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Moisture Design to Improve Durability of Low-Slope Roofing Systems

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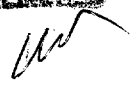
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MOISTURE DESIGN TO IMPROVE DURABILITY OF LOW-SLOPE ROOFING SYSTEMS

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ABSTRACT

The roofing industry has traditionally held that moisture control in low-slope roofing comprises two independent elements: (1) provide a waterproof exterior covering (or membrane) to protect the low-slope roof from external sources of moisture and (2) perform a condensation calculation to determine if a vapor retarder is required to protect a roof system from internal moisture sources.

The first criterion is assumed to be satisfied if a membrane system is specified; in reality, all membrane systems eventually fail, and existing moisture control strategies offer no mechanism for analyzing the inevitable failure. The means of assessing the second criterion, the need for a vapor retarder, has evolved in recent years. The criteria have become more liberal with time because it has been observed that roofing systems installed in a geographic area in which the old criteria required a vapor retarder, have performed well without one.

The service life of a roofing system ends when it can no longer provide the necessary protection from the environment. All too often, moisture accumulation in the roofing system accelerates its demise. The effectiveness of the roofing industry's existing moisture control philosophy needs to be questioned. The average service life of a roofing system is a fraction of the life of other building envelope components, and the primary reason for failure is water leakage. An improved moisture control

strategy may very well be the key to improving the durability of low-slope roofing.

In this paper, we propose a new moisture control strategy that addresses not only condensation control, but also water leakage. We compare the new strategy with those predating it, describe the benefits of the new strategy, and illustrate by example the necessary inputs to implement it.

INTRODUCTION

A major cause of roof replacement is excessive accumulation of water in portions of the roofing system, caused by failure of the roofing membrane, poor system design, or poor construction practices. The existing moisture control strategies the roofing industry uses are concerned exclusively with moisture flow into the roofing system when the roofing system is performing properly. Most often, we require that a waterproof membrane be placed on the climate side of the roofing system to prevent water from penetrating into the insulation layers and deck below, yet we are unconcerned about the inevitable leak that will allow access to water. We perform condensation (or dewpoint) analyses that dictate whether a vapor retarder is needed to control moisture entry from the building interior during wintertime, yet we know that these analyses include simplifications that impact the precision of their predictions. When our dewpoint analyses indicate that a roofing system needs a vapor retarder, we know that the vapor retarder

can compromise the long-term performance of the roof by trapping leak water in the insulation layers. Today, we simply accept this compromise.

In this paper, we propose new moisture control guidelines for low-slope roofing systems. These guidelines consider the impact of wintertime control of moisture as well as the performance of the system after a leak has occurred. A new technique for assessing winter moisture uptake is proposed and compared with the existing procedures. Leak prevention and rapid dissipation of leak water into the building interior as water vapor are discussed.

HISTORICAL PERSPECTIVE

The only moisture control strategy presently employed in low-slope roofing systems is to prevent condensation in the insulation layers. The National Roofing Contractors Association (NRCA) Roofing and Waterproofing Manual (NRCA 1996) describes three procedures to determine whether a vapor retarder should be added to the roofing system.

For many years, NRCA has maintained that a vapor retarder should be considered when the outside average January temperature is below 4°C (40°F) and the expected winter indoor relative humidity is 45% or greater. Figure 1 depicts the areas of the United States that experience an outside average January temperature below 4°C (40°F).

NRCA cites The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) *Handbook of Fundamentals* (ASHRAE 1993) as the second source for vapor retarder criteria. The author reviewed all editions of this reference dating back to 1971 and found no listing of any criteria for low-slope roofing. A procedure for determining whether condensation

occurs inside a building envelope component is described. The discussion presented in the handbook can be simplified to recommend the addition of a vapor retarder if the dewpoint falls within the insulation layer; we will assume that this is the procedure the NRCA manual is referencing.

Many researchers, designers, builders, and building owners felt that these two assessments to determine the need for a vapor retarder did not fit their collective experience, and that the existing criteria prescribed vapor retarders where experience indicated that roofing systems performed adequately without them. Following a procedure introduced by Baker (1980), the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) developed a series of maps of the United States to assess "progressive" and "seasonal" wetting of roofing systems (Tobiasson and Harrington 1986). "Progressive" wetting refers to a yearly buildup of moisture in the roofing system; "seasonal" wetting is used to describe the amount of moisture accumulated during the winter vapor drive. By comparing mean monthly air temperatures and vapor pressures for 363 U.S. cities, monthly vapor drive maps were created. Comparing the ratio of the vapor drive for the wetting and drying seasons yields the potential for "progressive" wetting, and looking at the vapor drive during the wetting season yields the "seasonal" wetting data. Since the seasonal map required vapor retarders for a larger area of the United States, it was selected as the controlling map. In a survey, roofing professionals were asked to select which map best represented their experience; they selected the map shown in Fig. 2 with a seasonal wetting vapor drive of

Fig. 1. The NRCA map for determining the need for a vapor retarder. If the building interior relative humidity is equal to or greater than 45% and the building is located in the shaded portion of this map, a vapor retarder is recommended. *Source:* NRCA 1996.

Fig. 2. The CRREL map for determining the need for a vapor retarder. If the building interior is controlled to 20°C (68°F), the map depicts relative humidity contours as a function of location. If the building exceeds the relative humidity values on this map, a vapor retarder is recommended. *Source:* Tobiasson and Harrington 1986.

2.0 kPa/month (0.6-in. Hg/month)
(Tobiasson 1988).

The preceding procedures for determining the roofing system moisture control strategy have limitations. The NRCA procedure does not consider the dynamic conditions created by weather and completely ignores the roofing system itself as having an impact on moisture control. The basis for the guideline is undocumented, and its derivation is unknown to the author. The ASHRAE guideline treats design conditions as if they are steady state and considers only the thermal performance of the roofing system components in its moisture control strategy (moisture properties are not considered). The winter design conditions are much too severe to be used as a basis for moisture control; the drawbacks of having a vapor retarder are too great to design for complete elimination of condensation. Finally, the CRREL analysis, by far the most sophisticated of the three procedures, required industry "calibration" to account for the dynamic nature of moisture flow driven by meteorological conditions and for the omission of solar effects that heat up the roof surface appreciably. In addition, it does not consider that the components of the roofing system can impact the moisture control strategy.

THE NEW GUIDELINES (SOME ARE A LITTLE OLD)

In the early 1970s, Powell and Robinson (1971) at the National Institute of Standards and Technology conducted a comprehensive study of the effects of moisture on roof assemblies. They stated that "the most practical and economical solution to the problem of moisture in insulated flat-roof constructions [is] to provide a design that would have in-service self-drying characteristics." We

feel that this statement is still applicable today. We have adapted Robinson's conclusions, in light of the need for controlling internally-generated moisture sources, into the following series of proposed guidelines for moisture control in low-slope roofing systems.

Under normal operating conditions (no leaks), condensation shall not occur under the membrane during winter uptake, and the total moisture content of a roof system shall not increase with time. Moisture vapor movement by convection must be eliminated, and the flow of water by gravity through imperfections in the roof system must be controlled. After a leak has occurred, no condensation on the upper surface of the deck shall be tolerated and the water introduced by the leak must be dissipated to the building interior in a minimum amount of time.

The first two rules are consistent with current common practice and echo the requirements introduced by Tobiasson (1986). We do not want to allow condensation to occur within the insulation layers of the roofing system (seasonal wetting) because of the deleterious effects water has on the thermal and mechanical performance of roofing systems. We are more specific in the guideline in that we are concerned with condensation under the membrane. Since this is the coldest part of the roofing system during times when we are concerned with wintertime uptake, condensation will first occur at this location in the insulation layer. If the total moisture content of the roofing system is increasing on a yearly basis (progressive wetting), then eventually condensation must occur under the membrane, causing it to fail our first guideline.

The third requirement, the absence of moisture movement by air movement or infiltration, is typically satisfied for low-slope roofing systems that have fully

adhered membranes. The complete attachment of the membrane to the outermost surface of the insulation prohibits the transfer of low pressures induced by winds blowing over the roofing system through the membrane. In the absence of a pressure difference, air movement through the insulation layer is typically negligible. Furthermore, low-slope roofing systems tend to be constructed with few interruptions in the insulation layers, and the materials used are dense and not very permeable to air. In roofing systems that employ a loose or mechanically-attached membrane that can transfer outdoor air pressure, precautions to eliminate air movement must be considered. An airtight deck or the addition of an air retarder should be considered.

Although most moisture control problems pertain to roof leaks, none of the existing moisture control strategies addresses this issue. Through proper roof design and selection of materials, it may be possible to eliminate dripping into the building interior from small to moderate leaks. Dripping manifests itself as condensation on the interior surface of a metal deck (or any deck that has no moisture absorptance). If the rate of water vapor being driven to the deck or the deck permeance can be controlled to prevent condensation onto the deck, dripping from roof leaks into the building can be eliminated.

A second way that leak water can flow from a roof leak to the deck is gravimetrically through cracks between the insulation boards and other imperfections in the insulation layer. This mode of transfer must be controlled to prevent leakage into the building interior; the use of a continuous layer of an absorptive material is proposed in situations where direct communication

between the leak and the deck is suspected.

Finally, after (if?) all of the above criteria are satisfied, the roofing system shall be optimized to dissipate leak water into the building interior through downward drying as expeditiously as possible. Any water entering the roofing system will begin to degrade the thermal and physical properties of the insulation, deck, and metal components. We therefore want to minimize the time they are exposed to the leak water.

Can all of these moisture control criteria be satisfied in a roofing system using traditional materials and construction practices? We have used a combined heat and mass transfer model to address this question.

THE ANALYSIS TOOL

In performing their research, Robinson and Powell believed that the theoretical basis for understanding combined heat and mass transfer processes was not sufficiently developed, and therefore analytical tools such as computer programs could not be produced. These concerns are no longer warranted. The International Energy Agency (IEA) (1993) has identified and evaluated 29 computer programs that are capable of analyzing heat and mass transfer. These tools can now be used to assist roofing professionals in designing roofing systems that will exhibit superior moisture control characteristics.

We used the computer program MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) (Rode 1990) to simulate the simultaneous effects of the transfer of heat and moisture in roofing systems. Rode (1991); Desjarlais et al. (1993); Desjarlais, Kyle, and Christian (1993); and Kyle (1994) have described,

validated, and used the model on low-slope roofing applications. MATCH is one of the computer simulation programs being scrutinized by IEA. The calculations of both modes of transfer are performed in a one-dimensional transient manner that accounts for the accumulation of heat and moisture. The version of the program we used utilizes vapor diffusion as the only moisture transport mechanism, with vapor diffusion being described by Fick's Law. Liquid capillary flow has been ignored; trial runs with liquid capillary flow enabled had an insignificant impact on the results. The storage of moisture is described by sorption isotherms of the materials, and water vapor permeability is defined as a function of moisture content. The transfer of heat is described by a contribution from the sensible conduction of heat (Fourier's Law) and a contribution from the energy of phase conversion of water between liquid and gaseous states. Changes in thermal conductivity due to temperature and moisture content are both accounted for by the model.

Environmental conditions can be input easily. Climate conditions are described by referencing typical meteorological year (TMY) data files (ASHRAE 1989) in the setup of the simulation run. The model uses the hourly data of air temperature, relative humidity, and solar radiation contained in the TMY files. The building interior environmental conditions are defined by specifying a temperature and relative humidity. Unfortunately, these inputs must be held constant for the entire simulation run. The thermal and hygric properties of the membranes, insulation materials, and decks are specified in a material library. We recently updated the hygric properties of most of the common insulation materials used by the U.S.

roofing industry (Burch 1995). Finally, the solar absorptance of a membrane can be specified to simulate radiational heating of the roofing membrane properly.

The advantages of using a simulation tool are obvious. We can now investigate moisture movement in a roofing system on an hourly basis, include the impact of solar heating of the membrane, include temperature- and moisture-dependent properties of the components that make up the roofing system, and economically study the impact the roofing design has on the moisture tolerance of the roofing system.

WINTERTIME UPTAKE

Since existing moisture control strategies emphasize wintertime moisture uptake, we will start our discussion with a comparison of the various strategies to assess the need for a vapor retarder. Our criterion for specifying the vapor retarder is simply to prevent condensation from occurring in the roofing system. For this exercise, we assume that the roofing system comprises a black single-ply membrane having a solar absorptance of 0.9, 25 mm (1 in.) of insulation, and a metal deck with a water vapor permeance of 57 metric perms (1.0 perms). We assume that the roof is located in either Knoxville, Tennessee, or Chicago (both cities have a January mean temperature less than 4°C or 40°F) and that the interior conditions of the building are maintained at 20°C (68°F) and 50% relative humidity. We analyze this roof system with both wood fiberboard and polyisocyanurate foam used as insulation. In summary, four systems are being studied: Knoxville with wood fiberboard, Knoxville with polyisocyanurate foam, Chicago with wood fiberboard, and Chicago with polyisocyanurate foam.

According to NRCA guidelines, all four roofing systems require a vapor retarder because they all satisfy the requirements that the January mean temperature be less than 4°C or 40°F and the interior relative humidity above 45%.

Following the "ASHRAE" procedure, we find that the winter design climatic conditions for Knoxville and Chicago are -11 and -22°C (13 and -8°F), respectively. The dewpoint for the building is 9°C (49°F). Knowing the thermal resistances of all of the roofing system components, we compute deck temperatures of 15, 17, 13, and 16°C (59, 63, 55, and 61°F), respectively. Since the dewpoint falls within the roof for all four systems, a vapor retarder is required in all instances.

According to the CRREL guidelines, the roofing systems in Knoxville do not require a vapor retarder; the CRREL map (Fig. 2) requires an indoor relative humidity of approximately 60% before a vapor retarder is required for this location. For the Chicago roofs, a vapor retarder is suggested; Chicago falls near the 40% RH requirement.

We model the four systems using the analysis tool described earlier in this paper. To track the movement of moisture within the insulation, we divide the insulation into three separate control volumes of equal size; the 25 mm (1 in.) thick insulation is divided into three layers each approximately 8.5 mm (0.33 inches) thick. The "top insulation" is directly underneath the membrane. We initially estimate the moisture content and temperature for the individual layers and run a complete yearly simulation. We then use the final temperature and moisture distributions from this initial simulation as our initial conditions and repeat the simulation. Figures 3 through 6 depict the moisture content of each of these layers (expressed as a weight

percent) as a function of time, with Time = 0 being January 1 for this second series of simulations.

To determine if condensation occurs within the insulation, we compare the moisture content of the insulation layers with the insulation material's sorption isotherms. The sorption isotherm of a material is simply the relationship between the amount of moisture a material can absorb at varying levels of relative humidity. To determine these data, samples of each insulation are typically exposed to a variety of levels of relative humidity until moisture equilibrium occurs, and the weight percent of moisture absorbed as a function of RH exposure level is the sorption isotherm for that material. Figure 7 depicts the sorption isotherms for wood fiberboard and polyisocyanurate foam.

Figure 3 depicts the moisture content of the insulation layers if the roofing system contained wood fiberboard and were located in Knoxville. We note that the initial moisture content for the top, middle, and bottom insulation layers is approximately 8, 6, and 5 weight percent, respectively. The moisture content of all three layers increases for the first 60 days (through the end of February), with the top layer's maximum moisture content peaking at approximately 10 weight percent. From day 60 (early March) to day 250 (early September), the moisture content of the top and middle insulation layer decreases to about 4 weight percent and remains relatively constant during the summer period, while the bottom layer's moisture content increases to about 6 weight percent. During this period, the vapor pressure drive is downward into the building interior; therefore, the lower layer will have the highest moisture content. At approximately day 250, the vapor drives

Fig. 3. The moisture content (% by weight) as a function of time of year for the layers of wood fiberboard insulation in a roofing system in Knoxville, Tennessee.

Fig. 4. The moisture content (% by weight) as a function of time of year for the layers of polyisocyanurate foam insulation in a roofing system in Knoxville, Tennessee.

Fig. 5. The moisture content (% by weight) as a function of time of year for the layers of wood fiberboard insulation in a roofing system in Chicago.

Fig. 6. The moisture content (% by weight) as a function of time of year for the layers of polyisocyanurate foam insulation in a roofing system in Chicago.

Fig. 7. The sorption isotherma for polyisocyanurate foam (PIR) and wood fiberboard (WoodFB) insulations during absorption and desorption.

reverse; the upper and middle insulation layers undergo an increase in moisture content while the bottom insulation layer's moisture content decreases slightly. From Fig. 7, we determine that the moisture content at saturation (100% RH) for wood fiberboard is 36 weight percent. Since none of the insulation layers obtained this moisture content during the simulation, condensation does not occur in the roofing system.

Figure 4 depicts similar information for the roof system containing polyisocyanurate foam and situated in Knoxville. Trends in the moisture content of the individual layers of insulation are similar to those in the previous simulation. The top insulation layer moisture content peaks at approximately 8 weight percent in January. From Fig. 7, whenever the moisture content exceeds 5.3 weight percent, condensation occurs. We should anticipate condensation under

the membrane for most of the period from December through January; this roofing system should contain a vapor retarder.

Figures 5 and 6 represent similar data for the roofing system installed in Chicago and containing wood fiberboard and polyisocyanurate foam, respectively. The roof system containing wood fiberboard (Fig. 5) has a maximum moisture content of approximately 16 weight percent; condensation would not occur in this roof. With polyisocyanurate foam (Fig. 6), condensation would occur from November to April; a vapor retarder would be required.

Using the moisture content data from the four simulations, we can determine the total amount of water vapor that is present in the roofing system as a function of time of year. These data are presented in Fig. 8. The peak total

Fig. 8. The total moisture content of the four simulated roofing systems as a function of time of year.

moisture content for the four roofing systems is 0.008, 0.022, 0.097, and 0.122 lb/ft² for Knoxville with polyisocyanurate, Chicago with polyisocyanurate, Knoxville with wood fiberboard, and Chicago with wood fiberboard, respectively. Note that condensation control is not based on moisture control; in fact, the roofing systems with the two lowest total moisture content levels had condensation problems. Based on these simulations, it is clear that a key element in controlling winter condensation is the sorption isotherm of the insulation material directly under the membrane. The ability of the wood fiberboard insulation to absorb six times more water vapor than the polyisocyanurate foam prevents condensation in roofing systems that include an absorptive insulation.

LEAK CONTROL

We used our simulation tool to assess the impact of a leak on the moisture control strategy of a roofing system. As in the previous discussion regarding winter condensation control, a leak through the membrane could be controlled if condensation were prevented from occurring on the deck. If condensation were prevented, the moisture would be dispersed into the building interior in the form of water vapor.

For these simulations, we assume that a leak occurs on January 1 and that the upper insulation layer is wetted by 10 percent by volume (335 and 36.5 weight percent for polyisocyanurate and wood fiberboard, respectively). A leak of this magnitude adds 0.85 kg/m² or 0.17 lb/ft² of water to the roofing system. The leak is repaired and no

additional water entry through the membrane is permitted. The leak water is added to the amount of water that already is present in the roofing system because of winter uptake.

Because the potential for water condensation on the deck is greater in warmer climates, we will analyze only the two roofing systems in the Knoxville climate. In this series of simulations, we are interested in monitoring the moisture content of the bottom insulation layer located directly above the metal deck. Figures 9 and 10 depict the simulation results for the roofing system containing wood fiberboard and polyisocyanurate foam, respectively.

For the first 30 days, the top layer of wood fiberboard (Fig. 9) remains above saturation. The top layer continues to lose moisture throughout the summer and fall months, reaching a moisture equilibrium (moisture content similar to the non-leak simulation shown in Fig. 3) during this period. In the late fall, the moisture content of this layer starts to increase because of winter uptake. In the winter and early spring, the moisture content of the middle and bottom layers increases slightly, and the bottom layer peaks at approximately 15 weight percent. This moisture is then transferred into the building interior as water vapor; condensation has not occurred on the deck, and leakage into the building interior therefore is averted. Note that all of the leak water has been dissipated into the building in approximately 6 months.

The behavior of the roof system with polyisocyanurate foam is somewhat similar. Moisture is driven out of the top layers, through the middle and bottom layers, and into the building interior for the first 3 months. In April, the downward vapor drive accelerates, and the lower layers cannot dissipate the water vapor into the building interior

rapidly enough; consequently, their moisture content increases beyond the saturation level and leakage into the building should occur. The leakage continues for approximately 2 months, or until the moisture content of the top layer is decreased below saturation levels. Afterward, the roofing system behaves similarly to the nonleaking roofing system depicted in Fig. 4. For this example, the leak water is completely dissipated in approximately 5.5 months.

Because the metal deck is the least permeable component of the roofing systems that we have simulated, it is possible to modify the moisture control characteristics of the system by changing the deck permeance. We assumed the deck to be ten times more permeable (570 metric perms or 10 perms) and repeated the leak simulations. The total roof moisture content results are shown in Fig. 11.

By increasing the deck permeance, we change the winter uptake characteristics of the roofing system. Note that the initial moisture content for the wood fiberboard with a 10 perm deck is almost 0.1 lb/ft² higher than for the similar system with a 1 perm deck. However, the higher deck permeance does not change our rating of this roofing system for winter uptake; although the moisture content is higher, it does not exceed saturation. Little change is noted in the initial moisture content of the two systems containing polyisocyanurate foam. When the deck permeance is increased, the polyisocyanurate foam becomes the least permeable component of the roofing system and controls winter uptake.

Note that the time to disperse the leak water is reduced with the higher deck permeance. The increase in permeance reduces the drying time of the wood fiberboard and polyisocyanurate foam roofing systems by approximately 80 and

Fig. 9. The moisture content (% by weight) as a function of time of year for the layers of wood fiberboard insulation in a roofing system in Knoxville, Tennessee, after a leak has occurred in the membrane.

Fig. 10. The moisture content (% by weight) as a function of time of year for the layers of polyisocyanurate foam insulation in a roofing system in Knoxville, Tennessee, after a leak has occurred in the membrane.

Fig. 11. The total moisture content of the two simulated roofing systems with varying deck permeances as a function of time of year.

40 days, respectively. Were we to design these roofing systems for moisture control, we could iteratively change deck permeance and insulation type to optimize the winter uptake and leak prevention and dispersion characteristics.

CONCLUSIONS

In this paper, we review the existing moisture control strategies for roofing systems and propose that new analysis tools are available that can assist the roofing professional in his design. We draw the following conclusions from this study:

- Existing moisture control strategies address only winter uptake. Since a large percentage of moisture problems do not occur until the membrane leaks, it is prudent to consider leak control as part of the overall moisture control strategy. Specific recommendations are proposed.
- The "ASHRAE" method specifies adding a vapor retarder in virtually every roofing system that contains insulation. This procedure is obviously flawed and should no longer be referenced. Similarly, the NRCA recommendation places vapor retarders in many roofs that experience has shown perform well without them. The usefulness of this recommendation should be questioned.
- The CRREL method reasonably predicts the need for a vapor retarder. The major weakness in this procedure is that simplicity has been exchanged for accuracy. Many attributes of the roofing system impact the moisture performance of a roofing system; the CRREL method does not include any of these characteristics.
- Moisture control and condensation control are not synonymous. In the examples cited in this paper, roofing systems that exhibited condensation

during winter uptake contained appreciably less moisture than roofing systems that prevented condensation.

- The critical property that controls condensation is the sorption isotherm or absorptance of the insulation material directly under the membrane.
- If desired, leak control can be designed into the roofing system. Properties to be considered are insulation material type and deck permeance.
- The critical selection of roofing system components for their moisture control capability should be included as part of each roofing system design.

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KEY WORDS

Roofing, sustainable, durable,
moisture, drying, leak.

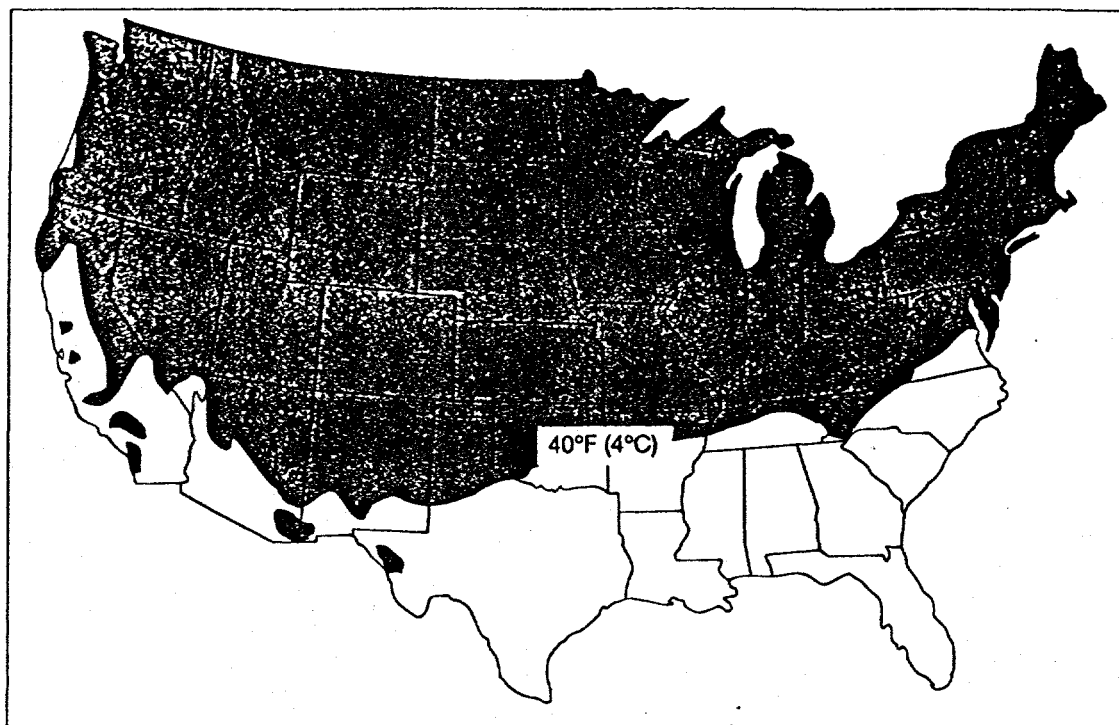
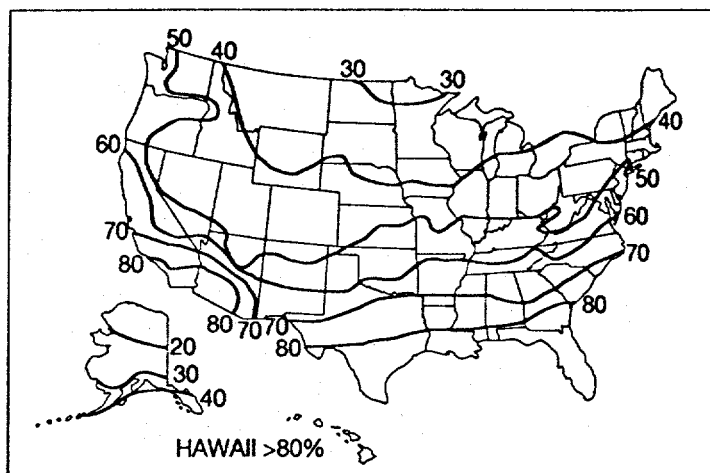


Table 10 January mean temperature map.

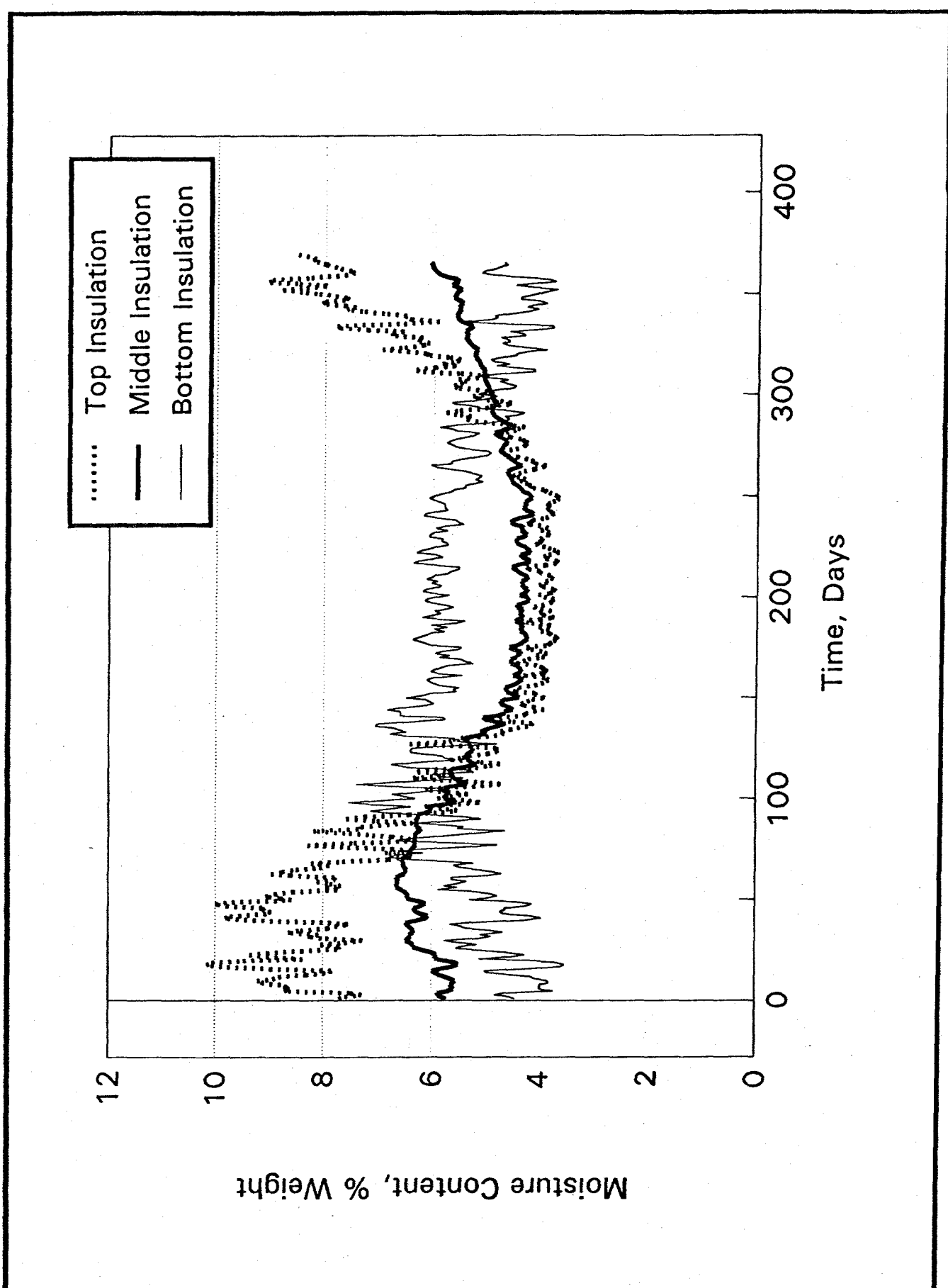
FIGURE 1



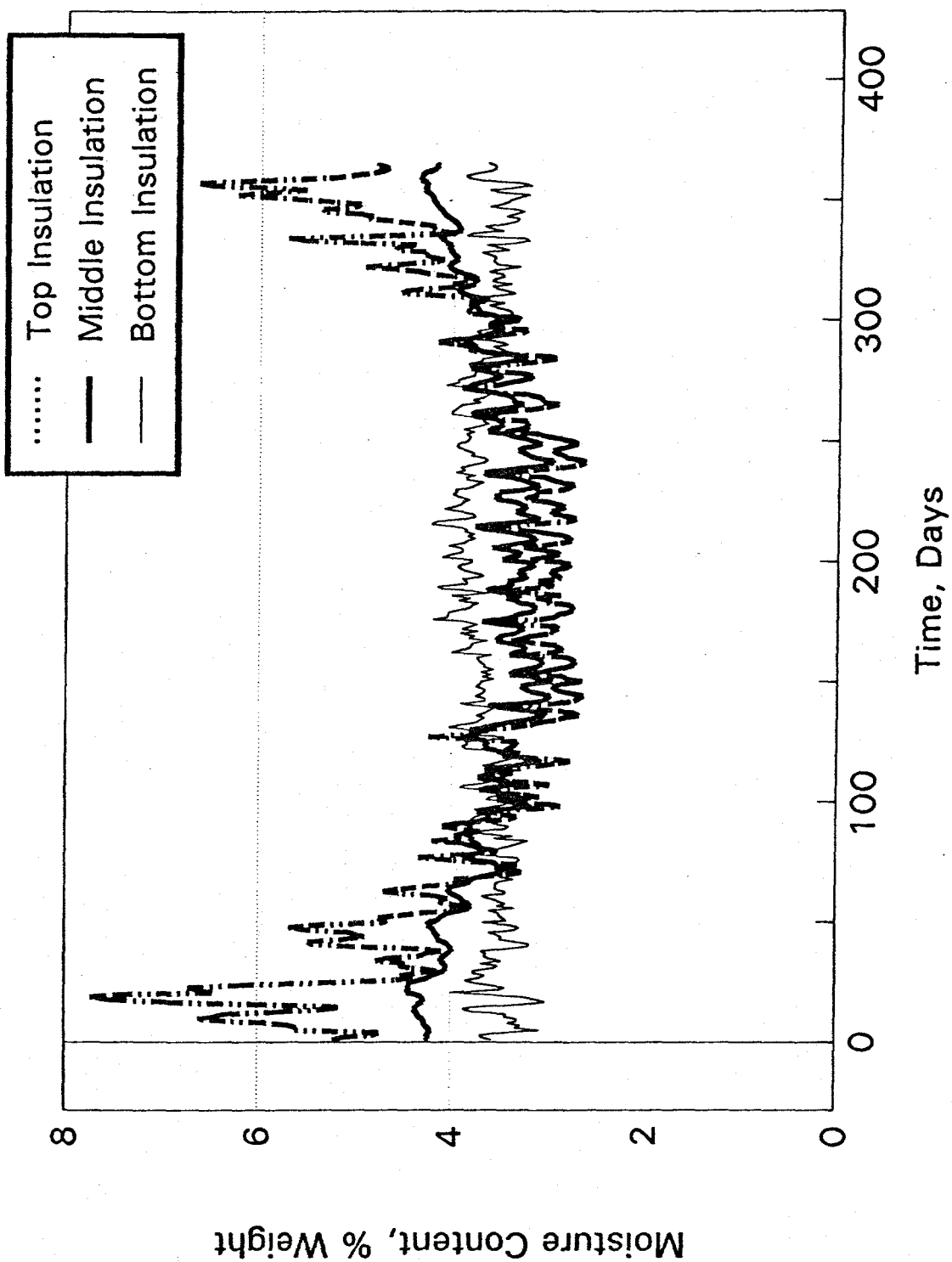
Indoor relative humidity at 68°F (20°C).

FIGURE 2

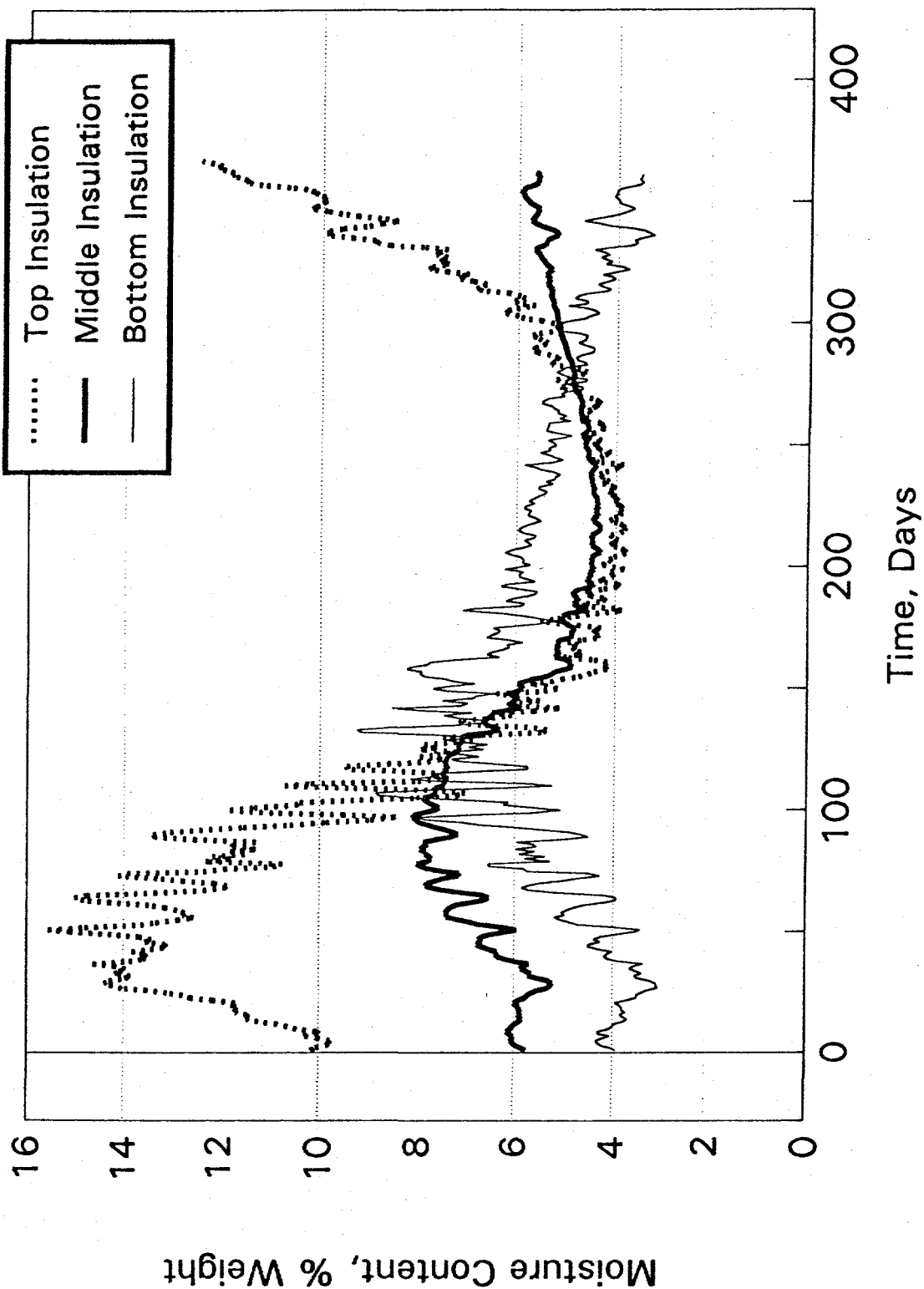
KNOW WFB
FIGURE 3



Knax AIR Figure 4



CHICAGO WFS FIGURE 5



Chaco PIR Figure 6

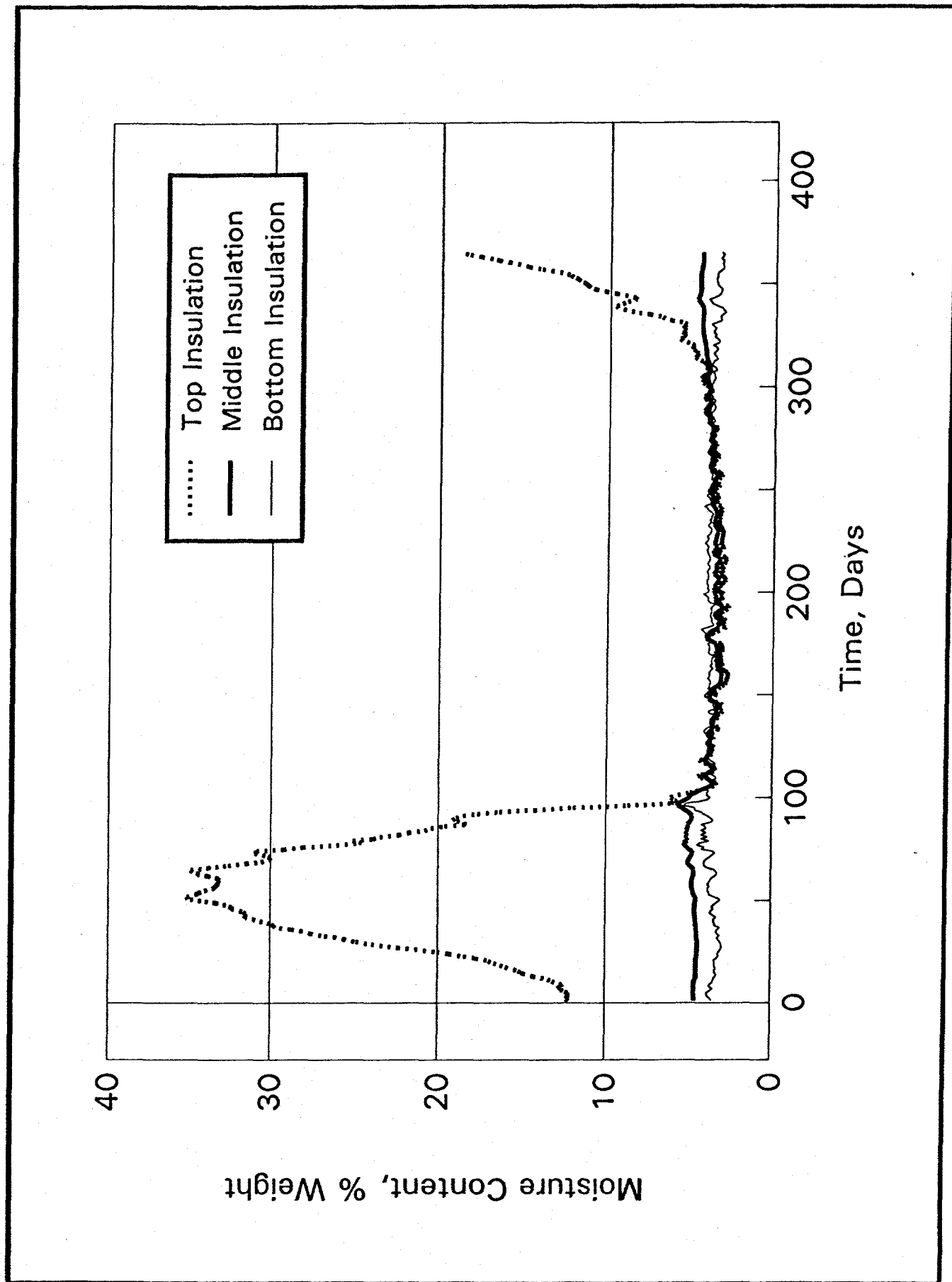


Figure 7

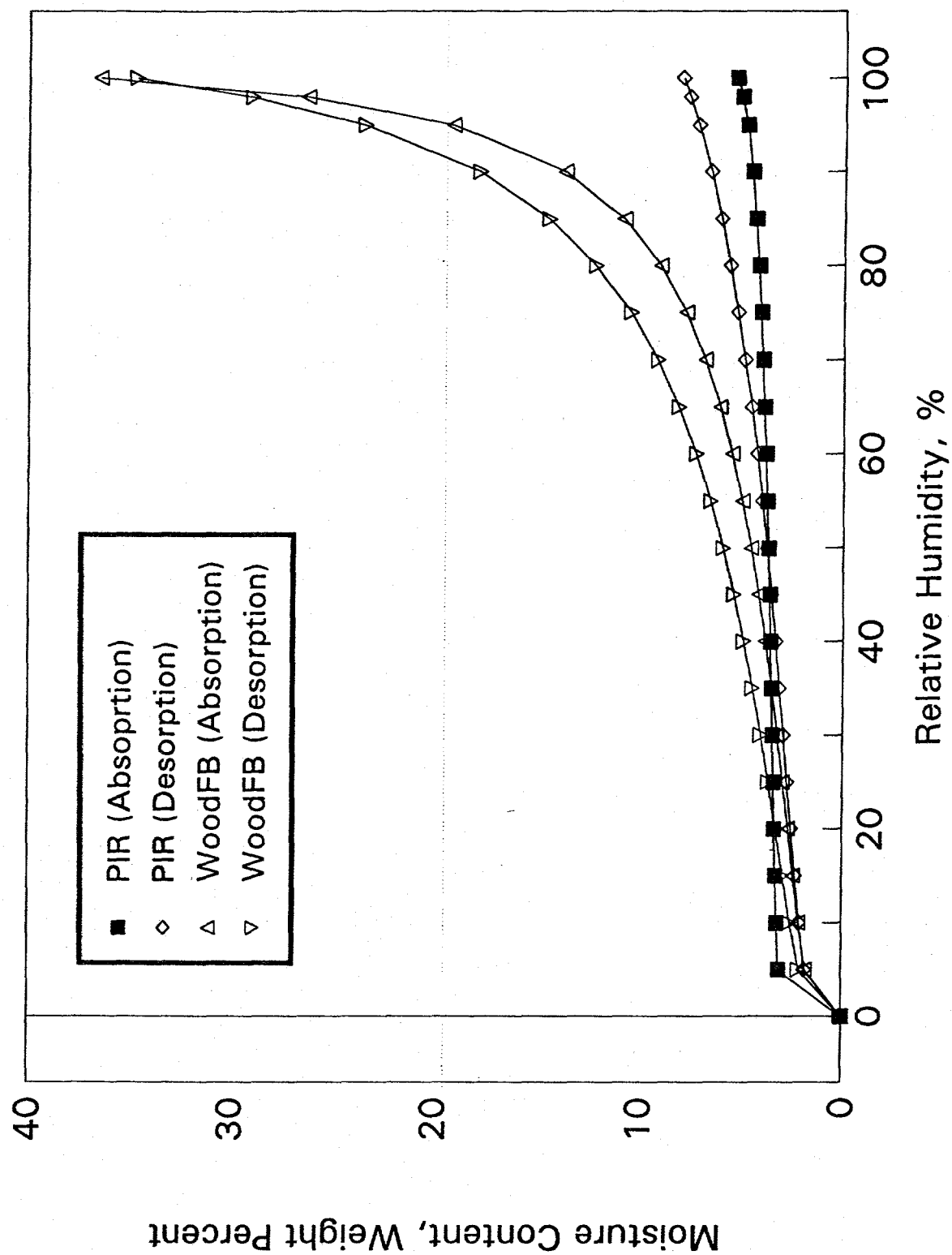


FIGURE 8

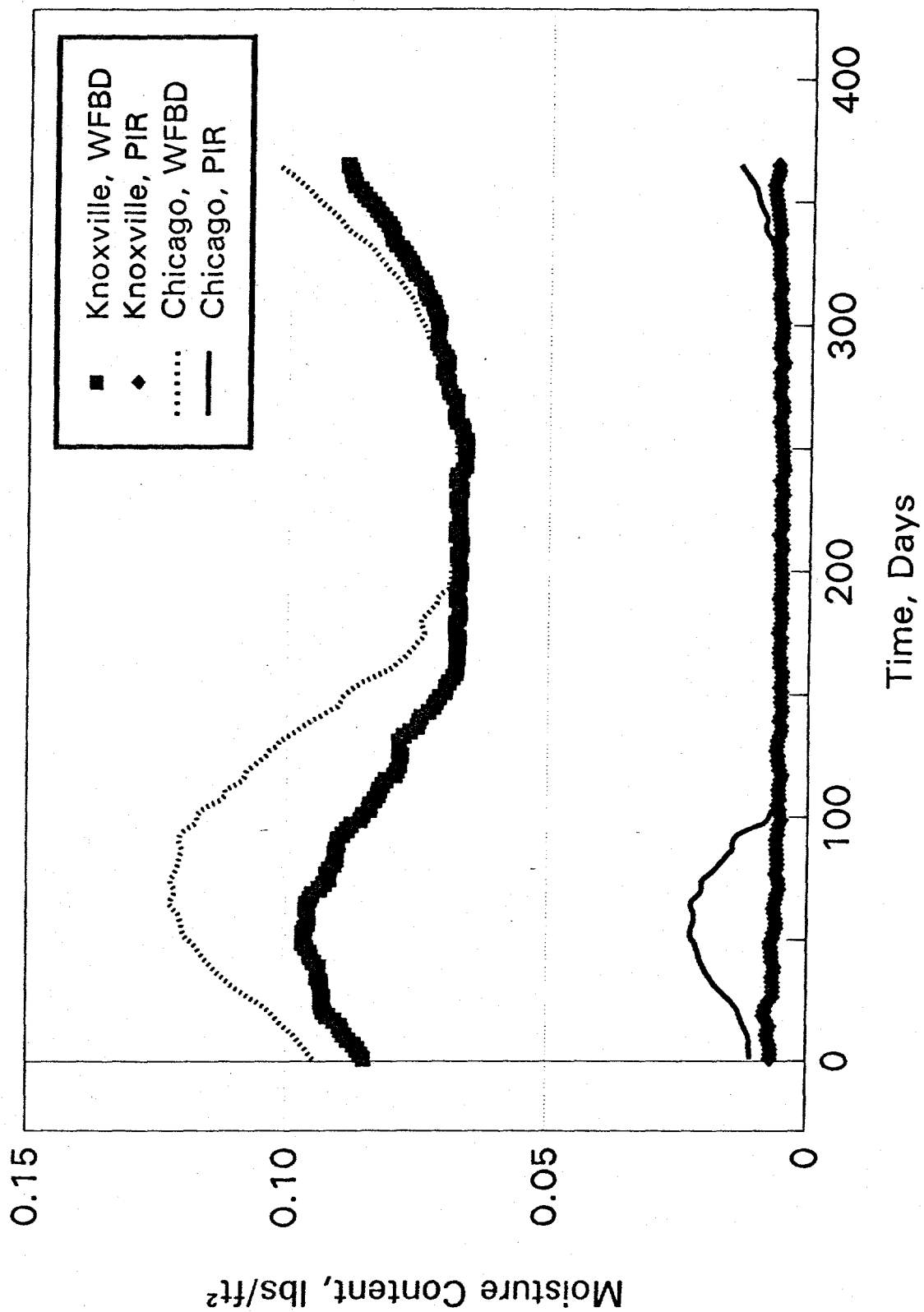


Figure 9

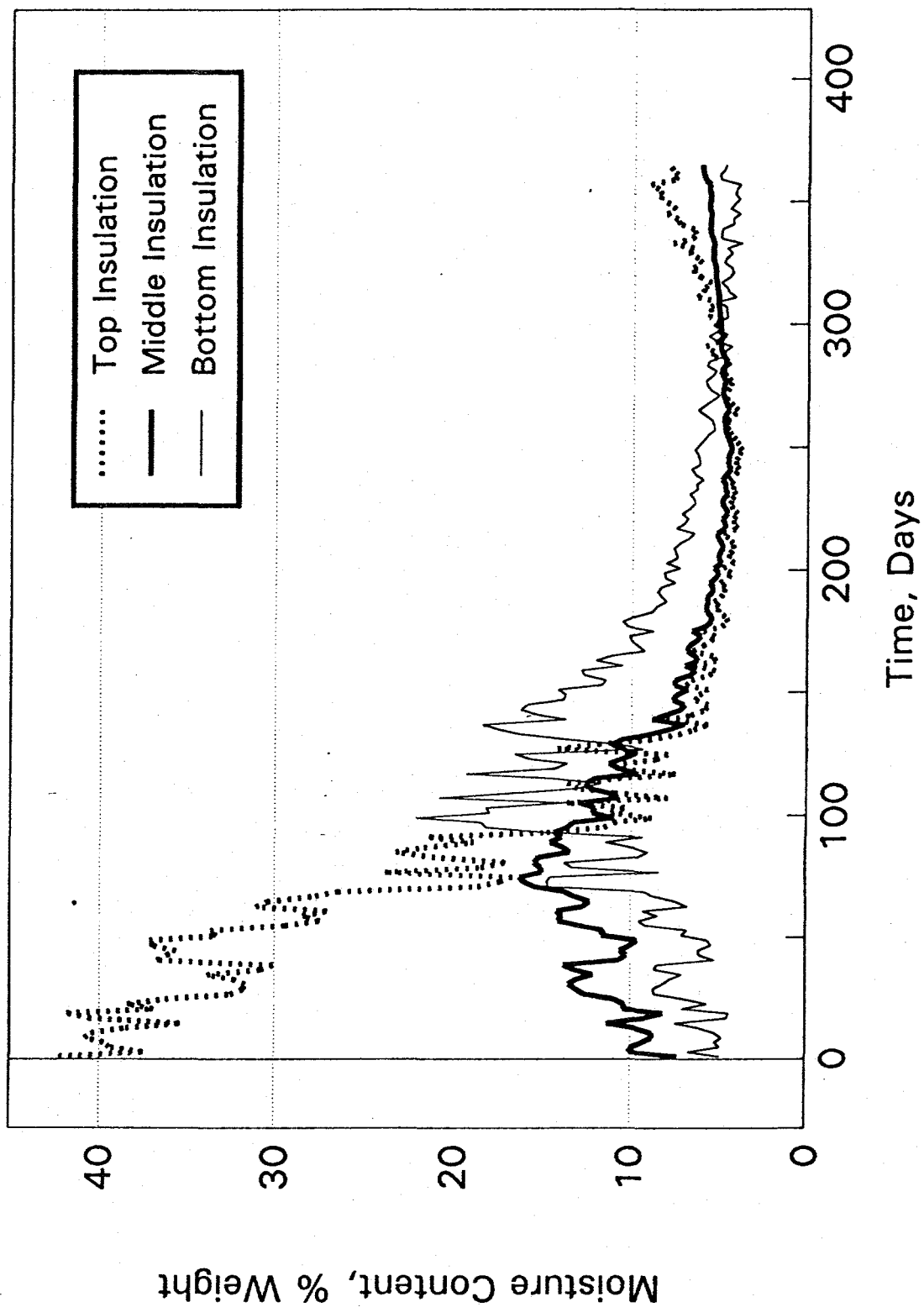


Figure 10

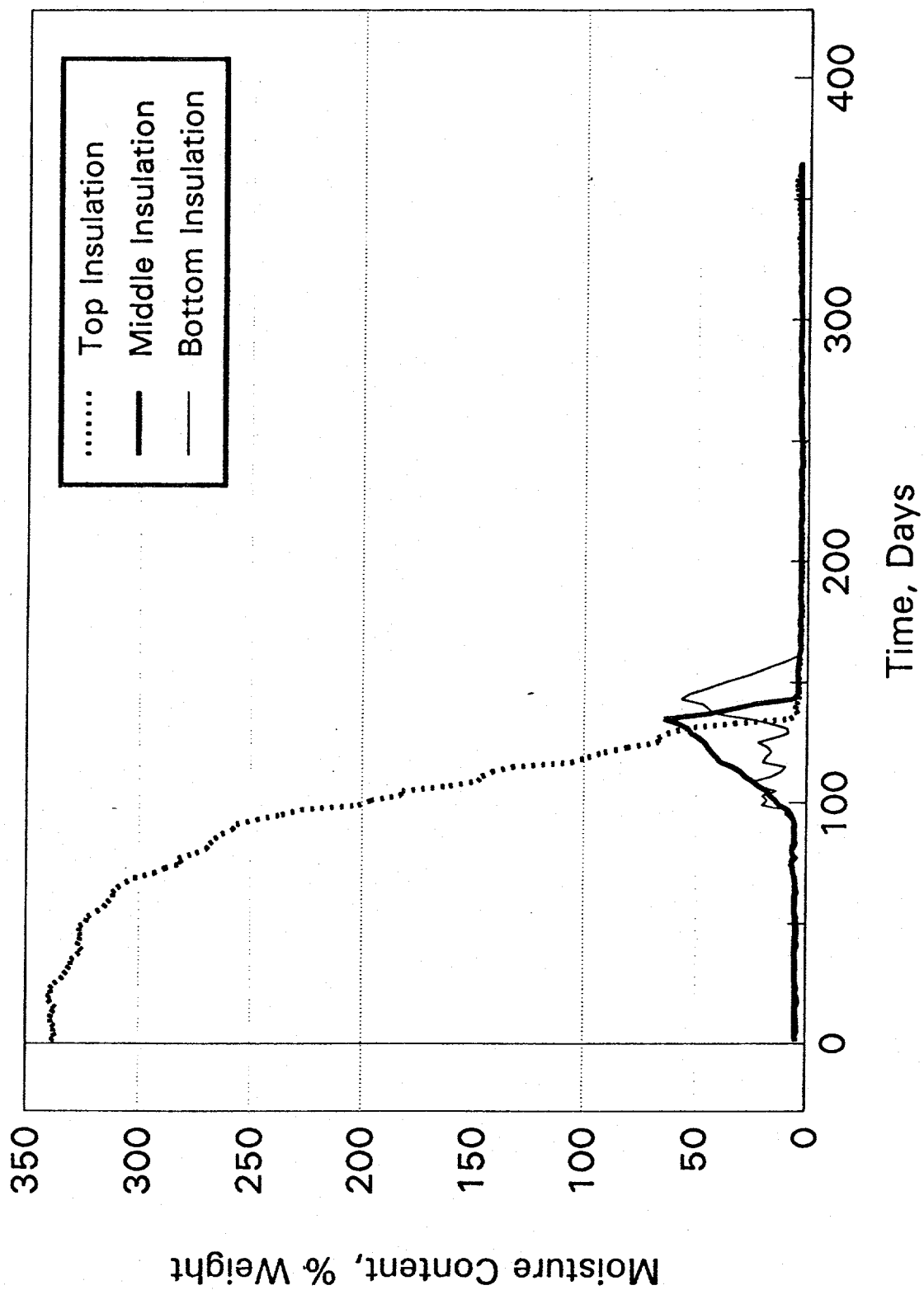


Figure 11

