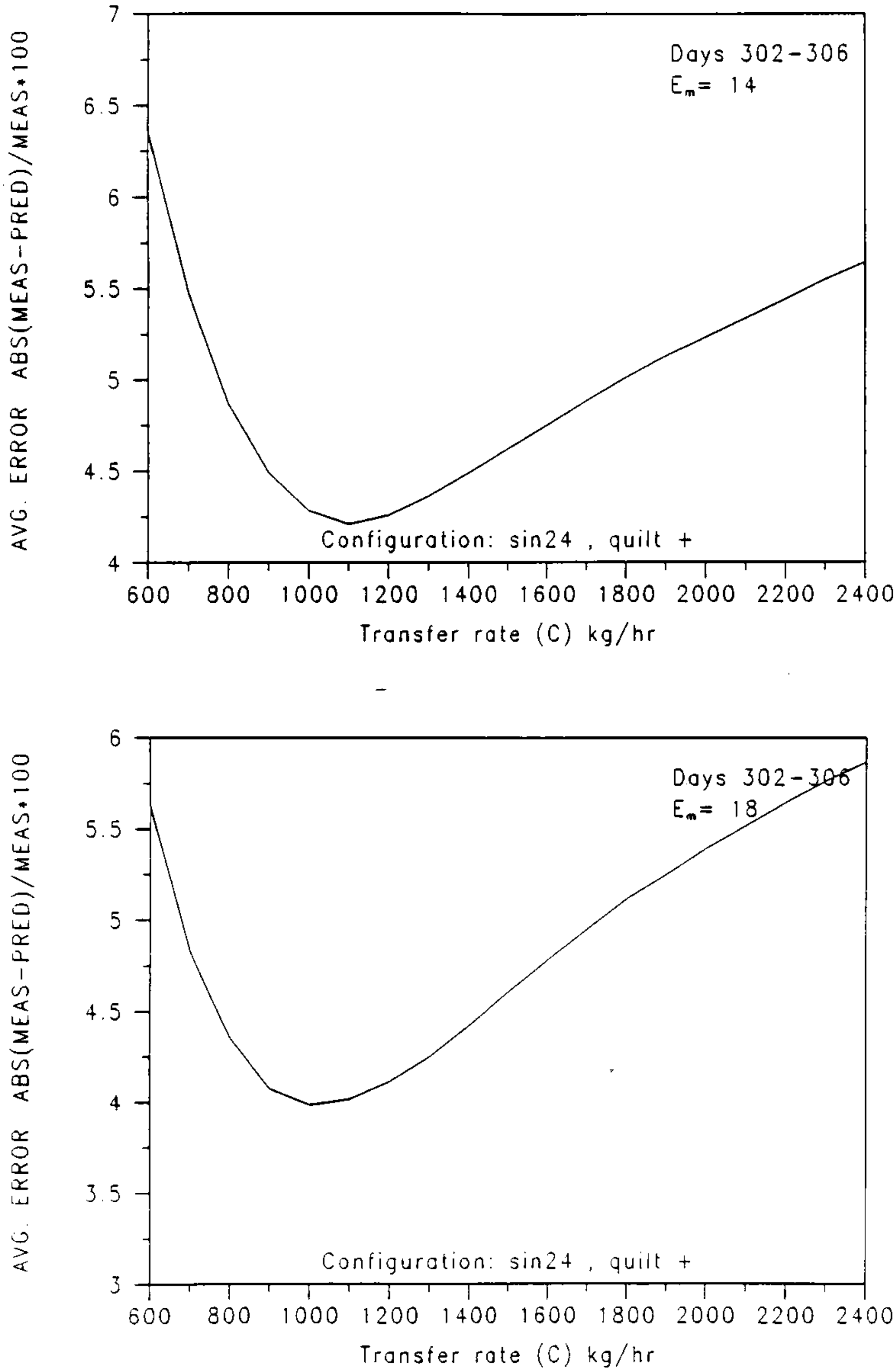


Figure 38. Error analysis for various moisture transfer factors (C) for sine24, quilt + configuration for the 2-room E_m model. AC and infiltration "characterized".

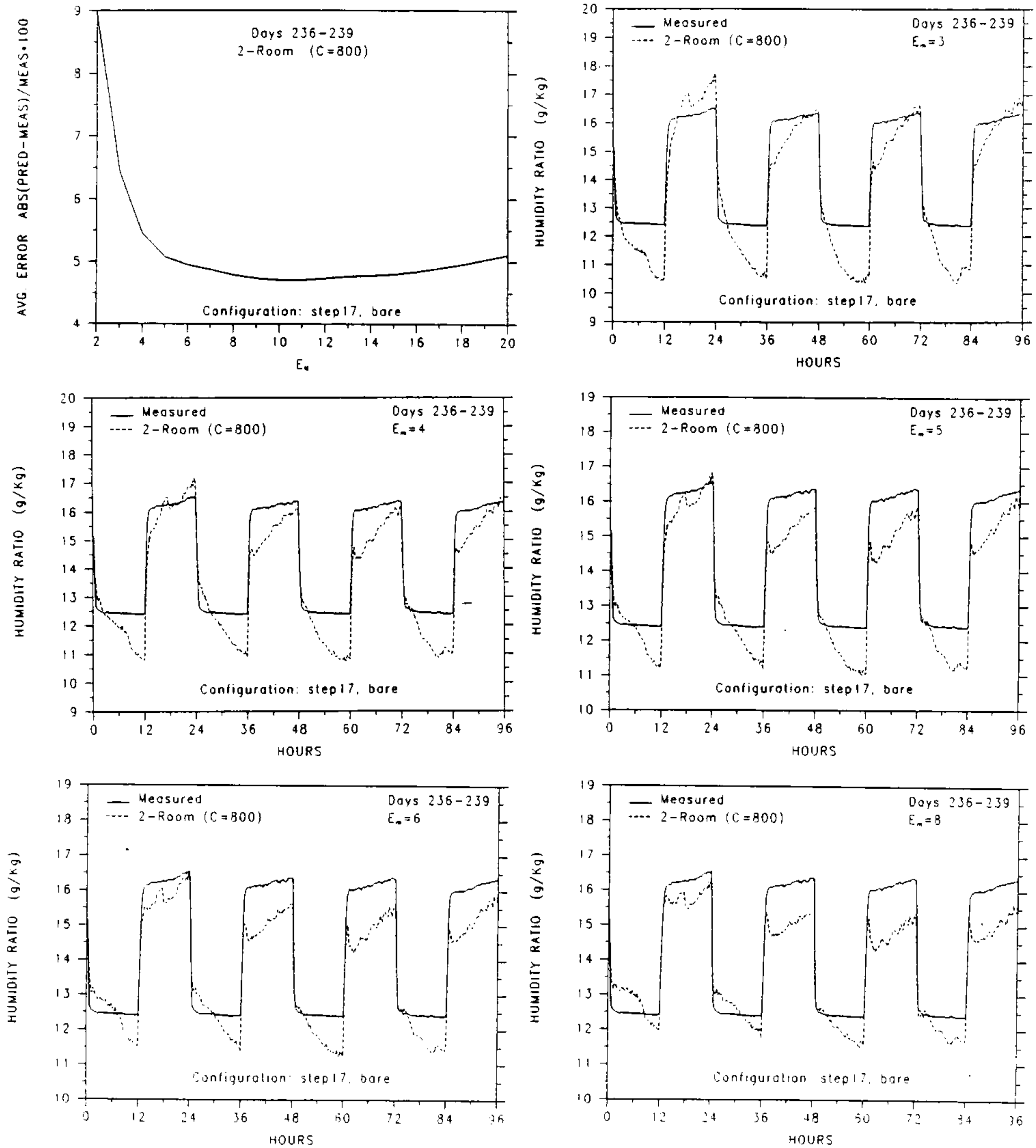


Figure 39. Error analysis and predicted humidity ratio plots for step17, bare experiment for the 2-room E_m model. AC and infiltration "characterized".

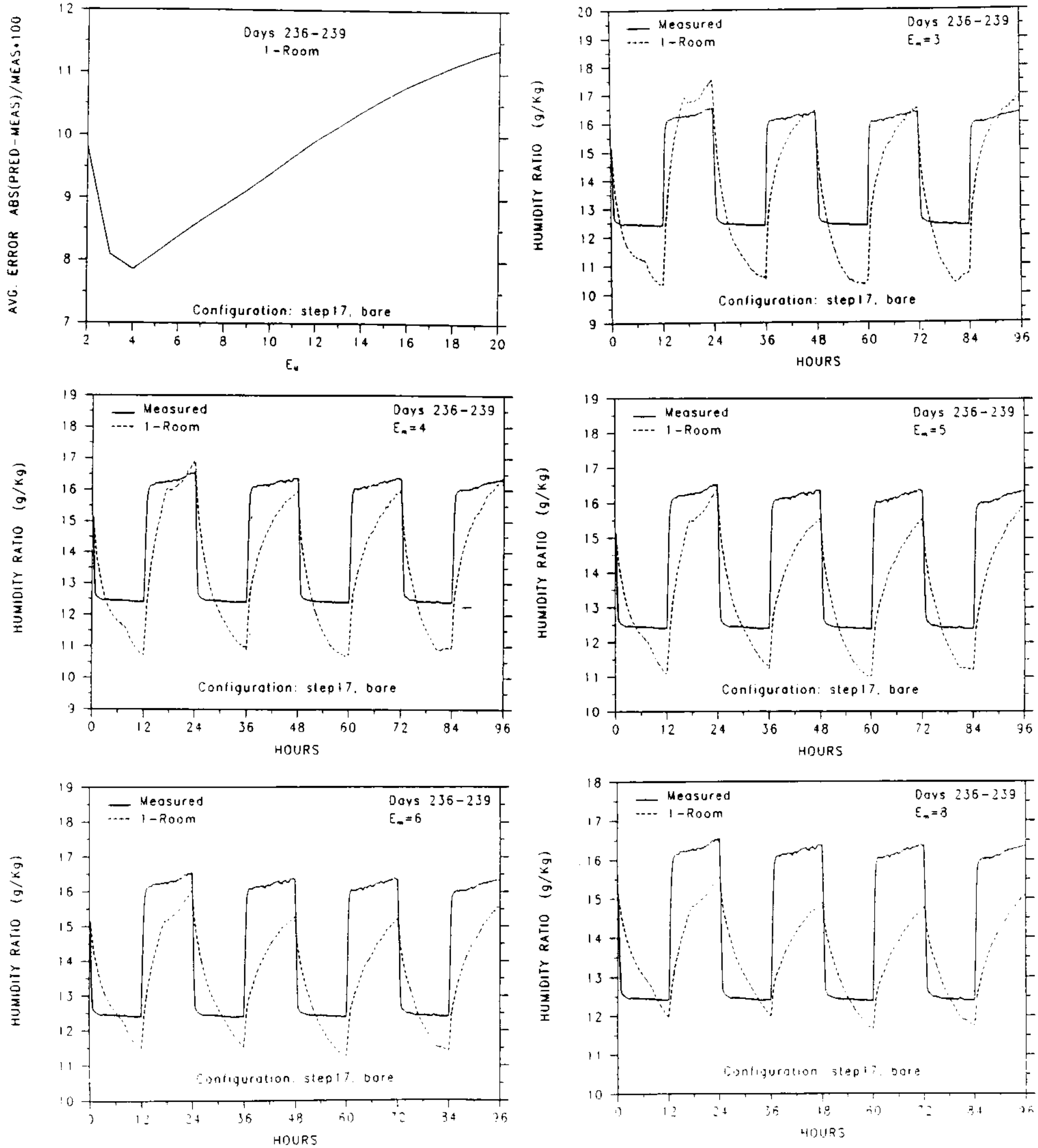


Figure 40. Error analysis and predicted humidity ratio plots for step17, bare experiment for the 1-room E_m model. AC and infiltration "characterized".

Modeling the Off-Peak Experiment

Modeling the off-peak experiment is a problem, as was previously discussed, because of the changing dry-bulb temperatures. From 8:00 A.M to 2:00 P.M the room temperature is depressed (24.0°C) and W_r is overpredicted (Figure 41). From 2:00 P.M. to 7:00 P.M. the room temperature rises from 24.0°C to about 28.0°C and W_r is underpredicted. However, during the periods when the room is at 25.6°C, the 2-room E_m models predicts superbly (E_m = 8 and 10). The overall prediction error is 4.9 percent, but the inability of the model to accurately predict the crucial "floating" period means that in its present form it cannot correctly assess whether comfort conditions exist for innovative cooling concepts. It appears that this problem with the E_m model could be corrected by making moisture transfer between air and furnishings to be a function of delta-RH rather than delta-W. This modification has not been attempted at this time.

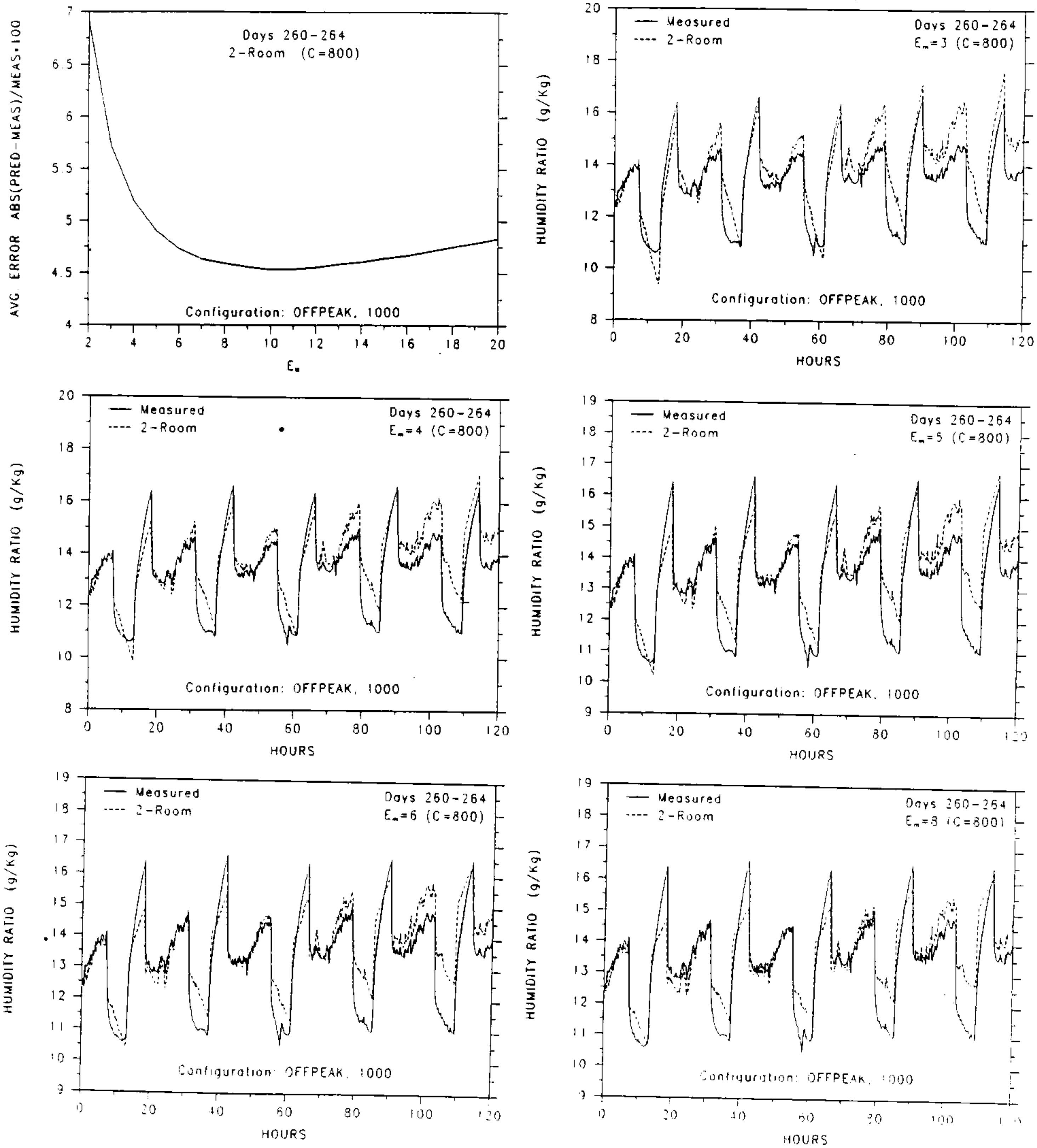


Figure 41. Error analysis and predicted humidity ratio plots for the off-peak, 1000 experiment for the 2-room model for various E_m values. AC and infiltration "characterized".

VII. CONCLUSION

Building materials and furnishings adsorb and desorb moisture in response to changes in relative humidity. A series of tests were performed at a townhouse (Rangewood Villas) to carefully monitor the impact of moisture storage capacity. These tests demonstrated that the effective moisture storage capacity of the low capacity configuration (carpet but virtually empty of furnishings) was about nine times the moisture storage capacity of the air alone, within the range from 40 to 80 percent RH. It appears to require three to four days for equilibrium between air and building to be approached. In a 12 hour exposure the effective storage capacity was about five times that of air. Thus, only about 50 percent of the total capacity is put to use in a diurnal cycle.

The building was reconfigured with high moisture and thermal capacity by introducing 345 kg of grade 59 silica gel and 1000 1-gallon jugs of water. In this configuration the total moisture storage was about 20 times that of the air. In a 12 hour exposure the moisture storage was about nine times that of air. Thus, less than 50 percent of the total capacity is put to use in a diurnal cycle.

A simple moisture capacitance model is presented, the effective air mass moisture capacity model (E_m). It is proposed in two forms, the 1-room and 2-room E_m models. The E_m model treats the furnishings as if they were a large volume of air, that is, with the same moisture storage characteristics of air. In the 1-room E_m model the room air is completely mixed with the "furnishings air". It has the drawback that moisture transfer between air and furnishings is assumed to be instantaneous. For this reason it does not correctly model the full amplitude of room air humidity ratio change and has a characteristic time lag from the measured data. In the 2-room model where the "furnishings air" is separated from the room air, moisture transfer between the two rooms is transacted by means of a moisture transfer factor, C, which in the model is an air mass transfer rate between the two rooms (e.g., C = 1000 kg/hour). For the sinusoidal experiment the 2-room model is able to predict the full amplitude of the RH response and it eliminates the time lag associated with the 1-room model.

Prediction of rapid changes in RH (step change) is not as good. The 1-room model cannot track this rapid change well (because of its assumption of instantaneous moisture transfer). The 2-room model can respond quickly to the change, but is not fully accurate because it tends to under-shoot or over-shoot the RH.

The E_m model has prediction difficulties for the off-peak cooling experiments. When the room dry-bulb temperature drops, it overpredicts room RH. When the room temperature rises, the model underpredicts room RH. The reason is that changing temperatures change the moisture capacity of the materials (because RH is changed). It is suggested that the E_m model could be improved by having moisture transfer between air and furnishings to be a factor of delta-RH rather than delta-W.

Modeling was done with measured data. All moisture fluxes into and out of the building (except for diffusion through the envelope) are known: infiltration moisture, generated moisture, and AC moisture removal. The only unknown was the moisture capacity of the furnishings. It was decided that since modeling of buildings does not generally have all these parameters known, that modeling should be done using characterized AC performance (moisture removal) and infiltration moisture calculated based on W_r, predicted rather than W_r, measured. Both of these tend to provide self-correction of prediction errors resulting from an inaccurate moisture capacity assumption. When modeled this way, it was found that knowing the correct moisture capacity was not quite as important to correct humidity ratio prediction, but it was still found to have a major impact.

Off-peak cooling and DESRAD experiments were also performed (descriptions in Section V). In the off-peak experiment the room dry-bulb temperature was lowered to 24.0°C (75°F) from 8:00 A.M. until 2:00 P.M. to sub-cool the space. The air conditioner was then turned off from 2:00 P.M. until 7:00 P.M. (the electric utility's summer demand peak) and the room air dry-bulb and dewpoint temperatures drifted upward. The dry-bulb temperature rose from 24°C to 28.5°C on average, and the RH moved up from about 58 to 70 percent. When 1000 gallons of water were added to the space, the dry-bulb temperature rose less, from 24.0°C to 17.7°C. The RH rose from 55 to 70 percent. When desiccant quilts with 760 pounds of grade 59 silica gel were brought into the space, the peak dry-bulb temperatures remained the same, about 27.5°C. However, the RH variation became small. During the floating period the RH rose only from about 62 percent to 69 percent. In this configuration, the highest RH, however, occurred during the early morning hours from 6 to 8:00 A. M. when it reached 74 percent.

DESRAD experiments were carried out only with the high thermal and moisture capacitance configuration. The weather had turned cooler by this time so we did not experience true summer conditions. The maximum indoor temperatures during the 15 hour floating period was 27.5°C with an RH of 66 percent. However, because the ambient conditions were cooler and drier than normal, this cannot be considered an adequate test of whether the DESRAD cooling scheme can work.

VIII. NEXT PHASE

The experiments described in this report have examined the moisture storage capacities of a whole building. They have assessed the moisture capacitance of the whole-buildings and have demonstrated simple models which achieve acceptable predictive results to pulses of moisture if temperatures do not change. However, greater accuracy in modeling the building should be achievable if the moisture capacity of specific materials are available. To this end, we are beginning moisture capacity versus RH experiments for a range of typical building and furnishing materials.

Rangewood Villas is now being used as an environmental chamber. The samples are located in the second floor bedroom surrounding the air handler. We have found that the dry-bulb temperature and relative humidity are fairly stable. Ninety-five percent of air dry-bulb temperature points including all three locations monitored in the room fall within $\pm$ .25°C of 24.0°C. Ninety-five percent of RH measurements from the three locations fall within $\pm$ 0.6 percent RH of the $RH_{setpoint}$. A 42 inch ceiling fan blowing toward the ceiling at its low speed setting is maintaining mixed air conditions within the upstairs bedroom. Measured air velocities at the samples are typically 5 FPM.

We have chosen to evaluate a selection of 15 materials which represent much of the moisture storage capacity of a typical residence. Table 2 (in Section II) shows the materials and sample weights included in the study. The basic materials are gypsum, carpet, fir wood, silica gel, cellulose insulation, an arm chair, and some high moisture capacity concrete mixtures. Gypsum is sampled bare, with flat latex paint, with semi-gloss latex paint, and with wall paper (as opposed to vinyl) surfaces. Nylon carpet with and without a foam pad is sampled, and polyester carpet without pad is sampled. Bare fir and varnished fir are sampled. One of the quilts of grade 59 silica gel used in the previous house experiments is a sample. Two light-weight disposable aluminum baking pans filled with about 7 inch depth of macerated cellulose insulation are a sample. A 47-pound arm chair is another sample. Two types of high moisture capacity concrete are sampled. One has phosphogypsum added to the mixture. The other has an oil absorber material (as is used on garage floors) in its mixture. These were prepared by Dr. Kalajian of Florida Institute of Technology as potential high moisture capacitance building materials.

The nine samples of gypsum, carpet, and fir are constructed in much the same way. Two equal size pieces are placed back-to-back with a sheet of aluminum foil secured between them. The two sides are adhered together by a thin layer of General Electric silicon caulking. A thermocouple is placed in the center of the samples, at the surface, and 1 inch away from the surface of the samples to monitor temperature distributions.

The moisture capacity of the materials is determined by measuring the weight of the samples. This is done using highly sensitive load cells. These load cells have rated accuracies of 0.25 percent of the full scale. The load cells have been calibrated in-house and tested for accuracy by placing one gram, 10 grams, and 100 grams on a tare weight equal to the full capacity of the load cell. The load cells give a continuous output signal which is approximately 2.0 mV per one volt excitation (e.g., 20.0 mV output for 10.0 volt excitation) at the rated capacity. The Campbell CR7 datalogger collects average 15 minute voltage measurements. These voltages are converted to weight and archived on the VAX 11-750 central computer system.

To provide a check against instrument drift, a 2000 gram reference weight (a 16" x 16" sheet of aluminum) is continuously measured by one of the load cells.

Current Status

The equipment was in place and the load cells were calibrated by January 1, 1988. The room dry-bulb was set at 24.0°C (75°F) and the RH was set at 37.5 percent at the same time. These conditions were maintained until January 16 at which time the RH was changed to 49 percent. The increase in weight was observed for the samples. On February 10 the room RH was changed to 65 percent.

Future Plan

The experiment will continue to obtain equilibrium points at 24.0°C dry-bulb temperature. It is anticipated that relative humidities of 60, 70, 80, and perhaps 90 percent will be obtained. Each stop will take about two weeks. Once at the top the RH will be stepped down in a mirror pattern to 37.5 percent RH.

Additional experiments may be performed on other materials at a later date.

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