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THE EFFECT OF BUILDING AIR LEAKAGE AND VENTILATION ON INDOOR RELATIVE HUMIDITY

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ABSTRACT

This paper describes a study whose purpose was to analytically model the relationship between indoor air relative humidity and air exchange in order to determine the influence of building air leakage or ventilation on the indoor moisture level and to examine the sensitivity of the results to a variety of building and weather parameters. Since a building's air leakage is a significant contributor to its annual heating cost, reducing air leakage has been a goal of weatherization for existing homes as well as energy efficient design and construction of new homes. However, as air leakage is reduced, the moisture generated inside the house cannot escape as easily and so indoor moisture levels increase. Unfortunately, when moisture levels become excessive, a variety of problems may occur, such as musty odors and dampness, or mold and mildew, or condensation on windows or other surfaces. Thus, it is of interest to analyze the impact of reduced air exchange on indoor moisture levels. In this study room humidity levels were determined from an equation describing the steady-state moisture balance between the interior moisture generation rate and the rate of interior moisture removal or dilution by air exchange. While the air leakage or ventilation rate was the primary independent variable, the sensitivity of the indoor moisture results to a number of other parameters was analyzed; the parameters varied included the outside air temperature and relative humidity, the atmospheric pressure, the indoor temperature and moisture production rate, and the building's floor area and ceiling height. The findings of the parametric analysis will be described. It is concluded from the study that when air leakage or ventilation rates are reduced below about one half air change per hour, indoor relative humidities rise dramatically, often necessitating additional mechanical ventilation or dehumidification. It is also concluded that mechanical ventilation alone may be ineffective during warm, humid weather when the outdoor air has an absolute moisture content that is near or higher than that of the indoor air.

INTRODUCTION

Experience has shown that weatherization of existing homes or airtight construction of new energy-efficient homes can produce high moisture levels within them during the winter heating season. That can lead to a number of potential problems, including condensation on windows and other surfaces, mustiness or odors, mold and mildew growth, staining, paint deterioration, and even structural damage. As a result of inspecting many hundreds of existing homes, it is the author's experience that mold and mildew will occur on cold walls when the relative humidity in the main living space is about 60-70% or greater, whereas condensation can occur on windows at considerably lower indoor relative humidities. What is usually unknown is the level of building tightness that will create such indoor relative humidity conditions.

There also has been considerable concern about indoor air quality in tight houses, and many utilities or agencies have required or recommended the use of air-to-air heat exchangers as a means of providing ventilation and satisfactory air quality. Oftentimes, a ventilation rate of 0.5 air changes per hour (ach) or so is recommended. However, it has not always been clear whether or not that ventilation rate would also result in the removal of sufficient moisture to eliminate or minimize moisture-related problems.

Meyringer[1] examined the ventilation requirements to prevent surface condensation and determined that an air exchange rate of 0.5 ach should be sufficient. However, his analysis was limited to a specific set of building and weather conditions; moreover, some critical parameters were not specified. In addition, Tenwolde2 has pointed out that as natural infiltration rates fall below about 0.5 ach, relative humidity buildings up rapidly. Conversely, he noted, ventilating past about 0.5 ach does little to lower humidity.

While a few researchers are aware of such results, the general relationship between the overall air exchange rate of a building and the average indoor moisture level (relative humidity) is not well understood within the building community. Moreover, the effect of a variety of weather, building, and occupant behavior parameters is not well known or understood. Thus, the purpose of this study is to analytically model the relationship between indoor relative humidity and air exchange in order to determine the influence of the air exchange rate on the indoor moisture level and to examine the sensitivity of the results to a variety of building, occupant and weather parameters. Others such as Tenwolde[2] and Quirouette[3] have modelled the moisture balance before for selected conditions. The new feature of this work is the further interpretation of such modelling results, presentation of the equations used, and analysis of the sensitivity of results to the input parameters.

ANALYTICAL MODEL

The average indoor moisture level or relative humidity in a house is the result of a moisture balance between moisture production and moisture removal. Moisture is more or less continuously generated inside the dwelling from a variety of occupant-related sources, such as respiration, cooking, showering, etc. Moisture is removed from the space by natural air leakage or by any of a variety of mechanical ventilation or dehumidification systems. In essence, the moisture in the indoor air is diluted by the introduction in the wintertime of cold, and thus relatively dry (in an absolute sense), outdoor air. Under certain conditions, such as when the outdoor weather is relatively mild and humid, the outdoor air can actually be more moist in an absolute sense than the indoor air, such that air leakage or ventilation will not produce a very significant reduction in the indoor relative humidity.

At any rate, a moisture balance exists such that if the indoor relative humidity is constant, the moisture input rate must equal the moisture removal rate. That is the basis of the analytic model to determine the steady-state indoor relative humidity as a function of the building's air exchange rate. For this study it was assumed that for the time scale of interest there is no net gain or loss of moisture from that stored in the building structure.

A minor calculational difficulty does arise in that the moisture loss from the existing air can not be determined until the moisture content of the air within the building is known; but the building's air moisture content is also a function of the moisture loss from the air exiting the building. Thus, the moisture content of the air within the structure and the moisture leaving the building because of air leakage must be determined simultaneously. The moisture input from the outside air can easily be found if the outdoor air conditions are known.

There were several assumptions made to expedite the indoor relative humidity calculations. The analysis assumes the building interior is a single zone box with uniform properties and air exchange. Obviously, different rooms in the dwelling can have different air exchange rates. For this simplified analysis that was neglected. In addition, it was assumed that air behaves as an ideal gas and that the moisture content of air does not appreciably affect its density and mass. Moreover, the pressure of dry air was assumed equal to the pressure of the moist air. These last assumptions produced a maximum error of less than one percent.

The moisture balance equation has the following final form:

$$RH_{in} = 59.56 \frac{(T_{in} + 459.6)}{p_{sat\ in}} \frac{1.679\ p\ (RH_{out}/100)(p_{sat\ out})}{(T_{out} + 459.6)\ (p - \frac{RH_{out}}{100} p_{sat\ out})} + \frac{S}{V.ach} \qquad (1)$$

where RH_{in} = indoor air relative humidity (%)
RH_{out} = outdoor air relative humidity (%)
T_{in} = indoor air temperature (F)
T_{out} = outdoor air temperature (F)
p = atmospheric air pressure (psia)
S = indoor moisture production rate (lb H_2O/hr)
V = building interior air volume (ft^3)
ach = air leakage or ventilation rate (air changes per hour)

and $p_{sat\ in}$ and $p_{sat\ out}$ are the indoor and outdoor saturated vapor pressures (in psi) at the indoor and outdoor temperatures, respectively. The relation between the saturated vapor pressure and temperature is approximated analytically[4] as follows:

If the outside or inside temperature is greater than or equal to 32 F (0°C):

$$p = 2.04466 \times 10^6 \exp(-7071.3/(T + 385)) \qquad (2)$$

If the outside or inside temperature is less than 32 F (0°C):

$$p = 5.24506 \times 10^6 \exp(-11071/(T + 459.6)) \qquad (3)$$

It can be seen that in order to examine the influence of air leakage on indoor relative humidity, the following parameters are needed:

1) Outdoor air temperature
2) Outdoor air relative humidity
3) Indoor air temperature
4) Indoor moisture production rate
5) Atmospheric pressure
6) Building's volume

One purpose of this study is to examine the influence of each of these parameters on the results.

MICROCOMPUTER PROGRAM

The moisture balance equation was programmed in BASIC to run on a Tektronix 4051/52 minicomputer so as to be able to use a Tek 4662 plotter for its graphical output. Results can be in plotted form or in tabular form.

In either case all the input variables are presented with the output as well. The program is menu-driven and all the inputs can be made in a few minutes. Calculations and screen graphing typically take only a few seconds. To verify the program's output, a number of checks were made. If no moisture sources are present in the building and the outdoor temperature equals the indoor temperature, then the indoor relative humidity should be calculated by the program to equal the input for the outdoor relative humidity. An error of less than one percent resulted, and that is largely due to the error in the equations relating saturation pressure and temperature. Furthermore, if no sources are present, for given outdoor conditions, the calculated indoor RH at a given indoor temperature should correspond to the same absolute humidity (or humidity ratio) as for the given outdoor conditions. It checked using a psychometric chart. In addition, the results appear to agree quite closely with the graphical results of Tenwolde[2]. It also should be noted that the program will shortly be converted to run on an IBM PC and can be obtained from the author.

RESULTS

Typical Results. The program was initially run for a small 1200 sq ft (112 m^2) home in Portland, Oregon under average winter outdoor conditions. The average outdoor winter temperature is 47 F (8°C) and the average outdoor winter relative humidity is 76%. An atmospheric pressure of 14.7 psia (100 kPa) was assumed. In addition, a moisture production rate of 20 lb/day (9.1 kg/day) for a typical family was assumed. The indoor temperature was taken as 68 F (20°C). The results are shown in Figure 1. The key feature is that indoor relative humidity increases a the air exchange rate is reduced. The change in indoor relative humidity is rather slight for air change rates above about 0.5 ach, whereas further house tightening below that critical point causes a substantial rise in the indoor moisture level. Ventilating above 0.5 ach would do little to lower humidity, whereas ventilating a tight house with an infiltration rate of less than 0.5 ach would quite effectively reduce the indoor relative humidity. For example, if ventilation is used to increase the air exchange rate from 0.2 ach to 0.5 ach, the relative humidity drops 24% (80.5 to 56.4%).

Analysis of Sensitivity to Input Parameters. Since weather, building, and occupant characteristics can differ or change, it seemed worthwhile to use the program to examine the sensitivity of the results to changes in the six input parameters. Initially only one parameter at a time was varied; the remaining inputs were those used for the typical result shown in Figure 1. The range of values of parameters varied is:

1) Outdoor air temperature: 0-80 F, in 10 F increments
2) Outdoor air relative humidity: 0-100%, in 20% increments
3) Indoor air temperature: 56-80 F, in 4 F increments
4) Indoor moisture production rate: 0-40 lb/day, in 10 lb/day increments
5) Atmospheric pressure: 9.7-14.7 psia, in 1.0 psia increments
6) Building volume: building's ceiling height, 8 ft; building's floor area: 600-3600 sq ft, in 600 sq ft increments

The results of each of the parameter variations will be examined in order.

Figure 2 shows the significant effect of changing the outdoor air temperature. Surprisingly, when the outdoor temperature is relatively low, indoor moisture levels remain relatively low because of the dilution with the cold and hence dry outdoor air. That is why moisture-related problems are relatively infrequent in very cold climates. However, as the outdoor temperature rises to values that might exist during transitional seasons or when the outdoor temperature is near the balance point temperature of the building (say, 55-60 F), then indoor moisture levels rise to very high levels. The transitional season periods when the driving forces for natural air exchange are the weakest are the most critical periods. For example, if the outdoor air is 55 F, then the indoor relative humidity will not drop below 60%, regardless of the air exchange or ventilation rate. In fact, below 0.5 ach the indoor relative humidity will be greater than 70% at 60 F. In order to keep indoor relative humidities to acceptable levels during relatively warm periods, it may be necessary to use a dehumidifier.

The effect of the outdoor air relative humidity is shown in Figure 3. Its influence on indoor RH is linear. Clearly dry climates will have lower indoor air moisture levels. Moreover, climates that are both cold and dry will have even lower indoor relative humidities. That is why homes in places like Denver have relatively few moisture-related problems.

The sensitivity to the indoor air temperature is presented in Figure 4. For a given absolute amount of moisture, as the indoor temperature drops, the relative humidity rises. Thus, the use of night setback might seem to make matters worse. However, the outdoor temperature drops at night as well, thus reducing indoor moisture levels, and that may counterbalance the effect of night setback. When indoor moisture levels are too high, a common recommendation is to raise the thermostat setting, even though that increases energy usage. That is helpful during the day as outdoor temperatures rise, but it may not be worthwhile at night.

As the indoor moisture production rate increases, the results of Figure 5 indicate that indoor moisture levels will increase. For relatively tight homes the effect is much greater than for relatively leaky homes. Clearly, reducing the sources of moisture in tight homes is extremely important. That is why it is wise to use kitchen, bathroom, and dryer exhaust fans to remove moisture locally before it has a chance to mix into the air of the whole living space.

As seen in Figure 6, variation in the atmospheric pressure has a negligible effect. Finally, the influence of the building volume, or in this case the square footage of living space, is indicated in Figure 7. Clearly, small, tight houses can have very high indoor moisture levels, whereas for large houses the indoor moisture levels are significantly lower and also insensitive to the air exchange rate except at very low values.

By considering different sets of input parameters it is possible to get a sense of what combinations of building, occupant, and weather parameters will result in high and low indoor moisture levels. For example, if a home is small with a large number of occupants that leads to increased moisture production and if the indoor temperature is relatively low, and if the weather is mild and humid, then exceedingly high indoor moisture levels will result, independent of the air exchange rate. If, however, a larger, warmer house is occupied by a fewer number of people in a cold, dry climate, it may be hard to get high indoor relative humidity values, except at very low air exchange rates. Two such examples are presented in Figures 8 and 9.

CONCLUSIONS

The relationship between indoor air relative humidity and air leakage and ventilation has been modelled and programmed on a minicomputer in order to determine the influence of the building's air exchange rate on the indoor moisture level and to examine the sensitivity of the results to a variety of building, occupant, and weather parameters. It has been shown that most of those parameters can have a significant impact on the indoor relative humidity versus air exchange rate results, especially at lower air exchange rates.

It seems worthwhile to point out that as a general rule indoor moisture levels are relatively unaffected by the air exchange rate when it is above some critical valued, which is often about one half air change per hour. Decreasing the building's ach below about 0.5 ach results in a substantial increase in the indoor relative humidity. Thus, when weatherization or construction techniques result in air exchange rates below about 0.5 ach, there will be a need to increase the air exchange rate by mechanical ventilation to about 0.5 ach or to utilize a dehumidifier, or to use exhaust fans that automatically remove moisture from its source (e.g., in the shower room) before the air is mixed with that in the rest of the house.

Finally, it is also concluded that it will be most difficult to maintain acceptable indoor moisture levels in tight houses during mild weather rather than colder weather as is commonly believed. When the weather is humid and relatively warm, such as in the transitional seasons, the outdoor air can have an absolute moisture content that is near to or even higher than that of the indoor air, such that ventilation alone may be ineffective as a means of removing moisture generated inside the house. In such cases dehumidification may be necessary to provide satisfactory indoor moisture levels.

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4. D. H. Matsen, "Psychometric Properties," HP-67 User's Library Program 867D, Hewlett Packard Co.; see also HP-41 User's Library Solutions, "Heating, Ventilation, and Air Conditioning," 1983.

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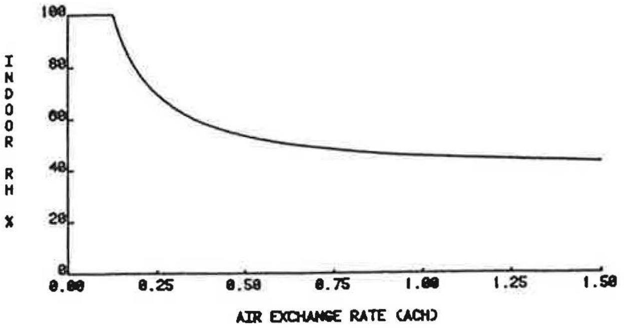

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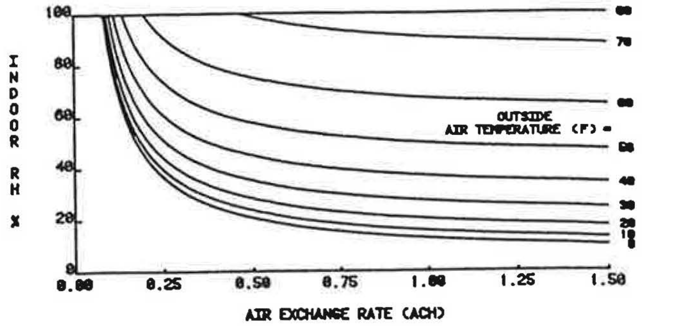
OUTSIDE AIR RELATIVE HUMIDITY = . 70 %
ATMOSPHERIC PRESSURE = ... 14.7 PSI
INDOOR AIR TEMPERATURE = ... 68 F
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 1. Typical effect of building air exchange on indoor relative humidity



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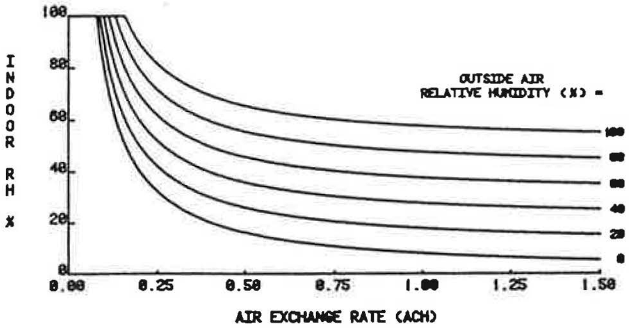
ATMOSPHERIC PRESSURE = ... 14.7 PSI
INDOOR AIR TEMPERATURE = ... 68 F
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 2. Effect of changes in outdoor air temperature



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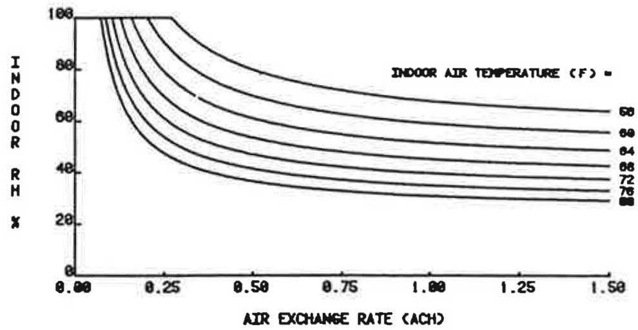
INDOOR AIR TEMPERATURE = ... 68 F
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 3. Effect of changes in outdoor air relative humidity



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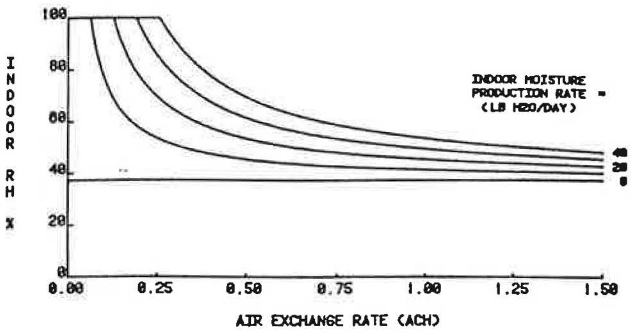
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 4. Effect of changes in indoor air temperature



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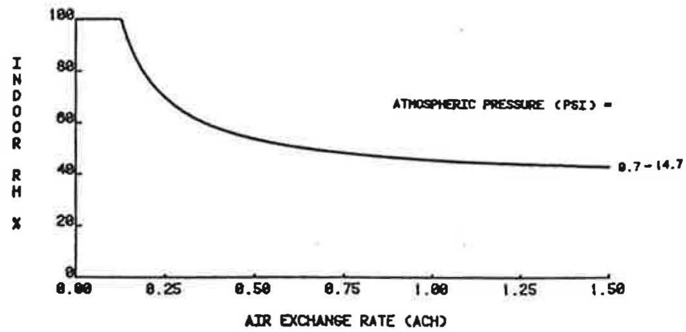
ATMOSPHERIC PRESSURE = ... 14.7 PSI
INDOOR AIR TEMPERATURE = ... 68 F
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 5. Effect of changes in indoor moisture production rate



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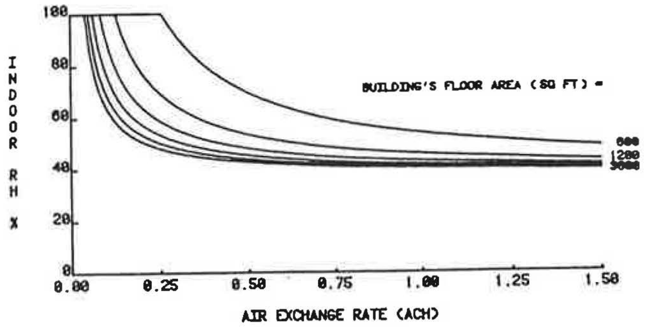
OUTSIDE AIR RELATIVE HUMIDITY = . 70 %
INDOOR AIR TEMPERATURE = ... 68 F
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1200 SQ FT
BUILDING'S CEILING HEIGHT = ... 8 FT

Fig. 6. Effect of changes in atmospheric pressure



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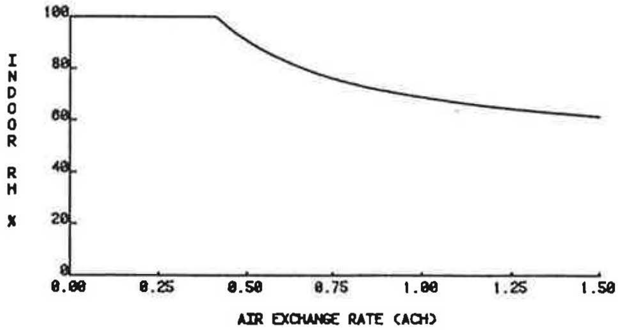
INDOOR AIR TEMPERATURE = ... 68 F
INDOOR MOISTURE PRODUCTION RATE = 20 LB H2O/DAY
BUILDING'S CEILING HEIGHT = . . . 8 FT

Fig. 7. Effect of changes in living space floor area



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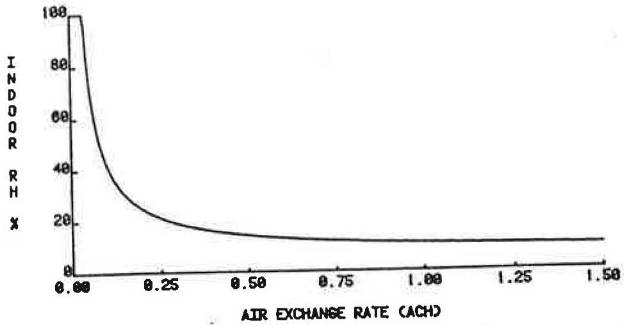
ATMOSPHERIC PRESSURE = ... 14.7 PSI
INDOOR AIR TEMPERATURE = ... 66 F
INDOOR MOISTURE PRODUCTION RATE = 30 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 750 SQ FT
BUILDING'S CEILING HEIGHT = . . . 7.5 FT

Fig. 8. Example of conditions leading to high moisture levels



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OUTSIDE AIR RELATIVE HUMIDITY = . 50 %
ATMOSPHERIC PRESSURE = ... 14.7 PSI
INDOOR AIR TEMPERATURE = ... 72 F
INDOOR MOISTURE PRODUCTION RATE = 15 LB H2O/DAY
BUILDING'S FLOOR AREA = ... 1800 SQ FT
BUILDING'S CEILING HEIGHT = . . . 8 FT

Fig. 9. Example of conditions leading to low moisture levels