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ASSESSMENT OF TECHNOLOGIES FOR CONSTRUCTING SELF-DRYING LOW-SLOPE ROOFS

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NOMENCLATURE

Arabic symbols

C_{recov}	cost of recover roofing, $/ft^2
$C_{replace}$	cost of replacement roofing, $/ft^2
C_{new}	cost of new roofing, $/ft^2
F_{recov}	fraction of all reroofing having recover membranes
$F_{replace}$	fraction of all reroofing having replacement membranes
h	enthalpy
j_v	vapor diffusion flux
j_l	liquid diffusion flux
k_{wet}	thermal conductivity of wet insulation
k_{dry}	thermal conductivity of dry insulation
$\dot{m}$	mass flow rate
N_{reroof}	annual reroofing activity, ft^2
N_{new}	annual new roofing activity, ft^2
$p_{v,x}$	vapor pressure at location x
p_{sat}	saturation vapor pressure
P_{recov}	probability that an unrecovered roof will be recovered after it fails
$P_{replace}$	probability that an unrecovered roof will be replaced after it fails
Q	energy flux
R_T	thermal resistance
R_v	vapor resistance
rh	relative humidity
SL_a	actual service life of a roof
SL_d	design service life of a roof
T	temperature
ΔT	indoor-outdoor temperature differential
w	moisture content
Δx	insulation slab thickness

Greek symbols

α_T	thermal diffusivity
α_v	vapor diffusivity
μ	vapor permeability of air
ρ	density
τ	characteristic time

Subscripts

a	air
bl	boundary layer
db	drybulb
dewp	dew point
ID	indoor
l	liquid
OD	outdoor
T	temperature
v	vapor

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ABSTRACT

Issues associated with removing excessive moisture from low-slope roofs have been assessed. The economic costs associated with moisture trapped in existing roofs have been estimated. Based on the limited amount of available data, the evidence suggests that existing moisture levels cause approximately a 40% overall reduction in the R-value of installed roofing insulation in the United States. Excess operating costs are further increased by a summertime heat transfer mode unique to wet insulation, caused by the daily migration of water within the roof. By itself, this effect can increase peak electrical demand for air conditioning by roughly 15 W/m^2 of roofing, depending on the type of insulation. This effect will increase peak demand capacity required of utilities in any geographic region (e.g., 900 MW in the South). A simple formula has been derived for predicting the effect that self-drying roofs can have upon time-averaged construction costs. It is presumed that time-averaged costs depend predominantly upon (1) actual service life and (2) the likelihood that the less expensive recover membranes can be installed safely over old roofs. For example, an increase in service life from 15 to 20 years should reduce the current cost of roofing ($12 billion/year) by 21%. Another simple formula for predicting the reroofing waste volume indicates that an increase in service life from 15 to 20 years might reduce the current estimated 0.4 billion ft^3/year of waste by 25%.

A finite-difference computer program has been used to study the flow of heat and moisture within typical existing roofs for a variety of U.S. climates. Nearly all publicly available experimental drying data have been consulted. The drying times for most existing low-slope roofs in the United States are controlled largely by two factors. The first is climate: in warmer weather, downward drying is accelerated; in cooler weather, the process is halted and even reversed. The second major factor is the permeability of the structural deck to water vapor or the presence of a vapor retarder; if typical decks could somehow be made highly permeable and the use of vapor retarders limited, drying times would be reduced in all climates. If the deck were much more permeable than the roof insulation, then in seasonal climates, the permeance of the insulation would significantly influence the drying rate, but presently this is uncommon. Based on a limited number of computer simulations, we found that adding a recover insulation layer and membrane over wet fibrous insulation decreases the drying time, while recovering a closed-cell foam insulation increases the drying time. In most cases, recover causes the water to remain cooler during the hottest drying weather, reducing drying; but normal winter *wetting* (water pickup from the building interior) is reduced or arrested because all of the water is shielded from the cold by the recover insulation. The overall drying times are a yearly average of these two phenomena.

Often, the calculated drying times will be considered unacceptably long. A variety of retrofit options for accelerated drying of existing roofs have been analyzed physically. New roof designs that allow for rapid self-drying are proposed. These use common materials and appear to represent no significant increase in cost. These designs are based almost entirely upon the comprehensive experiments of Powell and Robinson [64]. It is argued that because of recent theoretical and computational work, the analytical tools are now in place to establish reliable self-drying design criteria for any region of the United States. Further validation of these tools through full-scale field studies is still required. An overall design methodology is proposed.

EXECUTIVE SUMMARY

A major cause of roof replacement is excessive accumulation of water in portions of the roof system, caused by the failure of the roofing membrane, poor system design, or poor construction practices. The accumulation causes dripping, accelerated membrane failure, poor thermal performance, the threat of roof structure deterioration, and the depreciation of building assets. Moisture accumulation can be reduced by controlling moisture ingress into the roofing system and facilitating its outflow. Traditionally, industry has addressed the issue by developing new systems that retard the rate of moisture inflow (i.e., improving the reliability of roofing membranes). Since most roofing systems will inevitably leak, our position is that the best strategy for reducing moisture accumulation in roofs must incorporate dependable ways of facilitating moisture outflow.

In the early 1970s, Powell and Robinson studied the issues of water contamination in roofing systems [64]. 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. . . . If the roofing leaks and the construction possesses self-drying characteristics, all that would seem necessary would be simple patching of the roofing, as compared to . . . costly replacement of roofing and insulation."

Their argument is as valid today as it was 20 years ago. In this report, we estimate the economic and environmental costs of allowing water accumulation to reside in roofs, we discuss the physical concepts surrounding water outflow from roofing systems, we look at methods to construct new roofs and retrofit existing roofs so that they are or can be made self-drying, and we describe the design mechanisms that roofing professionals can use to start constructing self-drying roofing systems.

We attempt to estimate the economic benefits associated with self-drying roofs. Excessive accumulation of water in the roof has the effect of increasing operating costs and time-averaged construction costs. The heating costs of a wet roof increase because water decreases the thermal resistance of roof insulation. Using the existing literature, we attempt to quantify the frequency and extent of water contamination and the thermal performance reduction due to the contamination. Using the surveys reported by Anderson [1] and the National Roofing Contractors Association [4, 5] and the laboratory thermal performance testing reported by Tobiasson [33], we estimate that the additional heating costs due to wet roofs for the U.S. roofing inventory is approximately 1.7 times the heat loss if all the roofs were dry. We estimate that the additional heating cost for a roof in the

Chicago area is approximately \$2.40/ft^2 for the design service life of the roof. Based on energy savings alone, a self-drying roof that adds less than this cost is economically viable.

Cooling costs are increased by water vapor diffusion through the roof insulation material. During a summer diurnal cycle, water vapor is driven to the cold (interior) side of the roofing system and condenses, releasing its latent heat. Using a combined heat and mass transfer model [78], we compute the hour-by-hour heat transfer for a variety of typical "dry" and "wet" low-slope roofs situated in Seattle, Chicago, and Knoxville. Using the surveys cited earlier and the mix of insulation products that were cited in these surveys, we estimate that for the American West, Midwest, and South, a summertime daily average of 500, 800, and 900 MW of electrical generating capacity, respectively, is required to offset the effects of water contamination in roofs. We estimate that the additional incremental electric demand charge associated with wet roofs in the Chicago area is approximately \$0.66/ft^2 for the design service life of the roof.

We state that the design service life of a roof system is shortened by water contamination. Freeze-thaw cycling of roofing components, accelerated membrane deterioration, corrosion of metal fasteners, and deck deterioration are all artifacts of water contamination. Uncontrollable dripping and the threat of structural failure (collapse) will motivate the building owner to address his or her roofing problem.

We have developed an expression that estimates the impact that self-drying roofs would have on roof construction costs. Annually averaged construction costs are a function of actual service life and the cost of new or reroof construction. Two types of reroofing are employed: tear off/replace, and recover. Presently, approximately 60% of reroofing (on an area basis) is recover. Recover roofs are considerably less expensive; we assume that replacement and recover costs are \$9.00 and \$4.00/ft^2, respectively. Clearly, recover practices dominate in determining average reroofing costs. While recover typically involves some risks, self-drying roofs, when appropriately used, will be safer to recover and therefore will reduce average construction costs. Based on our analysis, we estimate that increasing actual service life from 15 to 20 years would reduce construction costs by 21%, while increasing the probability of roof recover to 100% would produce a 7% reduction. Both an increase in actual service life and increased recover practices are likely benefits of self-drying roofs.

Using a similar analysis, we estimate that construction waste would decrease if self-drying roofs were constructed. Increasing actual service life from 15 to 20 years would reduce construction waste by 25%; increasing the probability of recover to 100% would reduce it by 11%.

Among other things, to design self-drying roofs requires a detailed understanding of how water will distribute itself within the roofing system. We again employ a combined heat and mass transfer finite difference model [78] to develop this understanding. We compare our modeling results to the field investigation of Hedlin [10, 11, 12, 13, 14] and find good agreement. We generalize these findings for roofs with relatively impermeable decks as follows:

Fibrous Insulations:
In highly permeable insulations (i.e., rigid fibrous glass, perlite, and fiberboard), moisture will quickly migrate to the low-permeance surface having the coolest daily average temperature, where it becomes highly concentrated. Moisture is broadly distributed only when averaged top and bottom temperatures are comparable.

Closed-Cell Insulations (plastic foams):

1. In regions with strong daily averaged downward heat flux in the summer *and* strong daily averaged upward heat flux in the winter, water is mainly distributed among the middle of the insulation thickness year round (more toward the top in Chicago, with stronger winters; more toward the bottom in Knoxville, with stronger summers). Some movement into and out of the top and bottom of the insulation occurs, but peak concentrations lag peak temperature differentials because of slow diffusion rates.

2. In seasonal climates with small downward heat flux in summer, most of the moisture steadily resides in the top portion of the insulation material. A relatively small portion is distributed in the middle layers (Seattle). In seasonal climates with small upward heat flux in winter, most of the water is in the bottom portion of the insulation thickness.

3. In climates with constant heating or constant cooling requirements, all of the water remains fixed in a thin layer in the insulation material adjacent to the coolest low-permeance surface (Miami).

With this understanding of how water distributes itself within the roofing system, we have developed a general formula to describe the rate at which water will flow into or out of a roof system.

$$\dot{m} = \frac{p_{v,indoors} - p_{v,x}}{\sum R_v} , \tag{1}$$

where $\dot{m}$ ($kg/m^2 \cdot s$ or $grains/ft^2 \cdot h$) is the rate at which water moves up into the roof assembly, $p_{v,indoor}$ (Pa or $in.\ Hg$) is the averaged indoor vapor pressure, $p_{v,x}$ is the vapor pressure at position x in the roofing system, and R_v is the resistance to vapor flow ($Pa \cdot m^2 \cdot s/kg$ or Rep) for each material in the roof between the indoors and position x [72, 73].

As water vapor diffuses into a region, the vapor pressure in the region continually increases until it reaches the maximum possible value, known as the "saturation vapor pressure," p_{sat}. As more water vapor enters the region, this excess vapor all condenses to liquid, since the humidity of the air no longer can increase. The saturation vapor pressure increases with increasing temperature. To show this dependence on temperature, we write $p_{sat} = p_{sat}(T)$.

We can now rewrite Eq. (1) for each season. During the summer, we know that just above the low-permeance deck, $p_{v,deck} = p_{sat}(T_{deck})$, since the insulation is saturated at that location. Application of Eq. (1) is now straightforward. During summer, the drying rate ($\dot{m}_v$) is given by

$$\dot{m}_v = \frac{p_{v,indoor} - p_{sat}(T_{deck})}{R_{v,bl} + R_{v,deck}} , \tag{2}$$

where $R_{v,bl}$ is the vapor resistance of the boundary layer beneath the deck.

During the winter, we know that just below the membrane, $p_{v,membrane} = p_{sat}(T_{membrane})$, since the insulation is saturated at that location. During winter, the drying or wetting is given by

$$\dot{m}_v = \frac{p_{v,indoor} - p_{sat}(T_{membrane})}{R_{v,bl} + R_{v,deck} + \sum R_{v,insulation}} . \qquad (3)$$

We find that Eqs. (2) and (3) apply for both fibrous and closed-cell insulations for parts of the year with roofs installed in seasonal climates. For climates that exhibit little seasonal change, Eqs. (2) or (3) can be used year around.

We use the finite difference program [78] to model some typical roofing systems with relatively low-permeance decks. Ignoring short-term diurnal effects, we note that summer drying is almost independent of insulation type. This observation is better understood by studying Eq. (2). In it, the only term impacting the drying rate that depends on the insulation material is $p_{sat}(T_{deck})$; the insulation R_T-value determines the deck temperature. However, winter drying is significantly impacted by insulation type since $R_{v,insulation}$ includes the vapor resistance of the insulation layer. A parameter that affects all moisture transfer is $R_{v,deck}$; it controls the rate of summer drying and contributes to the wintertime vapor resistance.

When roofs are recovered, the material-dependent values in Eqs. (2) and (3) change. During recover, roofers typically add some thermal resistance between the wetted portion of the roof and the climate and keep the old membrane in place and essentially intact under the additional insulation. During the summer, this additional thermal resistance reduces the temperature of the deck and therefore $p_{sat}(T_{deck})$. The net effect is a reduction in the drying rate. During winter, $p_{sat}(T_{membrane})$ is significantly increased, reducing the potential for roof wetting. If a substantial amount of insulation is added, $p_{sat}(T_{membrane})$ can become larger than $p_{v,indoor}$, and drying can occur year-round, even in northern climates. It is important to note that recover effectively creates a vapor retarder between the existing roof system and the recover system; to maintain self-drying characteristics, the old membrane must be made permeable.

We consider various reroofing retrofit options that can be used to enhance the moisture tolerance of the roofing system. These options use one of the following processes: downward diffusion, downward diffusion with bottom ventilation, upward diffusion, upward diffusion with top ventilation, and ventilation of the insulation layer itself. In any retrofit, it will be necessary to determine whether the deck has been structurally impaired and whether it will maintain its integrity during the time required for the roof system to dry.

Several researchers have successfully enhanced downward diffusion by drilling holes into the insulation/deck to reduce the vapor resistance of those components. Experiments performed at Oak Ridge National Laboratory (ORNL) on a metal deck indicate that for 13 mm (1/2-in.) diameter holes spaced 0.6 m (2 ft) apart in each direction (2.7 holes/m^2 or 0.25 holes/ft^2), the deck permeance increases by approximately 8.0×10^{-8} g/Pa·s·m^2 or 0.14 (English) perms. Caution needs to be exercised when using this procedure; modifying the deck can downgrade fire resistance and reduce the structural integrity of the deck (i.e., if the deck is prestressed concrete, the risk of damaging the reinforcing may be great), and certain bituminous membranes may drip into the building.

A means of further enhancing downward drying is to add bottom ventilation. A proposed method for doing so would be to ventilate the uninterrupted flutes of a metal deck. If the roofing system has a vapor retarder, the retarder must be perforated. The following principles are suggested for "safe" bottom ventilation.

- No wetting can occur if the dew point of the ventilating air stream is below the lowest temperature of any roof material exposed to the ventilation air.

- Often at night, radiative cooling brings the outer membrane temperature below the dew point of any available air stream (as evidenced by frost and dew). Contact between ventilation air and materials close to the outer membrane may cause wetting at this time.

- Energy conservation requires that for bottom ventilation, we select the indoor airstream under the constraints listed above. Selecting unconditioned outdoor air to bottom ventilate would thermally compromise the roofing system.

It has been speculated that upward diffusion might be a useful means to dry out roofs. A typical moisture relief vent is the most prevalent device that takes advantage of upward diffusion. Vents open up a small amount of area in the membrane for vapor diffusion. Experiments by Hedlin [44] and Tobiasson [56] demonstrated that very little drying occurs through vents. We verify these results analytically.

As with bottom ventilation, top ventilation (installing a ventilation layer between the existing roof system and the recover system after removing or compromising the permeance of the failed roof membrane) offers the opportunity to expose the entire top surface of the wetted roof system to outdoor air. Energy conservation practices require that unconditioned outdoor air be used for top ventilation, subject to the other limitations stated for bottom ventilation. During the heating season, $T_{membrane} \geq T_{db,OD} \geq T_{dewp,OD}$. $T_{dewp,OD}$ is also the dew point temperature of the ventilation stream when it enters the roofing system. It follows that the saturation vapor pressure just beneath the membrane, $p_{sat}(T_{membrane})$, is greater than the vapor pressure of the ventilation stream. During summer, we are accustomed to thinking of moisture being driven downward, not upward, in a wet roofing system. When an outdoor air stream is introduced, this thinking must change. The vapor pressure of the outdoor air stream is less than the saturation vapor pressure throughout the insulation—even the insulation near the cool deck—except occasionally in the Southeast. As a result, liquid anywhere will evaporate and diffuse toward the ventilation stream.

In the literature, "forced drying" refers to a technique that involves pumping air through the insulation by some mechanical means. As air flows through the insulation, some water will evaporate and be carried off in the airstream. This technique offers the opportunity to remove large amounts of water from the roof system. Several researchers [44, 46, 56, 60] have reported using this technique. The condition of the deck must be carefully considered when using this method because if the deck is not sealed, air from the building interior may be drawn into the roofing system. The type of insulation plays a critical role in forced drying; the amount of air that flows through an insulation material is dependent on the air permeability of the insulation material.

We have quantified the effectiveness of forced drying. Using the Chicago climate as an example, we calculate that, for a sealed deck with any type of insulation material, each cubic foot per minute of air flow removes 41 kg (91 lb) of water from May through October and 11 kg (25 lb) of water from November through April. For an unsealed deck, it turns out that for every 1 cfm of air flow from leaks, 36 kg (79 lb) of water are removed during May through October, and 13 kg (28 lb) of water are *deposited* from November through April. Note that these accumulations can be locally concentrated. Finally, because of the low air permeability of roofing insulations, we recognize that forcing even very small flow rates may be economically prohibitive.

We offer suggestions on how to design a self-drying roof. From the exterior side downward, the roof should include a membrane, an insulating board that is relatively impermeable to water vapor, a wicking layer to disperse any liquid, an insulation board that is relatively permeable to water vapor, a second wicking layer, and a vapor-permeable deck. The methodology includes a procedure for determining if a vapor retarder is required; if needed, it eliminates the use of a self-drying roof for that application.

If the deck is very permeable (very low R_v), then a layer of concentrated liquid should almost never form at the bottom of the insulation as a result of downward vapor diffusion. This speculation has been confirmed analytically, but it should be validated with full-scale testing before this approach is put into general practice. Any localized leaks will be dispersed by the wicking layer and allowed to diffuse into the building interior. The absence of water accumulating over the deck will significantly reduce the potential for dripping and deck deterioration.

The total vapor diffusion resistance, R_v, of the insulation layers has it optimum value when the expected wintertime moisture accumulation is equal to the maximum allowable accumulation. Installing less resistance than this would cause excessive moisture accumulation during winter. Installing more resistance than this would result in unnecessarily long drying times. This total vapor diffusion resistance should comprise a high-resistance upper layer and a low-resistance bottom layer. The low-resistance bottom layer is recommended to alleviate the possibility that water leaking into the roofing system might become trapped between the two insulation layers. The high-vapor-resistance layer provides the needed vapor resistance to control winter moisture uptake. The construction of the self-drying roof system should not include any high-vapor-diffusion resistance layer, such as asphalt used to adhere two layers of insulation material.

We list a simple methodology for designing self-drying low-slope roofs and the necessary inputs for their design. The roof designer's job is to design a reliable roof system having the maximum total thermal resistance, R_T, that is economically justifiable, and the *optimum* total vapor diffusion resistance, R_v, while maintaining the structural integrity and fire resistance of the roofing system. We suggest a procedure for specifying the optimum total R_v having four elements:

1. Calculate the expected wintertime moisture accumulation for a proposed design.

2. Compare the calculated accumulation with the "moisture limits".

3. If the moisture limits are exceeded, increase the vapor diffusion resistance of the design. If the calculated accumulation is far less than the moisture limits, reduce the vapor diffusion resistance of the design.

4. Finally, calculate the summertime drying. It should exceed winter accumulations in nearly all continental U.S. climates. If drying does not exceed wetting, then self-drying

roofs are not viable in the geographic region of interest and vapor retarders should be considered.

To perform these calculations, the designer must know the average summertime vapor pressure immediately below the membrane, $p_{sat,summer}$, and the average wintertime saturation pressure immediately below the membrane, $p_{sat,winter}$. These can be provided by researchers, who can calculate typical values using computational tools. The vapor pressure immediately below the membrane depends strongly upon the local climate and should therefore be calculated separately for each region of the country. The vapor pressure also depends upon the membrane type and color (which can change with time), which establish the radiative heat transfer properties, and upon the total R_T value of the roof. In summary, the designer will need a table pertaining to each geographic region that presents $p_{sat,summer}$ as a function of the membrane type and roof R_T. Another such table should present $p_{sat,winter}$. In addition, moisture limits for roof insulation materials must be set. These inputs dictate the maximum allowable amount of wintertime water accumulation.

1. INTRODUCTION

The service life of a roof ends when it is no longer capable of providing the desired protection. This failure usually is due to excessive accumulation of water in portions of the roof. The accumulation causes dripping, which can damage the building and its contents and can be a nuisance to occupants. The accumulation also causes depreciation of building assets through accelerated membrane failure and structural decay. Accumulated water also tends to increase operating costs by degrading the efficiency of the thermal insulation.

To reduce these effects, it is necessary to prevent moisture accumulation in all portions of the roof and reduce accumulation if it occurs. Moisture accumulation can be reduced both by delaying the inflow of water into the roof assembly and by facilitating the controlled outflow of water from the assembly. Historically, most roof systems and design strategies for preventing moisture accumulation have focused on preventing the inflow of water, for example, by improving the reliability of roofing membranes. This focus is rational in the sense that, so long as water is prevented from entering, there is no need to be concerned with controlling its outflow. Of course, many roofing membranes inevitably leak because of deterioration and other causes. For this reason, our self-drying strategy for preventing moisture accumulation incorporates economical and dependable ways to facilitate the controlled outflow of water from the roof assembly. This strategy should be considered by the roof designer.

In the early 1970s, Powell and Robinson at the National Institute of Standards and Technology (formerly the National Bureau of Standards) conducted an exceptionally comprehensive investigation of drying in roof assemblies [64]. 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. . . . If the roofing leaks and the construction possesses self-drying characteristics, all that would seem necessary would be simple patching of the roofing, as compared to . . . costly replacement of roofing and insulation." Furthermore, with a self-drying construction, "the insulating integrity of the roof construction could be maintained year-round," because water from minor leaks would not accumulate. The economic argument is as clear today as then. In Chapter 2, we use available data on current roofing practices to show that significant energy savings would be realized if roofs in the United States were self-drying. The capital that could be saved and the environmental benefits due to the longer service life associated with self-drying roofs also are shown to be significant.

Although excessive water may accumulate in portions of a roof, the owner may lack sufficient funds to replace it. For this reason, there is a practical need for *converting* a moisture-accumulating roof into a self-drying roof. First, the inflow of water must be stopped, for example by repairing or recovering the membrane. Subsequently, many roofs will eventually dry out [51]. After some preliminary physical concepts are discussed in Chapter 3, the drying rate of currently installed roofs is examined in Chapter 4.

After verifying the structural integrity of the deck, one can exploit techniques that facilitate the controlled outflow of moisture. In Chapter 5, we describe new and previously reported methods to facilitate drying. While our interest is in inexpensive options, the focus in Chapter 5 is not on cost but on the physical principles governing the operation of each technology. Several retrofit schemes are shown to be ill conceived, while others exploit sound physical principles and appear to warrant field testing and commercialization.

In Chapter 6, we assess methods for constructing new self-drying roofs. The roof assembly must allow invading moisture to leave the system within, say, a year. Simultaneously, the assembly must prevent a harmful amount of water from entering the assembly in the form of vapor. In Chapter 7, we argue that with a modest up-front engineering effort, these two goals can be achieved following simple guidelines and using existing, commonly installed materials. Because they will remain dry more consistently, these simple designs should extend the service life of many roofs and improve their year-round thermal efficiency.

Excellent summaries have already been written which discuss moisture issues in insulated low-slope roof systems [70, 73, 75]. This report is unique for its focus on roof drying technologies and assessment of their physical basis, using everyday language whenever possible to characterize these processes. Whenever new ideas require a more scientific discussion, a "Technical Note" is introduced in a way that does not interrupt the normal flow of the text. Full literature reviews have been conducted and are presented throughout the paper for each major topic.

2. ECONOMIC EFFECTS OF EXCESSIVE MOISTURE

Excessive accumulation of water in any portion of the roof not only increases operating costs but also increases time-averaged construction costs. In this chapter, we attempt to quantify these two effects. The calculations are qualitative because necessary information is lacking. Although imprecise, the results demonstrate the cost-effectiveness of self-drying roofs, and they are included for this reason.

2.1 OPERATING COSTS

The goal of this section is to compare the heating and cooling costs associated with existing roofs with those costs that would be associated with self-drying roofs. There are four subsections. The first quantifies potential reductions in winter heating costs. The second subsection describes physically how vapor migration within the roof assembly can increase building cooling loads. The third quantifies potential reductions in air-conditioning costs. The last briefly describes other types of operating costs that can be associated with excessive roof moisture.

2.1.1 Heating Costs

In this section, we estimate the potential heating energy that could be conserved by installing self-drying roofs, or by converting existing moisture trapping roofs into self-drying roofs.

Thermal conductivity of wet insulation

To quantify the increase in heat conduction due to moisture contamination, it is first necessary to learn how the thermal resistance value, R_T, varies as a function of moisture concentration. Heat conduction in moist materials has been investigated by an impressive list of authors, including, in English alone, references 7, 9, 10, 11, 15, 16, 17, 21, 22, 27, 29, 31, 32, 33, and 36. We have found Tobiasson's work [31, 32, 33] to be of practical use because he and his coworkers test the most common products used in the United States with consistent procedures.

The relationships between thermal conductivity and moisture concentration that have been reported for any given type of insulation can differ significantly. The variations are more pronounced for open-cell and fibrous insulations and are in part due to effects of vapor that is diffusing from one region in the insulation to another while the testing is conducted. This effect is acknowledged by nearly every author, and has been the subject of many thorough investigations [7, 16, 18, 19, 20, 22, 27, 29]. Variations can also be due to differences in *where* water is concentrated within the insulation as the testing is conducted. To our knowledge, this effect has not been measured. In Appendix A, a theory is developed for predicting how heat conduction will depend upon the time-averaged moisture distribution. In Appendix B, we review a few simple examples that show the effect can be very significant; we estimate that the water distribution can impact the heat flux through wet insulation by as much as 25%.

Moisture concentrations in installed roofs

Quantifying the increase in heat conduction also requires that we learn the moisture concentrations present in installed roofs. To our knowledge, the only extensive survey on this issue is by Anderson [1]. His results are based on 1,600 core samples. He does not describe in detail the method for determining the coring location on each roof, nor how the roofs were selected, so we cannot assess the statistical bias in his study.

A reviewer of this report expressed concern that these data greatly exaggerate the amount of water in roofs. We are probably using the data in a manner that is not consistent with their intended use. We are assuming that the moisture distributions presented in this survey are representative of the roofing inventory in the United States. It is probably safe to assume that a roof moisture survey company was not contracted to survey new roofs. We did discover that the company had several contracts with large commercial building owners to survey their entire building stock periodically. In summary, it is likely that the referenced survey does overestimate the amount of water contamination. However, we are unable to find another reference that contains this information. Until better information becomes available, the referenced survey is the *only data* in existence that supply the necessary information to estimate the economic impact of water in roof systems.

Heat loss calculations

Anderson's results for perlite are shown at the top of Fig. 2.1. Conduction data [33] are shown directly beneath them for the same moisture concentration range. We would like to know the ratio k_{wet}/k_{dry} where k_{wet} is the average conductivity of the wet insulation board and k_{dry} is the average conductivity of the dry insulation board. To estimate the average k_{wet}/k_{dry} for perlite roofs installed in the United States, we first multiply the frequency of occurrence for each moisture concentration value shown at the top of

Fig. 2.1 by the corresponding value of k_{wet}/k_{dry} shown at the bottom of this figure. The overall national average is obtained by summing the results from all of the concentration values. We note that Anderson published full histograms like the one shown only for perlite and for polyurethane. We have assumed that the perlite distribution, based on percent by volume, applies to all fiber-based insulations, and that the polyurethane results, based on percent by volume, apply to the closed-cell insulations.

Table 2.1 shows the average k_{wet}/k_{dry} for each insulation type. If a building owner knows the insulation type for a particular roof but lacks concentration data, then the third column in Table 2.1 can be regarded as an estimate of the excess heat loss through the roof.

Table 2.1 also shows the fractional rate of use for each insulation type for the period 1983–88 [4] and 1992 [5]. Reference [5] does not include a listing for wood fiber; the amount shown in Table 2.1 accurately reflects the reference but introduces an uncertainty in the analyses. When we multiply k_{dry} for each insulation by its fractional rate of use and sum the results for all insulations, we obtain a national average k_{dry} for all roofs installed in the United States: For roofs installed during 1983–88, overall k_{dry} = 0.036 W/m·°C (0.25 Btu·in/h·ft^2·°F); for roofs installed during 1992, overall k_{dry} = 0.032 W/m·°C (0.22 Btu·in/h·ft^2·°F). When we multiply k_{dry} by k_{wet}/k_{dry} and by the fractional rate of use for each type of insulation, and sum the results for all insulations, we obtain a national average k_{wet} for all roofs installed in the United States: For roofs installed during 1983–88, overall k_{wet} = 0.063 W/m·°C (0.44 Btu·in/h·ft^2·°F); for roofs installed during 1992, overall k_{wet} = 0.053 W/m·°C (0.37 Btu·in/h·ft^2·°F). The ratio of the overall k_{wet} to k_{dry} is a measure of the fractional increase in heat conduction attributable to excessive moisture in roofs for the entire United States: For roofs installed during 1983–88, overall k_{wet}/k_{dry} = 1.75; for roofs installed during 1992, overall k_{wet}/k_{dry} = 1.65. For example, if the initial R_T-value of roofing insulation installed during 1983–88 was 1.4 m^2·°C/W (8.0 h·ft^2·°F/Btu), then the effective R_T-value today would be 0.8 m^2·°C/W (4.6 h·ft^2·°F/Btu), on average. This is a startling 43% degradation in R_T-value.

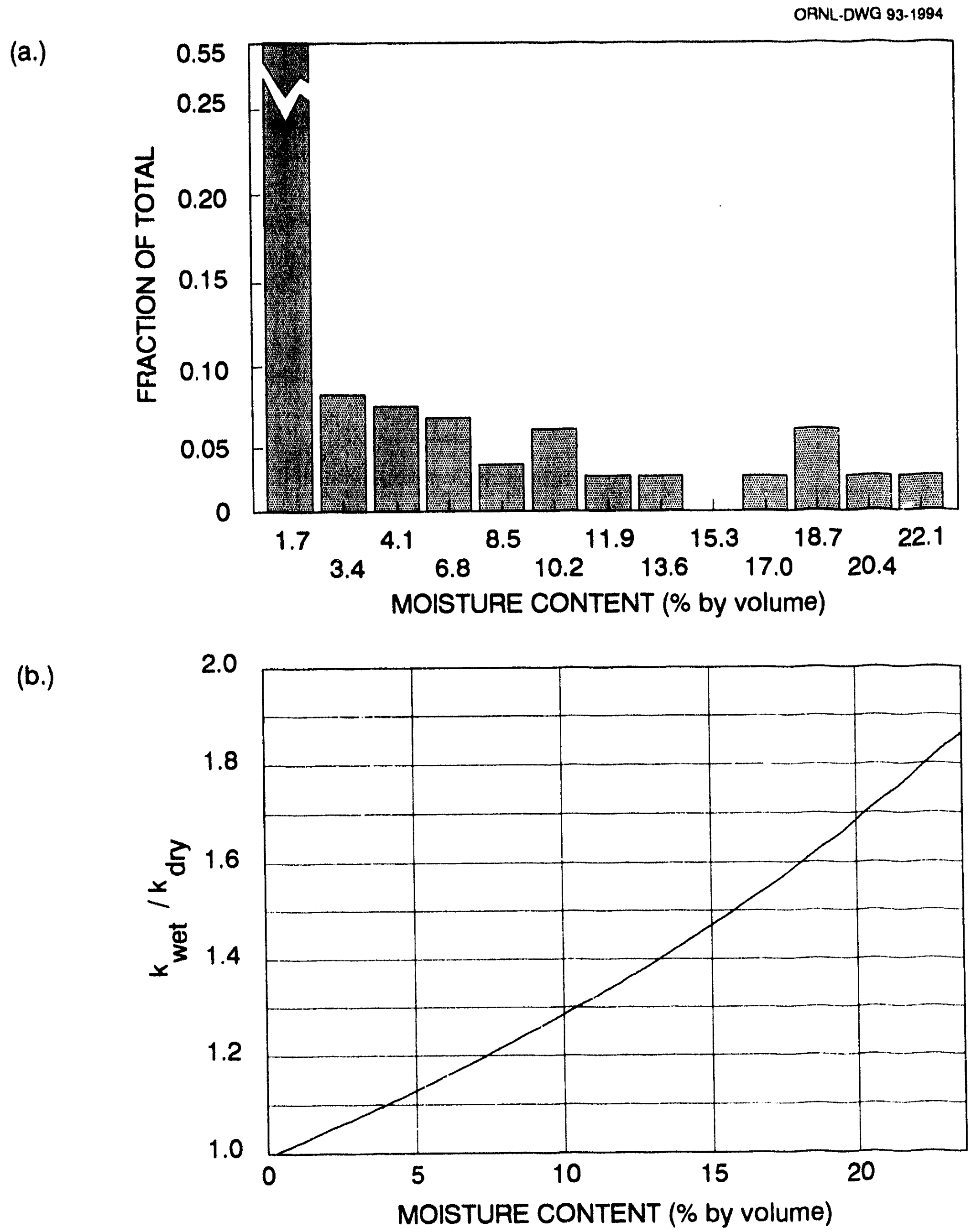

Fig. 2.1. Thermal effects of moisture in perlite insulation installed in the United States. (a) Distribution of moisture concentration derived from roof coring [1]; (b) thermal conductivity as a function of moisture concentration for perlite [33].

Table 2.1. Average ratio of wet to dry thermal conductivity k_{wet}/k_{dry} and relative rates of use for each common insulation type. Values for k_{wet}/k_{dry} were calculated as described in the text. Where original National Roofing Contractors Association tables listed "composite," "combination," or "other" types of insulation, those quantities were reapportioned over the eight insulations shown

Insulation	k_{dry} (W/m·°C)	k_{wet}/k_{dry}	Fraction of total installed: 1983–88 [4]	Fraction of total installed: 1992 [5]
Polyisocyanurate	0.021	1.14	0.28	0.49
Expanded polystyrene	0.034	1.22	0.08	0.12
Extruded polystyrene	0.029	1.27	0.08	0.06
Phenolic	0.016	1.30	0.00	0.03
Polyurethane	0.027	1.14	0.05	0.00
Wood fiber	0.058	1.76	0.18	0.00
Perlite	0.052	2.14	0.10	0.25
Glass fiber	0.036	2.35	0.22	0.07

Technical Note 2.1 Excess Conduction Heat Transfer Due to Roof Moisture

We first calculate the heating season heat flux through a typical roof assuming the insulation conductivity to be $\bar{k}_{dry}$ = 0.036 W/m·°C (0.25 Btu·in/h·ft²·°F). We have used C. Rode's computer program to calculate the wintertime heat transfer through a 51-mm (2-in.) insulated roof in Chicago [78]. We found that for a typical roof in Chicago, $\bar{Q}_{dry}$ = 14.6 W/m² (4.6 Btu/h·ft²) when averaged over the period from November through April.

When a roof is dry, the following traditional formula is often used to calculate the rate of heat loss:

$$\bar{Q}_{dry} = \bar{k}_{dry} \frac{\bar{T}_{deck} - \bar{T}_{membrane}}{\Delta x} . \qquad \text{(T2.1-1)}$$

Equation (T2.1-1) can be quite accurate, if the conductivity is not too dependent upon temperature, and if the averaging period is long. If the roof is wet, it is convenient to suppose

$$\bar{Q}_{wet} = \bar{k}_{wet} \frac{\bar{T}_{deck} - \bar{T}_{membrane}}{\Delta x} , \qquad (T2.1\text{-}2)$$

where T_{deck} and $T_{membrane}$ are the same as in Eq. (T2.1-1). Equations of the form (T2.1-2) are valid for wet systems under certain rather restrictive conditions that have been analyzed in Appendix A. We shall assume it is valid for now. Note that it is commonly observed that moisture has only a minor effect on the time averaged temperature.

Dividing Eq. (T2.1-2) by Eq. (T2.1-1), we find

$$\bar{Q}_{wet} = \bar{Q}_{dry} \times \left[\frac{k_{wet}}{k_{dry}}\right] . \qquad (T2.1\text{-}3)$$

Applying (T2.1-3) to the "dry" numerical results, and using k_{wet}/k_{dry} given in Table 2.1, yields

$$Q_{wet} = 14.6 \text{ W/m}^2 \times 1.75 = 25.5 \text{ W/m}^2 \text{ (8.1 Btu/h·ft}^2\text{)} .$$

The excess heat loss due to moisture contamination is therefore

$$Q_{wet} - Q_{dry} = 25.5 \text{ W/m}^2 - 14.6 \text{ W/m}^2 = 10.9 \text{ W/m}^2 \text{ (8.1 Btu/h·ft}^2\text{)} .$$

Heating costs

In Technical Note 2.1, the calculations show that from November to April, the seasonal heat transfer through a 51-mm (2-in.) thick insulated roof in Chicago that is attributable to excessive water is on the order of 10.9 W/m^2 × 180 days × 24 h/day × 3.6 kJ/W·h = 170,000 kJ/m^2 (15,400 Btu/ft^2).

Assume

15,400 Btu/ft^2 average excess annual heat loss,
138,000 Btu/gal heat of combustion for heating oil,
0.7 overall heating system efficiency,
$1.00/gal heating oil cost, and
15-year actual service life.

The annual heating cost savings will be

$$15{,}400 \text{ Btu/ft}^2\text{/year} \div 138{,}000 \text{ Btu/gal} \div 0.7 \times \$1.00\text{/gal} = \$0.16\text{/ft}^2\text{/year } (\$1.72\text{/m}^2\text{/year}).$$

The approximate present worth of savings over the life of the roof will be, assuming escalation rates equal to discount rates (simple payback),

$$\$0.16\text{/ft}^2\text{/year} \times 15 \text{ year} = \$2.40\text{/ft}^2 \ (\$25.80\text{/m}^2)\ .$$

If the roof is found to be wet, then excess annual energy costs do not justify the increase in amortized construction cost ($\sim\$8/\text{ft}^2 \div 15$ year $= \$0.53/\text{ft}^2/\text{year}$ or $\$5.75/\text{m}^2/\text{year}$) that would be incurred from replacing an otherwise serviceable roof. On the other hand, at the time of reroofing, installing a self-drying roof is economical based on energy savings alone so long as it adds less than $\$2.40/\text{ft}^2$ or $\$25.80/\text{m}^2$ in construction costs. In Chapter 4, we describe self-drying roof designs that cost far less than this, or at the limit, cost no more than a roof system that traps moisture.

2.1.2 Physical Description of Heat Transfer by Vapor Diffusion

Consider the heat transfer that occurs when a boiling pot sits on an electric stove. Heat flows from the electric grid through the pot into the water, but the water temperature does not increase! This means that heat is not accumulating in the water; the heat that is conducted into the pot of water must be balanced by energy that is being transferred out of the pot of water. It is the vapor rising from the pot that transfers this thermal energy. Water vapor has much "latent energy" in every unit of mass (equal to the amount of heat it took to vaporize it). For each pound of steam that flows past the rim of the pot, about 1,000 Btu flows past the rim. *Vapor transport is another form of heat transfer—just like conduction.*

Next, consider any absorbing material that contains some water but has remained in an unchanging thermal environment for a period of time. A microscope would reveal tiny amounts of water clinging to filament and pore surfaces throughout the material. Now, suppose the temperature in one portion of the material is suddenly increased. Porous materials respond to such temperature changes in a special way. The total amount of water and water vapor within the heated region does not change immediately. What *does* occur immediately is that some fraction of the water is converted into vapor. This process is only slightly more complicated than the boiling that occurs in a pot. As in the pot example, *liquid inside an absorbing material is converted to vapor when heat is added.*

When a small region of the absorbing material is heated and some liquid is converted to vapor, there is suddenly an excess of vapor in that region. The water molecules want to spread out by moving away from the heated region to regions of lower vapor concentration, and they do. Unlike in the case of the boiling pot, the water molecules are not entrained by any moving air; the air inside the porous material is stationary, but the water molecules move anyway. The movement of water molecules through stationary air (and stationary solids) is called diffusion. As stated above, this vapor transport is a form of heat transfer but is not driven by temperature differences directly. Instead, concentration differences cause vapor to flow. We measure the concentration of water molecules using vapor pressure.

Drying Principle 2.1: Heat Transfer by Vapor Diffusion

When one region of a porous material is heated, liquid is converted to vapor within that region and the water vapor molecules become concentrated. We say that there is a high vapor pressure in the region. The molecules diffuse to regions where the vapor pressure is low. This movement of vapor is a form of heat transfer because the latent heat accompanying the vapor is transported to the regions of low concentration.

Langlais et al. have conducted laboratory studies of vapor diffusion through high-density fibrous glass boards [21]. When the temperature at the surface of the boards was abruptly increased, the heat flowing from the hot to the cold side of the moist boards would leap to four times the dry insulation value. The effect was due to water evaporating from the heated side and diffusing to the colder side, carrying latent heat with it. Hedlin studied glass fiber boards outdoors and measured significant heat transfer by vapor diffusion even at low concentrations (0-1% by volume) [13, 14]. Others have made related observations [7, 16, 18, 19, 20, 22, 27, 29].

2.1.3 Summer Air Conditioning Loads from Vapor Diffusion

In many roofs, at the dawn of each summer day, there is moisture distributed throughout the insulation. As the day proceeds, the roofing membrane warms up, and so does the insulation material directly beneath the membrane. Vapor is formed in this layer and immediately starts to diffuse downward. This is a form of heat transfer into the building; if the vapor enters the building and must be removed to control humidity to an acceptable level, a latent load is placed on the air conditioning. If the vapor condenses at a surface below the insulation and transfers the energy released during condensation into the building, a sensible load results.

Heat transfer by vapor diffusion in fibrous glass insulation has been studied numerically by Pedersen (now Rode) and Courville [79]. Using Rode's finite-difference code [78], they calculated the conduction heat transfer and vapor diffusion heat transfer on an hour-by-hour basis for four different U.S. cities. We have repeated their calculations with glass fiber and have extended the study to include polyisocyanurate (PIR), expanded polystyrene (EPS), perlite, and wood fiberboard. We examine the hour-by-hour heat transfer in roofs containing 51 mm (2 in.) of these insulations, with a built-up roof (BUR) membrane above and an impermeable deck below. We considered two different initial levels of moisture content. The "dry" case assumes an initial moisture content equal to what would be stored in the insulation if it were placed in an 80% relative humidity (rh) environment for a long time. We chose this condition to demonstrate that roofs need not leak to exhibit vapor diffusion effects. The "wet" case is 1% by volume. We chose 1% because it is small enough that the impact of the water on the wet R_T-value is small (see Subsect. 2.1.1), and the diffusion effects at this concentration have been shown to be significant [14, 79].

Figure 2.2 shows the average summertime values for the daily maximum heat flux for Seattle (representing the western U.S. climate), Chicago (representing the midwestern climate), and Knoxville (representing the southern climate). The averages are obtained by adding together the peak heat flux values recorded for each individual day during June, July, and August and then dividing this sum by the number of days. These averages provide representative values for calculating the surplus in peak electrical demand that the electric utilities in these cities are required to produce to meet air conditioning loads. We note that on nearly every day, the peak in roof heat flux occurs between 1:00 and 4:00 P.M., when electricity demands are high.

Clearly, vapor diffusion has the greatest impact on heat flux for wet glass fiber insulation, as depicted in Fig. 2.2. This fact is mainly due to the very low resistance to vapor migration in glass fiber; its vapor resistance is roughly half that of wood fiberboard and perlite and is two orders of magnitude less than that of EPS and PIR. Glass fiber, which starts out at 80% rh (its "dry" value), exhibits almost no vapor diffusion effect. The reason is that at relative humidities below approximately 98%, glass fiber stores very little water. With so little "moisture capacity," once a small amount of vapor diffuses away from

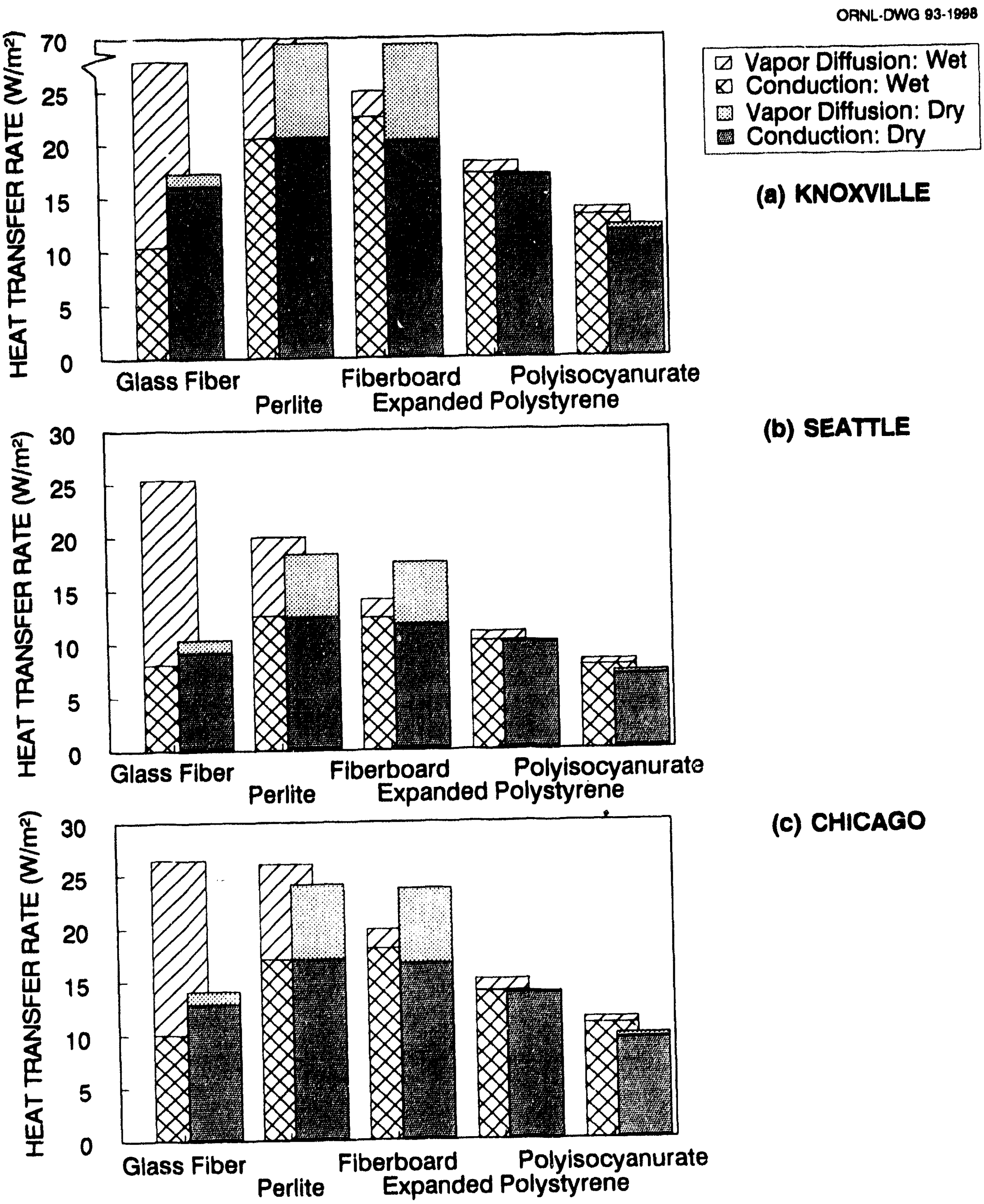

Fig. 2.2. Peak values in heat flux during summer for various insulations: "Wet" insulation contains 1% water by volume, and "dry" corresponds to equilibrium in a 80% rh environment. Data were calculated using a finite-difference computer program [78]. Values represent arithmetic average of daily peak flux values during June, July, and August. (See p. 10 of this report for roofing constructions.)

a heated region, the high vapor pressure in the region that was responsible for driving the diffusion cannot be sustained, and the diffusion rate falls off quickly.

Perlite and wood fiberboard are hygroscopic materials. This means that, when the surrounding dry air has an rh = 80%, the insulation material holds a relatively large amount of moisture. In perlite, this amount is almost equal to 1% by volume (our wet condition). In Fig. 2.2, we see that the vapor diffusion (or latent heat) transfer in the dry board (rh = 80%) is almost as great as for the wet case (1% by volume). Wood fiberboard is even more hygroscopic than perlite. In Fig. 2.2, the latent heat transfer for the dry case (rh = 80%) actually exceeds wet condition (1% by volume).

Finally, EPS and PIR are *not* hygroscopic. As with glass fiber, the moisture content at 1% by volume (wet) greatly exceeds the moisture level at rh = 80% (dry). Unlike fibrous glass, however, these closed-cell foams are highly impermeable to vapor diffusion. In Fig. 2.2, almost no latent heat load is seen even for wet boards.

The economic consequences of heat transfer by vapor diffusion are summarized in Table 2.2. An average wet and dry heat flux has been calculated by weighting the heat flux for each insulation type shown in Fig. 2.2 for three climates by the fractional rates of use shown in Table 2.1. The difference between the wet and dry averages represents the additional heat transfer through low-slope roofs attributable to water contained in roofs that are not self-drying. Using an estimate of the regional roof area and multiplying by the heat flux averages, we obtain the total rate of roof heat loss for each region. Multiplying this rate by the estimated air conditioning efficiency, assuming that the air conditioning is electric, provides an order-of-magnitude estimate for the excess daytime summer electrical generating capacity required as a result of vapor diffusion heat transfer. In the western United States, a summertime daily average of 500 MW is required in excess of what would be needed if roofs were self-drying. A surplus of 800 MW is needed in the Midwest and 900 MW in the South.

Table 2.3 displays the one-time absolute maximum heat fluxes that occurred at some moment during the 3-month summertime calculation period. These data are useful to building owners in each region for assessing the demand charges incurred as a result of moisture trapped in the roof. A sample calculation follows.

Table 2.2. Average daily maximum kilowatt demand due to summertime heat transport

	West			Midwest			South		
	Dry	1% wet	Diff	Dry	1% wet	Diff	Dry	1% wet	Diff
Weighted average flux for all insulation (W/m^2)[a]	12.0	16.0	4.0	13.6	17.2	3.6	17.9	21.3	3.4
Regional roof area ($10^9 m^2$)[b]	0.25	0.25	0.25	0.44	0.44	0.44	0.46	0.46	0.46
Regional demand(MW)[c]	1500	2000	500	3000	3800	800	4100	[illegible]000	900

[a] Derived from the quantities displayed in Fig. 2.2, weighted by the fractional installation rates listed in Table 2.1.
[b] Assumes $1.5(10^9)m^2$ installed low-slope roof area in the United States, divided among the four National Roofing Contractors Association market regions in proportion to their area. The Northeast has not been included in this table [5].
[c] Assumes air conditioning system coefficient of performance = 2.0.

Assuming

> 3,700 m^2 (40,000 ft^2) of roofing in Chicago,
> $30.00/kW-month incremental electric demand charge,
> 3 months of cooling,
> COP = 2.0,
> 10.6 W/m^2 cooling load reduction for 51-mm (2-in.) dry perlite roofs (Table 2.3), and
> 15-year actual service life.

Annual demand cost savings will be

$$10.6\ W/m^2 \times 3{,}700\ m^2 \times \$30.00/Kw\text{-}month \times 3\ months \div 2.0 = \$1{,}760\ .$$

Approximate total savings over the life of the roof, assuming simple payback economics, will be

$$\$1{,}760/year \div 40{,}000\ ft^2 \times 15\ year = \$0.66/ft^2 \text{ or } \$7.10/m^2\ .$$

2.1.4 Increased Maintenance Requirements

Once water enters the roof, it interacts with roofing assembly components in a way that often accelerates the degradation of the membrane. These effects are discussed by Bushing et al. [37], Tobiasson [70], Baker [73], and references cited therein. We note that

Table 2.3. Summer peak heat flux (W/m^2)

	Seattle			Chicago			Knoxville		
	Dry	1% wet	Diff	Dry	1% wet	Diff	Dry	1% wet	Diff
Glass fiber	10.9	48.6	37.7	15.1	50.3	35.2	22.6	53	30.4
Fiberboard	32.1	23.6	0	39	32.8	0	47.2	37	0
Expanded polystyrene	14.8	20.2	5.4	21.7	27.2	5.5	23.8	32.8	9.0
Perlite	32.0	35.6	3.6	36.4	47.0	10.6	46.4	54	7.6
Polyisocyanurate	12.3	15.1	2.8	15.6	20.7	5.1	20.3	25.	4.7

the cost of annual repairs can become extremely expensive, and is known to have forced the decision to reroof in many cases. Unfortunately, the literature does not provide the hard data required to quantify the increased roof maintenance costs, or costs associated with the need for premature reroofing resulting from moisture invasion.

2.2 TIME-AVERAGED CONSTRUCTION COSTS

In the Introduction, we stated that uncontrollable dripping and the threat of structural deterioration are caused by excessive accumulation of water in the roof. In many cases, it is one of these concerns which motivates the building owner to reroof. It follows that if these concerns could be reduced, then the service life of installed roofing materials would be extended. The results would be that (1) the building owner would enjoy lower annually averaged construction costs, and (2) the volume of construction waste generated annually in the United States would diminish significantly.

This section covers three topics. In the first subsection, we review published research concerning the processes that shorten service life. In the second subsection, the annual cost of roofing in the United States is estimated as a function of service life and as a function of tear-off and recover practices. In the third subsection, the volume of roofing waste is estimated as a function of service life and as a function of tear-off and recover practices.

2.2.1 Issues Affecting Service Life

Dripping

Occupants' intolerance of chronic dripping is surely a major factor in many reroofing decisions. Despite this, no published research was found specifically on dripping in low-slope roofs. Statistical information regarding the cost associated with interior damage due to dripping roofs would aid in identifying the full economic benefit of self-drying roofs.

Decks with vapor retarders are quite impermeable to water vapor ($<< 5.7 \times 10^{-8}$ g/Pa·s·m^2 or 1 English perm). Therefore, if a small leak in the membrane is persistent or regularly occurring, then over time, significant water can build up inside a roof system that is not self-drying. Water can travel laterally, especially along the surfaces of closed-cell insulation boards and through rigid glass fiber boards, so eventually the water usually finds a small opening through which to leak. System design may also impact lateral mobility of water. For example, water leaking into a mechanically attached single-ply system will be more mobile than in the same single-ply system with a fully adhered membrane. The leak is difficult to control because the source can be far from the drip and therefore difficult to find. Because of the buildup of water, the leak may not stop immediately after the membrane is repaired.

This is one possible scenario suggesting that chronic, uncontrolled leaks are more likely to occur if the material making up the deck both is relatively impermeable and has small openings. This conjecture is supported by a National Roofing Contractors Association (NRCA) survey of 41 problem low-slope roofs [2]. A reported 44% of the roofs had metal decks; yet of the roofs in which dripping was reported, a disproportionate 75% had metal decks. Although metal decks are considered to be permeable, they are in fact a composite of highly impermeable metal for a large percentage of their area and highly permeable air spaces (e.g., joints, burn holes) for the remaining area. Structural concrete that is poured in place is also quite impermeable, but it has a smaller percentage of openings due to cracks and consequently a lower rate of reported dripping.

There are only a few physical processes that lead to water buildup on the top surface of the deck. This buildup is necessary for dripping to occur. In Chapter 6, we describe how roofs can be designed to mitigate the processes leading to condensation on the deck and prevent water leaks from migrating to the deck through cracks and openings in the insulation. Our hypothesis is that these designs can virtually eliminate chronic, uncontrollable dripping.

Freeze-thaw cycling and delamination

Laboratory test procedures reported in the literature have involved the submerging of insulation samples for long periods before freeze-thaw cycling [40] or submerging the sample with every cycle [38, 39]. These tests simulate the performance of insulation materials in roofs containing copious amounts of water. Indeed, the reported tests were intended to investigate the suitability of insulations used in road construction [40] and in protected membrane roofs [38, 39]. Freeze-thaw damage in roof systems has been discussed by others as well [41, 42, 43].

It is important to note that these researchers have used test procedures that lead to moisture content levels of 50-90% *by volume* before the material finally breaks down. In fact, those materials that are able to absorb such amounts fastest are seen to break down first. We know of no reported freeze-thaw testing of absorptive insulations at moisture content levels that are typical of standard installed low-slope roofs (0-5% by volume) [1]. Experiments, which will be designed to test low-slope roofing materials and systems, should use realistic moisture content levels. They should also independently control the number of freeze-thaw cycles and the moisture content.

Metal corrosion

The issue of fastener corrosion has been examined comprehensively by Rossiter et al. [35; see references cited therein]. The issue of corrosion of steel decking used with phenolic insulation is explained by Smith and Carlson [36]. General discussions on corrosion found in references 35 and 36 are also informative.

The presence of water, or some electrolyte, is necessary for the corrosion of steel. In fact, the results of surveys show very strong correlations between fastener corrosion and insulation that is reported to be wet [35]. No quantification of moisture content was reported so that a more useful correlation could be developed. It appears qualitatively that (1) most insulations are hygroscopic materials and therefore contain some water, and (2) metal fasteners serve well in most installations. It follows that it is incorrect to think of insulations and fasteners as either wet or dry. Rather, there exist a range of relatively safe moisture concentrations, above which conspicuous corrosion occurs.

Winter condensation from upward diffusion is, by itself, an improbable cause of corrosion.[1] Condensation levels have been calculated using a finite difference program [78]. The results are shown in Fig. 2.3. For a roof composed of a BUR membrane, 51 mm (2 in.) of PIR insulation without facers, and a metal deck of average permeance (5.72×10^{-8} g/Pa·s·m^2 or 1.0 English perms), the peak wintertime moisture content is seen to be 0.2% by volume. The assumed indoor conditions were 22°C (72°F) and rh of 40%, and the Chicago climate was used as the outdoor conditions. These conditions do not necessarily apply to all buildings; buildings with higher interior levels of relative humidity will have higher concentrations of water diffusing into the roof. For glass fiber insulation, the peak concentration climbs to 0.4% by volume. Of all the roofs installed in the United States during 1983–93, 89% have no vapor retarder [4] and are subject to concentrations of ~0.4%. Most of these roofs have at least one layer of insulation mechanically fastened to a metal deck. We have already pointed out that metal fasteners serve well in most installations. The conclusion is that temporary seasonal moisture concentrations of the order of ~0.4% from upward diffusion are not a primary cause of rapid corrosion of metal fasteners.[2] Moreover, Anderson's survey indicates that the median moisture concentrations in installed roofs are of the order of 1–4% by volume [1]. Figure 2.3 suggests that upward vapor diffusion is not the primary source for the observed concentrations.

There is evidence that short periods of intense moisture contamination do not often result in advanced corrosion. Lightweight insulating concrete decks are cast in place with considerable mixing water. For some types of lightweight insulating concrete, the water is retained for some time. Subsequent inspection of steel fasteners used in constructing the systems reveals that the fasteners generally do not degrade significantly [51]. On the other hand, if membrane leaks exist, which cause prolonged wetting of the fastener, then these same fasteners may degrade. Typically, the portion of the fastener not in the deck degrades, as the concrete provides some protection for the embedded portion of the fastener.

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[1] Depending upon the ambient conditions and interior relative humidity, condensation-induced corrosion for phenolic foam cannot be ruled out.

[2] Fasteners, particularly those produced within the past few years, have much greater corrosion resistance than most decks.

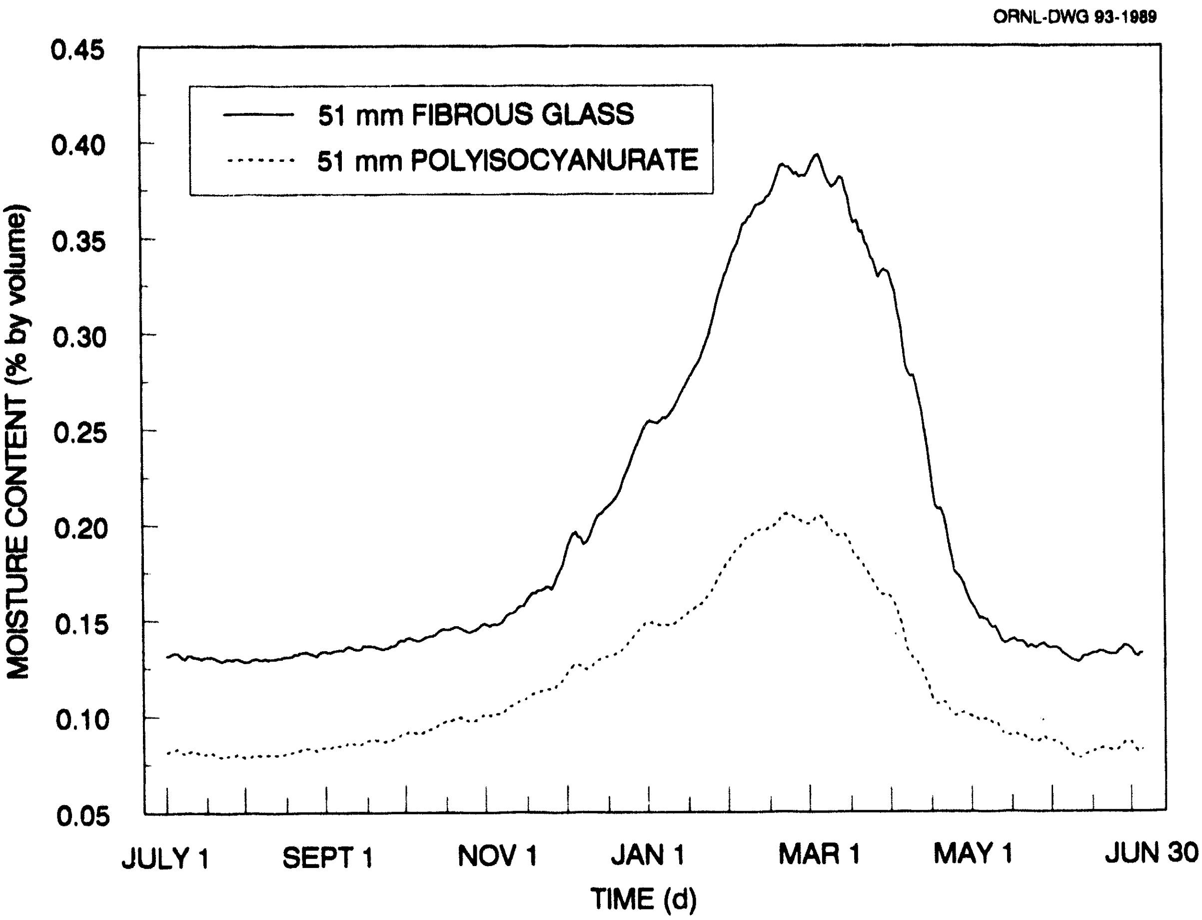

Fig. 2.3. Moisture concentration resulting from vapor diffusing through a typical metal deck. The data were calculated using a finite-difference computer program [78] assuming Chicago weather. Indoor conditions were 22°C (72°F), 40% rh. See text for construction details.

2.2.2 Calculation of Annually Averaged Construction Costs

Annually averaged construction and maintenance costs are mainly a function of the service life and of the cost of new roof and reroof construction. In the previous subsection, several problems relating to service life were discussed, but estimating the increased service life from data in the open literature is not possible. Therefore, in this subsection we treat service life as an independent variable, which presumably can be estimated by some method.

We shall consider the effect that recover practices have on the average cost of reroofing. In 1992, recover comprised roughly 40% of the U.S. commercial reroofing market and tear-off comprised 60% (on a dollar basis) [5]. A total of $9.3 billion was spent for reroofing (not including new construction). Recovered roofs are considerably less expensive. If we assume, based on an informal limited survey, that replacement costs are on the order of $9.00/ft^2 and that recover costs are on the order of $4.00/ft^2, then it follows that ~60% of the reroofed area was recovered, and only ~40% of the reroofed area was torn off. If all roofs had been recovered, $6.3 billion would have been spent; if all roofs had been torn off, $14.2 billion would have been spent. Reroofing practices (the selection of tear-off or recover) determine average reroofing costs.

The safest reroofing option is to tear off. This reroofing option clearly allows for a more thorough evaluation of the deck integrity. Recover typically involves varying amounts of risk of premature failure [46, 47, 48, 51]. These risks are usually associated with the possibility of trapped water in the old insulation and with the structural integrity of the deck and fasteners. Clearly, these risks are reduced for roofs that continually self-dry. Thus, in addition to extending service life, *self-drying roofs will reduce the average reroofing and overall construction costs in the United States because they are so often safe to recover.*

Equations (T2.2-4) and (T2.2-2) in Technical Note 2.2 describe the annual cost of commercial roofing in the United States as a function of service life and of P_{recov}, which is the probability that an unrecovered roof will be recovered after it fails. Currently, P_{recov} = 0.60 in the United States [5]. Equation (T2.2-4) in Technical Note 2.2 has been plotted in Fig. 2.4. It is assumed that unit costs for each type of construction are the same for self-drying roofs and currently installed roofs. These costs are as follows:

- 1.56(10^9) ft^2 annual reroofing construction [5],
- 0.54(10^9) ft^2 annual new roofing construction [5],
- $4.00/ft^2 recover cost,
- $5.00/ft^2 new construction cost, and
- $9.00/ft^2 replacement cost.

From Fig. 2.4, it appears that the greatest opportunity for reducing costs comes from increasing the service life. For example, an increase from 15 to 20 years reduces annual U.S. costs by roughly 21%. Increasing P_{recov} from the current 0.60 to the theoretical maximum of 1.00 produces only another 7% reduction. Self-drying roofs can reduce building costs because both these cost savings, an increase in service life and a greater opportunity to practice recover, can be obtained.

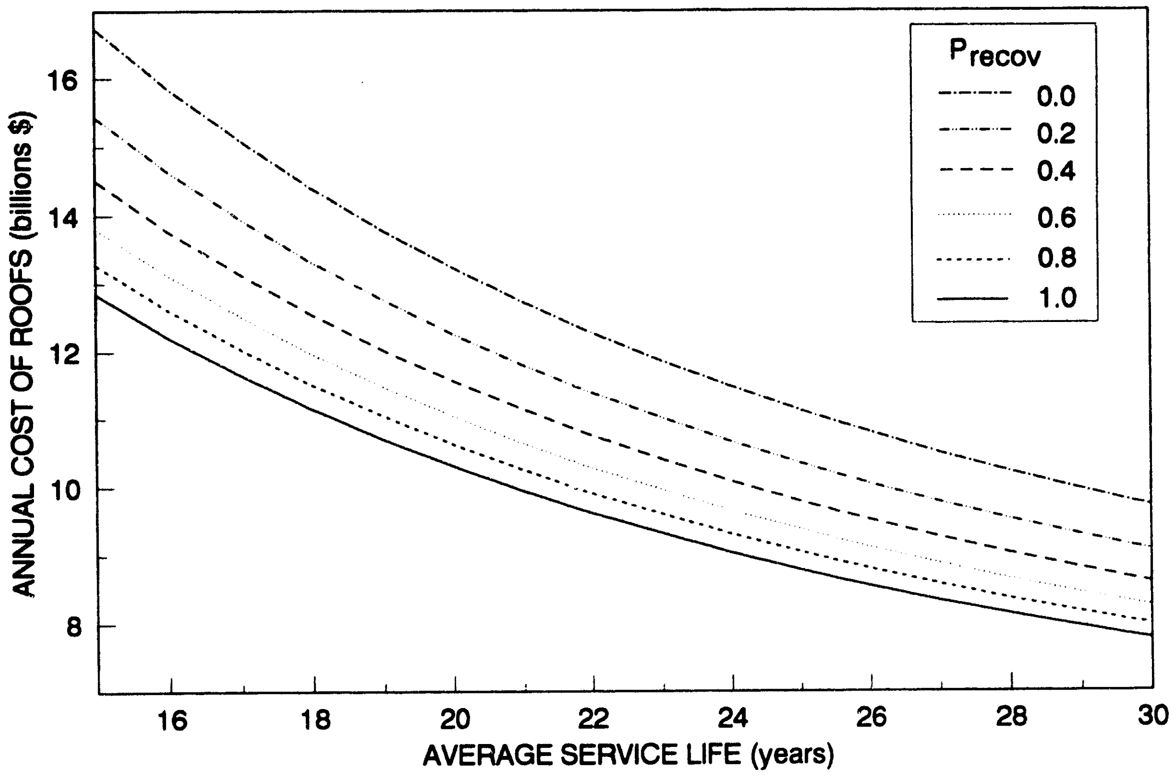

Fig. 2.4. Annual cost of roofing in the United States as a function of service life and recover practices. P_{recov} is the probability that a failed roof will receive a recover system if it does not already have one. The data are calculated using Eq. (T2.2-4) in Technical Note 2.2. See text for assumed parameter values.

2.2.3 Waste Volume Generated from Roof Replacement

The volume of waste generated from roof tear-off before replacement can be estimated using Eqs. (T2.3-1) and (T2.3-2) in Technical Note 2.3. The results are shown in Fig. 2.5. The greater opportunity for reducing waste volume appears to lie in increasing service life rather than improving the probability of recover. An increase from 15 to 20 years would decrease waste volume by 25%. Increasing P_{recov} from the current 0.60 to the theoretical maximum 1.00 would produce only an 11% reduction.

Technical Note 2.2: Total Annual Roof Construction Costs

Using several simple assumptions, we derive an expression that captures the dependence of U.S. construction costs on (1) average reroofing costs, and (2) service life.

Determining the Recover Rate:

Let P_{recov} denote the probability that an unrecovered roof will be recovered after it fails. The fraction of roofs that will not be recovered is $P_{replace} = 1 - P_{recov}$. Now, consider all of the unrecovered roofs in the United States which require reroofing this year. Of these roofs, P_{recov} will be recovered. Jumping forward in time to the next period when the same set of buildings again requires reroofing of some sort, what fraction of the original set of roofs will be recover roofs after the *second* reroofing? Because many building codes do not allow more than a single roof recover (no more than two roofs), the roofs being recovered must be chosen from roofs that were *torn off* the time before; the fraction receiving recover roofs this time is $P_{recov} \times P_{replace}$. All other roofs in the set will be torn off to satisfy the building code requirements. Generalizing to n cycles, it follows that

On the n^{th} reroofing:

$$F_{recov}(n) = F_{replace}(n-1) \times P_{recov} \qquad \text{(T2.2-1)}$$
$$F_{replace}(n) = 1 - F_{recov}(n)$$

where $F_{recov}(n)$ is the fraction of the roofs that will have recover roofs installed during the nth reroofing. $F_{recov}(n)$ is the recover rate, and $F_{replace}$ is the replacement rate. Eq. (T2.2-1) defines a sequence $F_{recov}(n)$ where n is an integer. It can be shown that the sequence $F_{recov}(n)$ converges to the following limit:

$$F_{recov} = \frac{P_{recov}}{1 + P_{recov}} \quad for \ n \to \infty \ . \qquad \text{(T2.2-2)}$$

Eq. (T2.2-2) describes the average recover rate after a *long* time for a single set of roofs starting at a certain time. What we are really interested in knowing is the fraction of recovered roofs at any *given* time in the *near* future, including roofs that were reroofed at all different times in the past. Statistically, these two averages are the same only if the reroofing process is assumed to be ergodic. Assuming that the ergodic hypothesis is true is basic to statistical reasoning but not easily proved. For the sake of arriving at an approximate formula, we shall assume the process is ergodic.

If F_{recov} from Eq. (T2.2-2) is taken as a representative value for the overall recover rate, F_{recov}, we can write down an approximate expression for the annual roofing construction costs. Let C_{recov} and $C_{replace}$ and C_{new} denote the per-square-foot cost of recover, replacement, and new building construction, respectively. Let N_{reroof} and N_{new} denote the number of square feet of reroofing construction, and of new building construction, respectively. Then,

$$Cost = N_{reroof}\left[F_{recov}C_{recov} + F_{replace}C_{replace}\right] + N_{new}C_{new} . \qquad (T2.2\text{-}3)$$

Service Life Effects:

If the average service life of installed roofs were twice as long, then the annually averaged cost of reroofing would be half the current value. That is, average reroofing costs in the United States are inversely proportional to the average service life. We simply modify Eq. (T2.2-3) as follows:

$$Cost = N_{reroof}\left[F_{recov}C_{recov} + F_{replace}C_{new}\right]\left[\frac{15}{SL_a}\right] + N_{new}C_{new} , \qquad (T2.2\text{-}4)$$

where SL_a is the average service life and the current average is presumed to be 15 years. Eq. (T2.2-4) therefore allows us to estimate the impact that the longer service life of self-drying roofs will have on average U.S. roofing costs, as well as the effect of increasing P_{recov} because self-drying roofs will usually be safe to recover.

Technical Note 2.3: Waste Volume Generated from Tear-Off

Using the assumptions presented in Technical Note 2.2, we derive an expression for the volume of waste generated whenever a roof is replaced. We express the volume as a function of (1) fraction of roofs recovered, (2) service life, and (3) average assembly thickness.

Recall from Technical Note 2.2 the following definitions. F_{recov} is the fraction of the total reroofing area that is recovered in any period. $F_{replace}$ is the fraction of the total reroofing area that is replaced. N_{reroof} denotes the area (in square feet) that is currently reroofed annually. SL_a is the average service life for replaced roofs, recovered roofs, and new construction.

The annual waste volume generated from tearing off unserviceable roofs is proportional to the total area of roofs that are being replaced that year. In the current market, Volume $\propto F_{replace} \times N_{reroof}$. If construction practices are changed so that the average service life, SL_a, is extended, then total reroofing area per year should vary as SL_a^{-1}. Finally, an informal survey of industry sources estimates that after the material is removed from the roof, the waste occupies twice its installed volume. The waste volume is also proportional to the average thickness of the roofs being replaced. Thus

$$Waste\ \ Volume = \frac{15}{SL_a}\left[N_{reroof}\ F_{replace}\right]\left[2\ \ \Delta x_{ave}\right], \qquad (T2.3\text{-}1)$$

where, in addition, the current average service life is presumed to be 15 years and Δx_{avg} is the average thickness of the roof system. We assume no tear-off waste is generated from recover work or from new buildings under construction, although some waste is generated in each case.

Average Thickness

Let Δx_1 denote the average thickness of installed roofs that have not been recovered. This is perhaps ~51 mm (2.0 in.) if we include the insulation and membrane. Let Δx_2 denote the average total thickness of installed roofs that are recovered. This is perhaps ~67 mm (2 5/8 in.). The average thickness of roofs that are torn off and replaced is

$$\Delta x_{ave} = \frac{\Delta x_2 F_{recov} + \Delta x_1 (F_{replace} - F_{recov})}{F_{replace}}. \qquad (T2.3\text{-}2)$$

From Technical Note 2.2 the following definitions are repeated

$$F_{recov} = \frac{P_{recov}}{1 + P_{recov}}; \qquad (T2.3\text{-}3)$$

and

$$F_{replace} = 1 - F_{recov} = \frac{1}{1 + P_{recov}}. \qquad (T2.3\text{-}4)$$

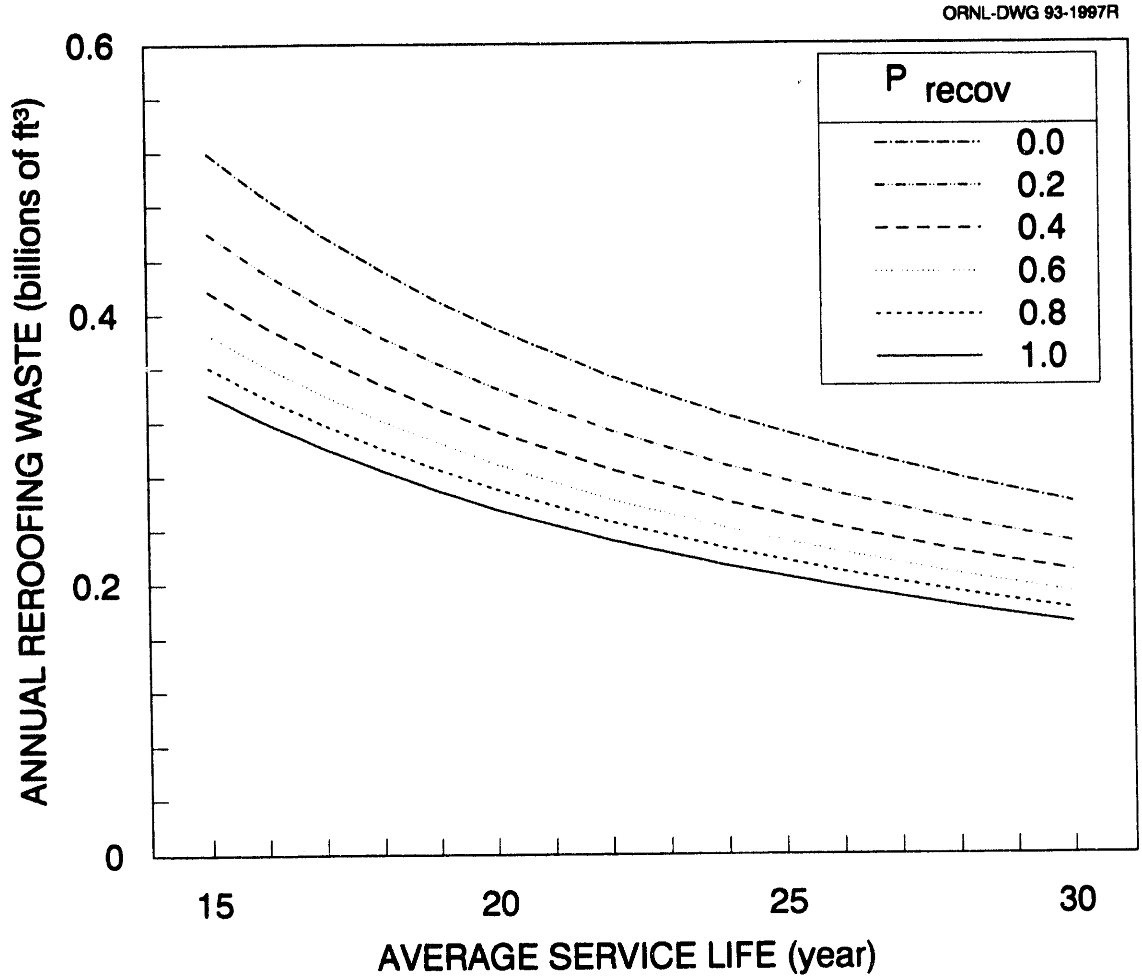

Fig. 2.5. Annual waste volume from roof replacement in the United States as a function of service life and recover practices. P_{recov} is the probability that a failed roof will receive a recover system if it does not already have one. The data are calculated using Eq. (T2.3-2) in Technical Note 2.3. See text for assumed parameter values.

3. VERTICAL DISTRIBUTION OF WATER WITHIN THE INSULATION

This brief chapter serves as preparation for the remainder of the report. It presents details on where water is expected to be found within the insulation as the year progresses. This knowledge is necessary to understand how existing roofs dry (Chapter 4) and how new drying techniques (Chapter 5) and new designs (Chapter 6) can help increase the drying rate. For example, if all the water moves to the bottom of the insulation during the summer, then this type of "vertical distribution" will strongly influence the summer downward drying rate.

How does the distribution of water vary in practice? Field studies that monitor the distribution of moisture are rarely reported in the literature. A notable exception is the work of Hedlin [10–14]. Hedlin installed glass fiber, phenolic foam, and extruded polystyrene in the roof of outdoor test facilities in Saskatoon, Saskatchewan, on the Canadian prairies. In that climate, the temperature on the top of the insulation is consistently colder than the bottom temperature during the winter. In summer, these temperatures are comparable, and solar effects cause the direction of heat and moisture flow to reverse diurnally.

The movement of moisture within Hedlin's facility is depicted in Fig. 3.1. The three solid curves represent the percentage of the temperature difference across the bottom 1/4 (curve above Bottom Quarter 4), bottom 1/2 (curve above Quarter 3), and bottom 3/4 (curve above Quarter 2) of the insulation material. The dotted lines represent the indoor/outdoor temperature difference, ΔT. For fibrous glass (Fig. 3.1a), summer (day 200) starts with slightly smaller temperature differentials near the bottom. This means that there is more water in the bottom, where the wet insulation readily conducts heat and cannot support a temperature differential. As winter arrives, the water moves to the top layers, where the temperature differentials become very small. This cycle repeats. A similar cycle occurs for the phenolic (Fig. 3.1b). Phenolic has a vapor permeance that is one order of magnitude smaller than that of glass fiber, and different sorption properties as well. These differences cause the water to stay near the top for a longer period than in the glass fiber. Finally, the extruded polystyrene exhibits only subtle variations in water distribution over time (Fig. 3.1c). Some water does migrate to the top in winter, but with less influence on the temperature differential, and the migration appears to lag behind the temperature history. In the summer, water leaves the top quarter but only gets as far as the adjacent upper-middle quarter, where the temperature differential finally becomes small in late summer. The bottom quarter is always quite dry. Note that extruded

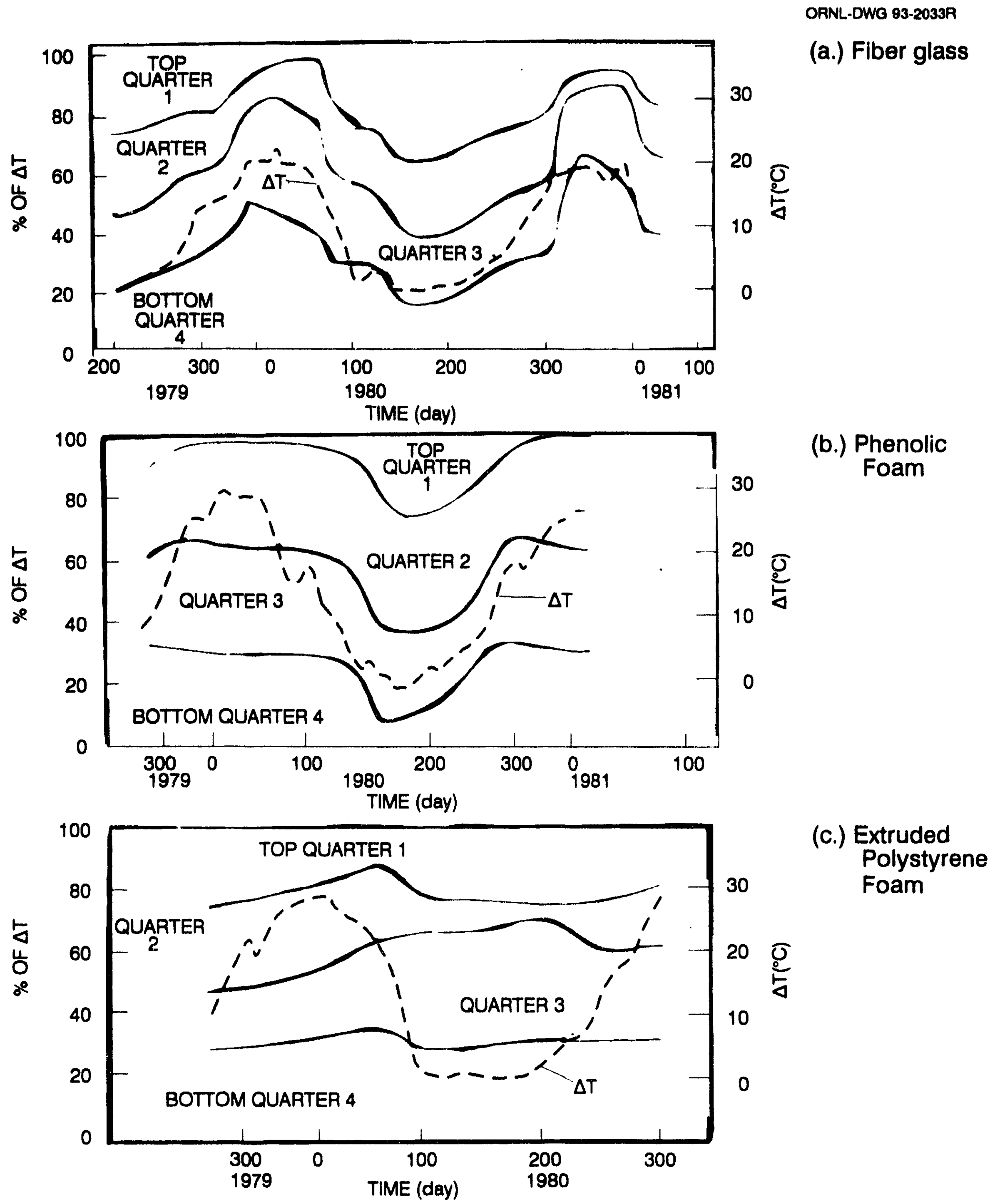

Fig. 3.1. Movement of moisture within various low-slope roofs located in Saskatoon, Saskatchewan, Canada. ΔT represents the indoor/outdoor temperature differential in °C. Temperature sensors were placed at quarterly positions within the insulation. Different temperature traces come close together whenever thermal conductivity increases within the bounded layer because of moisture accumulation. Time is measured in days (January 1 = Day 0). *Source:* Hedlin [11].

polystyrene has a permeance that is one order of magnitude smaller than that of phenolic and two orders of magnitude smaller than that of fibrous glass.

To learn more about how roof moisture migrates in the field, we have used a finite difference program for combined heat and moisture transport [78]. The model is validated with regard to predicting temperature and moisture distributions [45]. The moisture distributions for Chicago, Seattle and Miami are shown in Fig. 3.2. The simulated roofs consist of a BUR membrane, 51 mm (2 in.) of insulation and an impermeable deck (to prevent any water loss from the roof system). The roofs contain 5% by volume of water. Figure 3.2a shows the water movement for a fibrous glass roof in Chicago. The movements are qualitatively the same as those observed by Hedlin for a fibrous glass roof in Saskatoon. The change from daily averaged upward heat flow in winter to average downward heat flow in summer causes a rapid migration of water toward the bottom of the insulation. Figure 3.2b shows a PIR roof, also in Chicago. PIR has moisture transfer properties somewhat similar to those of the extruded polystyrene used by Hedlin in Saskatoon. As concluded from Hedlin's in-situ measurements of temperature, the bottom portion of the PIR is usually quite dry. The water migration into the top is slow and exhibits a time lag relative to the fibrous glass system. Figure 3.2c shows that a PIR roof in Seattle exhibits almost no moisture redistribution in the summer, primarily because of the reduced direct solar heating due to the overcast conditions prevalent in Seattle. Finally, we note that for the Gulf climate of Miami, the water never leaves the bottom layer during a typical year (Fig. 3.2d).

Generalizations drawn from Hedlin's in-situ observations and numerical studies at ORNL for roof systems with impermeable decks are highlighted in Drying Principle 3.1.

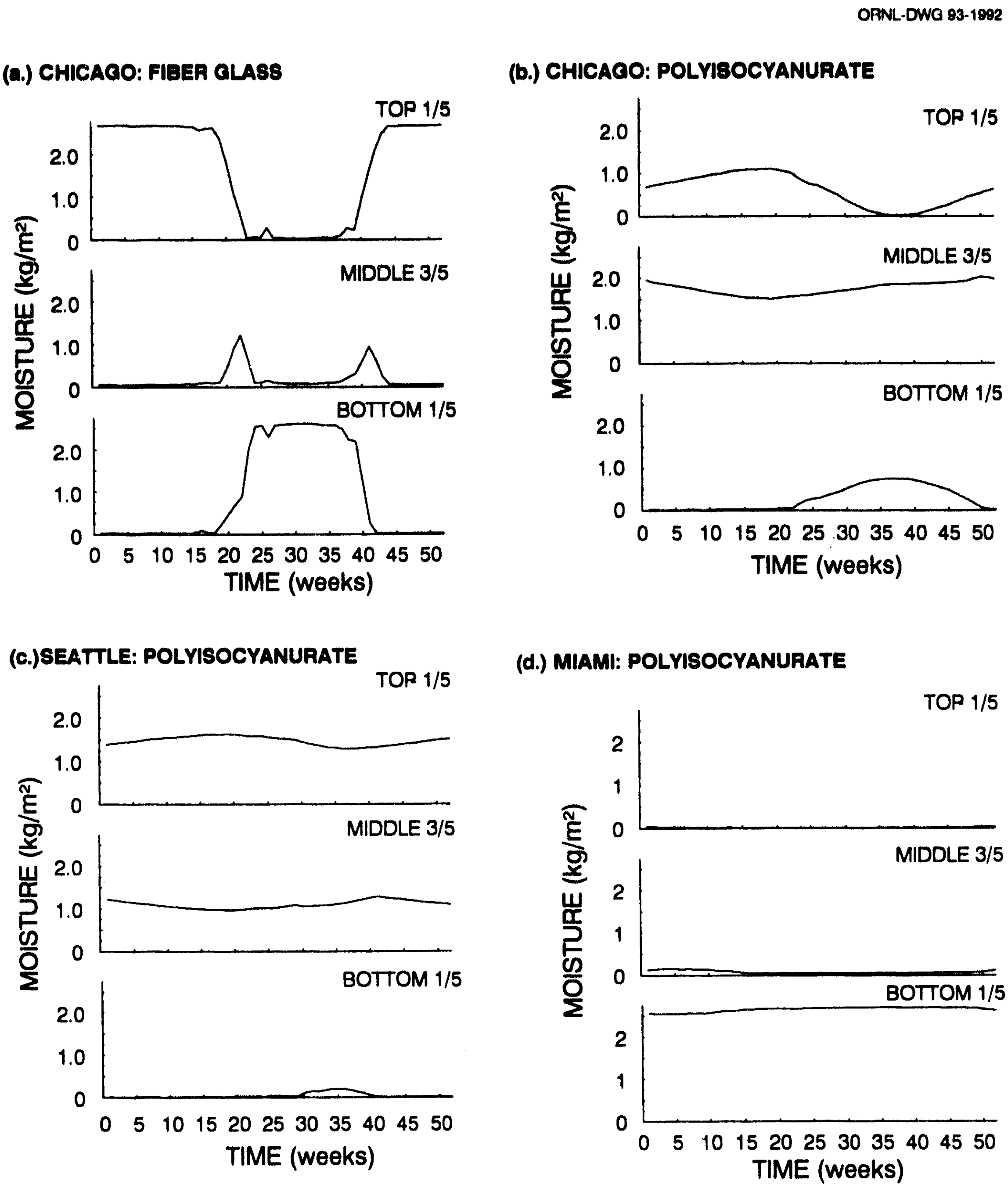

Fig. 3.2. Moisture distribution as a function of time for various U.S. cities. Traces show the annually repeating pattern, long after initial start-up effects have dissipated. The roofs are sealed by a built-up roof membrane on top and an impermeable deck below. The moisture concentration is 5% by volume. Time is measured from January 1 (week = 0) to December 31 (week = 52).

Drying Principle 3.1: Vertical Distribution of Water with Impermeable Decks

Fibrous Insulations:

In highly permeable insulations, moisture will quickly migrate to the impermeable surface having the coolest daily-averaged temperature, where it becomes highly concentrated. Moisture is broadly distributed only when averaged daily top and bottom temperatures are comparable.

Closed-Cell Insulations:

1. **In regions with strong daily-averaged downward heat flux in the summer *and* strong daily-averaged upward heat flux in the winter, water is mainly distributed among the middle layers year around (more toward the top in Chicago, with stronger winters; more toward the bottom in Knoxville, with stronger summers). Some movement into and out of the top and bottom layers occurs, but peak concentrations lag peak temperature differentials because of slow flow rates.**

2. **In seasonal climates with small downward heat flux in summer, most of the moisture resides steadily in the top layer. A relatively small portion is distributed in the middle layers (Seattle). In seasonal climates with small upward heat flux in winter, the picture is inverted.**

3. **In climates with constant heating or constant cooling requirements, all of the water remains fixed in a thin layer adjacent to the coolest low-permeance surface (Miami).**

4. DOWNWARD DRYING IN COMMON ROOF ASSEMBLIES

4.1 INTRODUCTION

Water vapor can move through every type of commercial decking, including wood, metal (at side and end laps as well as at penetrations), structural concrete, lightweight insulating concrete, gypsum, and cement wood fiberboard. The rate at which water vapor moves is a function of the deck type. The ability of water vapor to move *upward* through the deck into compact, low-slope roof assemblies is well established by qualitative field observations of roofs in very cold climates and roofs over high humidity interiors [69]. Powell and Robinson [64] have measured wetting from upward diffusion in the laboratory under simulated outdoor conditions. Moreover, it is universally acknowledged that installation of a vapor retarder is rational under certain circumstances. The sole purpose of these retarders is to inhibit water vapor, which would otherwise move upward through the deck, from penetrating the rest of the roof assembly.

There is no construction feature of any deck that allows vapor to move more easily up than down. In fact, it is *very commonly* observed in practice that water vapor is driven downward out of excessively moist roof assemblies. Here we are referring to the case where lightweight insulating concrete is poured onto permanent formboards or decking. When the decks and formboards are reasonably permeable to vapor (permeance > 5.72×10^{-7} g/Pa·s·m^2 or 10 English perms), then the free water contained in the concrete will dry downward in a period of between one season and a few years [47, 48, 64]. This process is seen in the drying data shown in Fig. 4.1. The data were obtained using actual field-installed cellular insulating concrete roofs at the University in Lund, Sweden, over 4 years [67]. The rate of downward drying has been analyzed numerically for the case of fibrous glass insulation [45], and general schemes for estimating the drying rate have been offered [51, 55, 68, 73]. Laboratory drying measurements with simulated outdoor conditions have been reported [52, 64] and outdoor measurements have been reported [47, 48, 65, 66, 67].

4.2 ESTIMATING THE WETTING AND DRYING RATES DUE TO DIFFUSION

4.2.1 General Formula

One way for water vapor to move through the deck is by diffusion. In Chapter 2, we defined diffusion as the movement of water vapor molecules through stationary air or

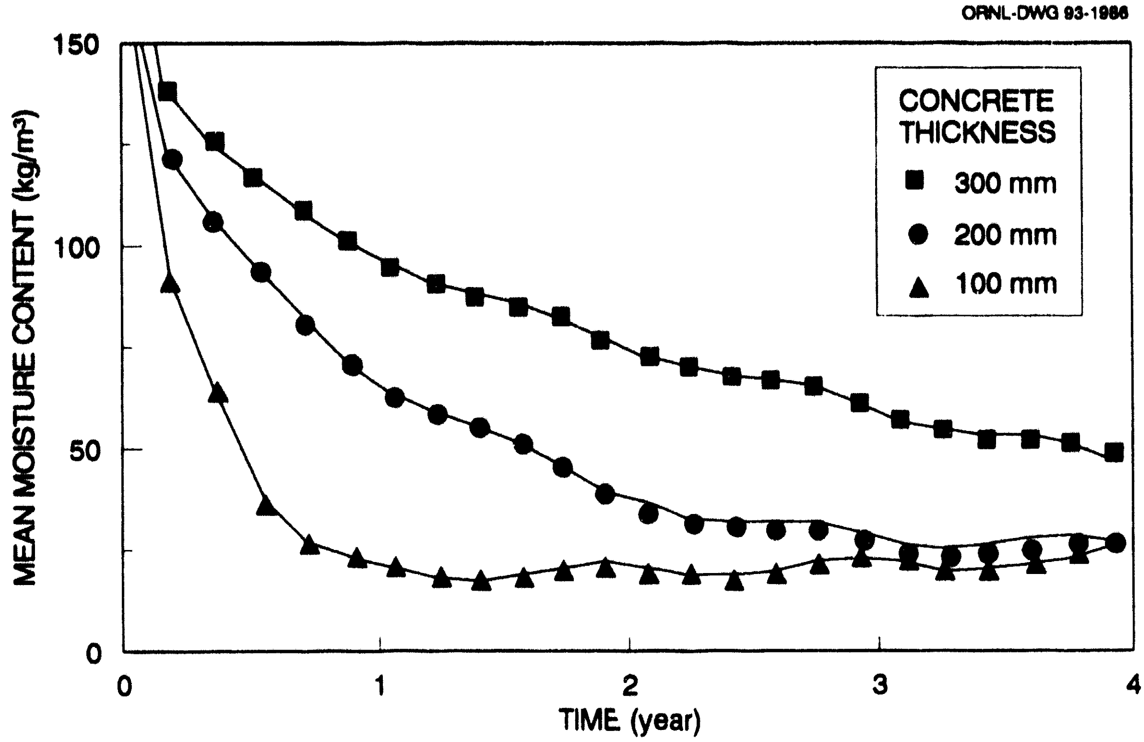

Fig. 4.1. Drying by downward vapor diffusion in poured insulating concrete slabs over metal decking located outdoors in Lund, Sweden. Indoor temperature was maintained at 22°C (72°F) *Source:* Nevander [62]).

other stationary materials. This movement occurs whenever the air in one region of insulation is more densely concentrated with vapor molecules than the air in a neighboring region. We measure the density of vapor molecules using "vapor pressure." The rate of water vapor diffusion between two points increases in proportion to the difference in vapor pressure between the two points. The diffusion rate *decreases* when the resistance to vapor diffusion increases. Mathematically, these effects can be expressed for the steady-state case as[3]

$$\dot{m} = \frac{p_{v,indoors} - p_{v,x}}{\sum R_v} , \qquad (4.1)$$

[3] Equation (4.1) is strictly valid for steady-state diffusion only. To use Eq. (4.1) for non-steady-state conditions, the R_v values must be essentially constant and no significant net accumulation of moisture can occur in any of the intermediary layers during the averaging period. Layers with concentrated liquid are likely to violate both these conditions.

where $\dot{m}$ is the rate at which water moves up into the roof assembly (kg/m^2·s or grain/ft^2·h), and R_v is the resistance to vapor flow (Pa·m^2·s/kg or Reps) for each material in the roof [72, 73]. $R_v = \Delta x/\mu$ where Δx is the thickness of each individual component in the roof (meters or feet), and μ is the permeability of the material to water vapor (kg/Pa·m·s or perm·in.). If we know the time-averaged indoor vapor pressure, $p_{v,indoor}$, and we know the time-averaged vapor pressure at position x within the roof, $p_{v,x}$, then we use Eq. (4.1) to calculate the time-averaged wetting and drying rate, $\dot{m}$. Since the resistance to vapor diffusion, R_v, for each of the intermediary layers can be obtained from *ASHRAE Handbook: 1993 Fundamentals* [72; see also 70] and we can easily measure $p_{v,indoor}$, finding $p_{v,x}$ somewhere in the roof is the task that remains.

If the concentration and temperature are known, simple formulas exist for finding $p_{v,x}$. Unfortunately, both temperature and moisture concentration are hard to predict accurately, because they are coupled together in a complicated way (see Appendix A). For the present purpose of estimating the drying rate, $\dot{m}$, we can use the general description of moisture distribution given in Chapter 3 (Figs. 3.1, 3.2) for estimating the moisture concentration. For the temperature, we will rely on direct measurement of average temperature. From them, we can then estimate $p_{v,x}$.

In the following sections, we differentiate between insulations that have high and low water vapor permeances. When we refer to "fibrous insulations," the discussions are applicable to all highly permeable insulations. We place rigid glass fiber, perlite, wood fiberboard, wood, gypsum, and insulating concrete in this category. "Closed-cell insulations" apply to expanded and extruded polystyrene, PIR, phenolic, and cellular glass. Although the specific discussions and model results apply to the named material, the discussions and trends predicted by the modeling qualitatively represent the category of materials.

4.2.2 Fibrous Insulations: Seasonal Climates

Figure 4.2 depicts the wetting and drying process for the case of fibrous glass in a seasonal climate. As shown in Fig. 4.2a and stated in Drying Principle 3.1, water will become highly concentrated at the top of the insulation, directly below the membrane, during the winter. During summer (Fig. 4.2b), water will become highly concentrated at the bottom of the insulation directly above the deck. These facts, together with the following Drying Principle, allow us to find a value for $p_{v,x}$ for each season.

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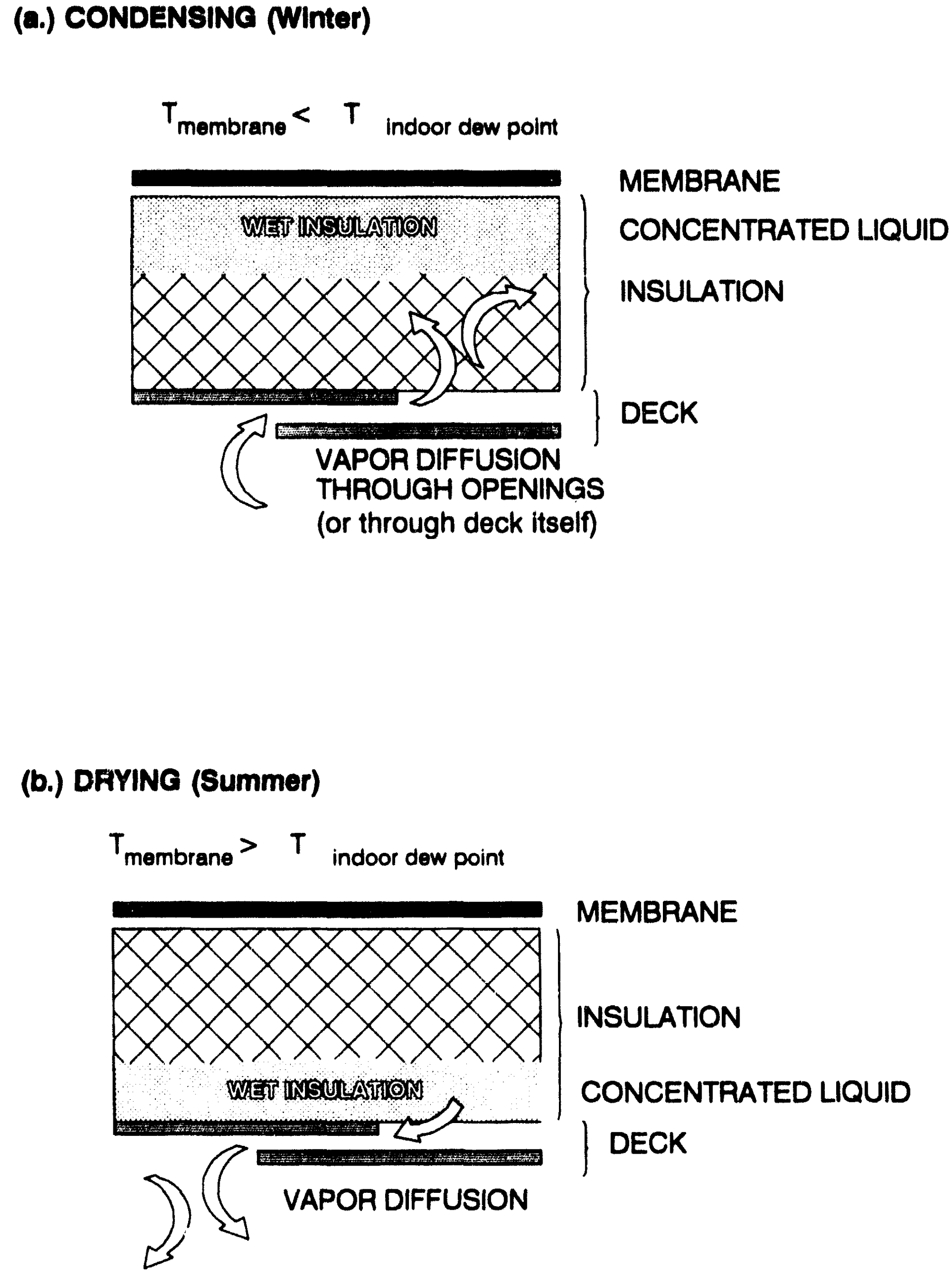

Fig. 4.2. Wetting and drying of rigid fibrous glass in a seasonal climate. Arrows represent vapor diffusion.

Drying Principle 4.1: Saturation Vapor Pressure

As water vapor diffuses into a region, the vapor pressure in the region continually increases until it reaches the maximum possible value, known as the "saturation vapor pressure", p_{sat}. As more water vapor enters the region, this excess vapor all condenses to liquid, since the humidity of the air no longer can increase. The saturation vapor pressure increases with increasing temperature. To show the dependence on temperature, we write $p_{sat} = p_{sat}(T)$.

During the summer, we know that just above the deck of a wet roof system, $p_{v,deck} = p_{sat}(T_{deck})$, since the insulation is saturated at that location (Fig. 4.2b). Application of Eq. (4.1) is now straightforward. During summer, the drying rate ($\dot{m}_v$) for fibrous insulation roofs is given by

$$\dot{m}_v = \frac{p_{v,indoor} - p_{sat}(T_{deck})}{R_{v,bl} + R_{v,deck}} , \tag{4.2}$$

where $R_{v,bl}$ is the vapor resistance of the boundary layer beneath the deck.

During the winter, we know that just below the membrane of a wet roof system, $p_{v,membrane} = p_{sat}(T_{membrane})$, since the insulation is saturated there (Fig. 4.2a). During winter, the drying or wetting is given by

$$\dot{m}_v = \frac{p_{v,indoor} - p_{sat}(T_{membrane})}{R_{v,bl} + R_{v,deck} + \sum R_{v,insulation}} . \tag{4.3}$$

4.2.3 Closed-Cell Insulations: Seasonal Climates

Closed-cell insulations have high R_v values, so the seasonal redistribution of water occurs slowly. Nevertheless, in many U.S. climates with both an air conditioning season and a heating season, Eqs. (4.2) and (4.3) apply, respectively (see Fig. 3.2b for Chicago with 5% water by volume). These remarks apply for roofs with excessive moisture contamination, which is precisely the case of interest in this section on drying.

4.2.4 Climates with Little Heating or Little Cooling Requirements

In Miami, water resides just above the deck in a wet roof system year around, and Eq. (4.2) can be used to estimate the drying rate throughout the year (see Fig. 3.2d for Miami with 5% water by volume). We would expect this to be a reasonable assumption for other regions with modest annual heating requirements.

In Seattle, overcast skies diminish radiative heating of the roofing membrane during summer (see Fig. 3.2c for Seattle with 5% water by volume). Moreover, summers are cool, requiring very little air conditioning. Here, Eq. (4.3) is applicable year around for a wet roof system,[4] although for the case of fibrous insulation, calculations show that the humidity level immediately below the membrane does fall below saturation briefly during the summer.

Finally, we note that schemes for comparing winter wetting with summer drying [51, 55, 68, 73] often have assumed that both processes are controlled by $p_{v,indoor} - p_{sat}(T_{outdoor})$. This assumption may be valid in Canada, where cold temperatures might maintain water directly beneath the membrane year around. In most U.S. climates, however, we have shown that summertime drying is controlled by $p_{v,indoor} - p_{sat}(T_{deck})$. The deck temperature is mainly dependent upon the interior temperature and not the outdoor temperature. Therefore, during summer for most U.S. climates, use of schemes with $p_{v,indoor} - p_{sat}(T_{outdoor})$ to predict vapor flow for wet roofs is invalid.

4.3 NUMERICAL RESULTS

Figure 4.3 shows the time required to dry a roof system with an initial water content of 10% by volume. The analysis uses Rode's model [78]. The roof assemblies used for these calculations consist of a BUR roof and 51 mm (2 in.) of unfaced rigid glass fiber, perlite, and PIR insulation boards. The decks have a vapor permeance of 1.0 (English) perm (R_v = 1.7 × 10^{10} Pa·m²·s/kg), which approximates the characteristics of metal decks with side/end laps and penetrations. Indoor conditions were T = 21°C (70°F) and rh = 49% for Chicago and Seattle, and T = 25°C (76°F) and rh = 55% for Miami. An initial

[4] Use of Eq. (4.3) for the Seattle climate will underestimate the drying potential since there are obviously some clear days when the membrane surface temperature can be elevated by radiative heating.

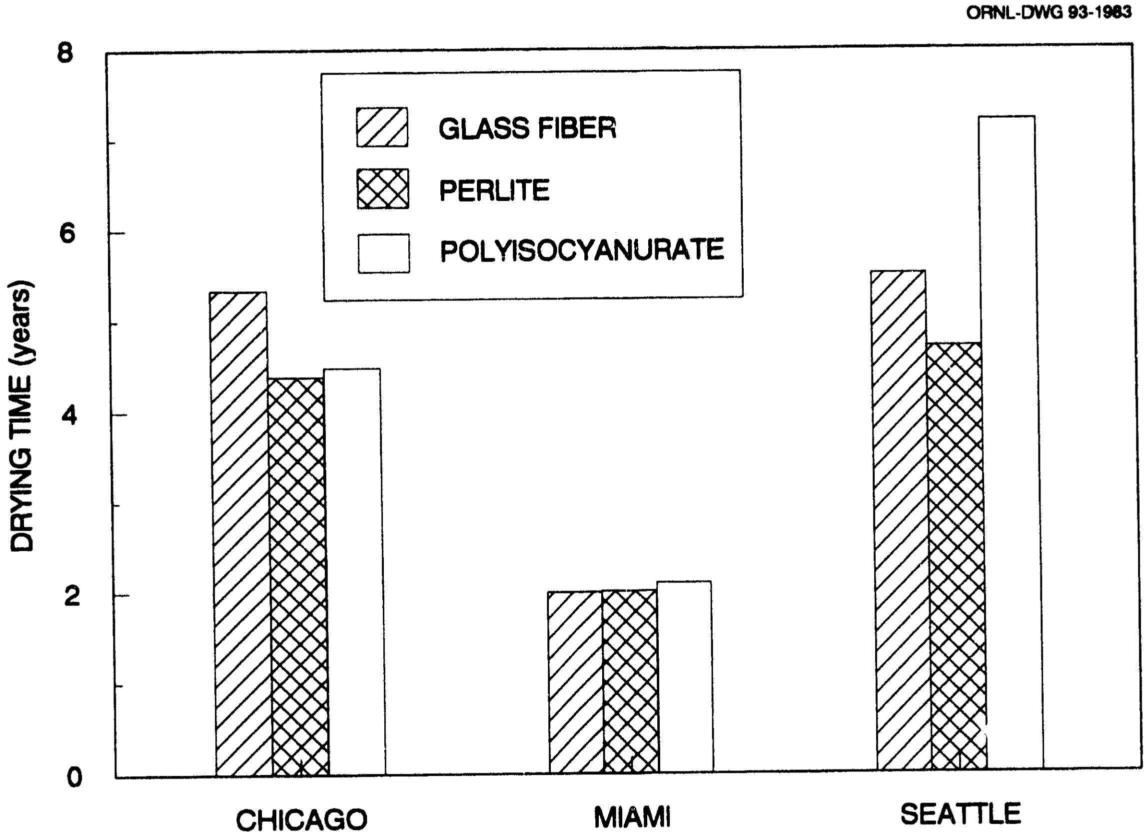

Fig. 4.3. Drying times for various types of insulation in three U.S. cities. Data were calculated using a finite-difference computer program [78]. Initial moisture content was 10% by volume. Indoor conditions were 25°C (76°F) and 55% rh for Miami, and 21°C (70°F) and 49% rh for Seattle and Chicago. Drying is defined as the reduction in water content to the equilibrium water content at the interior conditions. See text for construction details.

water content equal to 10% by volume was assumed, and it was placed entirely in the top 10 mm (0.38 in.) of insulation to simulate a leak. For these simulations, the drying time was defined as the time necessary to reduce the water content of the different insulations to their equilibrium water content for the interior conditions listed.

The numerical results suggest that, in any given geographic location, the drying rate appears to be almost independent of the insulation type. This can be better understood if we refer to Eqs. (4.2) and (4.3). In Miami, (4.2) nearly always applies. If T_{deck} is not too sensitive to insulation type, then neither is $p_{sat}(T_{deck})$. None of the other terms in Eq. (4.2) has any dependence on insulation type; Eq. (4.2) therefore predicts very little dependence on the insulation. This is consistent with the modeling results.

In Chicago, Eq. (4.2) applies during summer, so that just as in Miami, the summer drying rate is insensitive to insulation type. During winter in Chicago, the wetting rate is nearly zero for all three insulations. Combining the seasons, the annually averaged drying is insensitive to insulation. Once again, our simulations concur. In Seattle, Eq. (4.3) pertains year around. The $R_{v,insulation}$ term in Eq. (4.3) is important in the case of roofs containing PIR. PIR insulation impacts the drying rate in Seattle, as seen in Fig. 4.3. Note that if the insulation is a fibrous type, then $R_{v,insulation} << R_{v,deck}$. In this case and in situations where Eq. (4.3) applies, the drying rate is only weakly affected by the insulation type. Our simulations show that the drying time for PIR foam in Seattle is appreciably longer than for the two fibrous insulations.

4.4 R_v VALUES FOR METAL DECKS

From Eqs. (4.2) and (4.3), we see that wetting and drying rates depend upon the value of R_v for the deck. No controlled experiments for determining R_v for metal decks have been published in the literature, despite the fact that the large majority of decks are metal [4]. R_v values for other deck types are available [c.f., ASHRAE (72)].

Using some detective work, we can deduce a rough estimate of the R_v value for metal decks by studying survey results published for lightweight insulating concrete that was installed over metal decks. Starting in the 1960s, lightweight insulating concrete was frequently placed over a light-gauge corrugated metal support, as shown in Fig. 4.4. These metal forms did not have any slots or perforations. Funk [47, 48] took cores from a large number of lightweight concrete decks of this type. As part of the research, roof areas that were far from any known leaks were examined. The samples were made up only of roofs with impermeable built-up membranes. It is therefore reasonable to assume that all recorded weight loss is due to vapor diffusing through overlapping joints and holes in the deck.

Funk states that "it was not unusual to find 50-90 percent of the original water still in the deck 5 to 8 years after the building was constructed." [48]. As representative quantities, let us assume that 30% of the original water evaporated after 6.5 years. Assuming a typical thickness (76 mm or 3 in.) and typical mixing practices [47], roughly

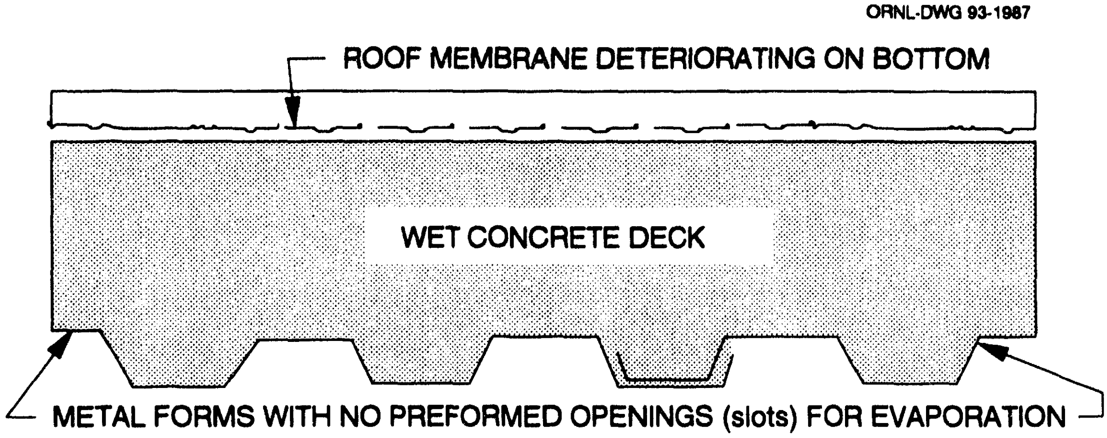

Fig. 4.4. Typical construction for poured lightweight insulating concrete over metal decking. In the early 1980s, perforated metal decking was recommended for this application (not shown).

26 kg/m^2 (5.4 lbm/ft^2) of free water was present initially following construction. The drying rate that results is

$$\dot{m} = 5.4 \text{ lbm/ft}^2 \times 0.30 \div 6.5 \text{ years} = 0.25 \text{ lbm/ft}^2\text{/year or } 1.2 \text{ kg/m}^2\text{/year} .$$

Several investigators have confirmed that, in seasonal climates, water migrates to the top of lightweight insulation in winter and to the bottom in summer [47, 48, 63]. Suppose that Eq. (4.3) applies for the colder half of the year and Eq. (4.2) for the warmer half.

Assume

T_{indoor} = 21°C (70°F), indoor rh = 35%, and $T_{membrane}$ = 12°C (54°F) during winter,

and

T_{indoor} = 23°C (73°F), indoor rh = 60%, and T_{deck} = 25°C (77°F) during summer.

Obtaining saturation pressures from the psychrometric tables [72] or from steam tables:

$p_{v,indoor} = p_{sat}(T_{indoor}) \times 0.35 = 0.87 \times 10^3$ Pa (0.26 in. Hg) and
$p_{sat}(T_{membrane}) = 1.40 \times 10^3$ Pa (0.41 in. Hg) in winter,
$p_{v,indoor} = p_{sat}(T_{indoor}) \times 0.60 = 1.69 \times 10^3$ Pa (0.50 in. Hg) and
$p_{sat}(T_{deck}) = 3.17 \times 10^3$ Pa (0.50 in. Hg) in summer.

For lightweight insulating concrete, R_v = 0.25 × 10^{10} Pa·m²·s/kg or 0.14 Rep [70]. Inserting the appropriate values into Eq. (4.2) for the warmest half of the year and into (4.3) for the coldest half of the year and summing, the total accumulations are 1.2 Kg/m²·year or 0.25 lbm/ft²/year. Thus, $R_{v,deck}$ = 2.7 × 10^{10} Pa·m²·s/kg or 1.54 Rep. The permeance is defined as the inverse of R_v: R_v^{-1} = 37 × 10^{-12} kg/Pa·m²·s or 0.64 (English) perms. This result is of the same order of magnitude as results obtained by Sheahan in an unpublished laboratory experiment [51]. The permeance of metal decks, the primary deck type used today, appears to be approximately in the range of 37 to 58 × 10^{-12} kg/Pa·m²·s (0.64 to 1.0 perms).

4.5 THE EFFECT OF RECOVER ON DRYING RATES

The decision whether to recover or tear off the existing roof involves several extremely important factors, which are discussed in good papers by Fricklas [46], Tobiasson [70], Sheahan [51], and Smith [54], among others. In this section, we shall concern ourselves solely with the impact of recover upon the drying rate of the pre-existing insulation, assuming the pre-existing membrane remains impermeable and protects the recover insulation from becoming wet.

4.5.1 Qualitative Response for Pre-existing Fibrous Insulation

The impact of recover on drying is easiest to understand for the case of fibrous insulation [45]. Assuming that a layer of insulation is placed over the existing membrane prior to recovering, the temperature near the top of the pre-existing fibrous insulation is significantly higher than the temperature near the deck during summer. Therefore, any water trapped in the pre-existing insulation moves to the bottom and condenses just above the deck, just as in the unrecovered case during summer (Sect. 4.2). As in the case without recover, the drying rate is given by Eq. (4.2). T_{deck} in Eq. (4.2) is slightly higher for the unrecovered case, so that summertime drying rates are somewhat higher for the unrecovered systems.

Figure 4.5 depicts how recover insulation affects moisture movement during winter by qualitative comparison of the temperature distribution in the original and recovered systems. During winter, in both systems, the temperature near the top of the pre-existing

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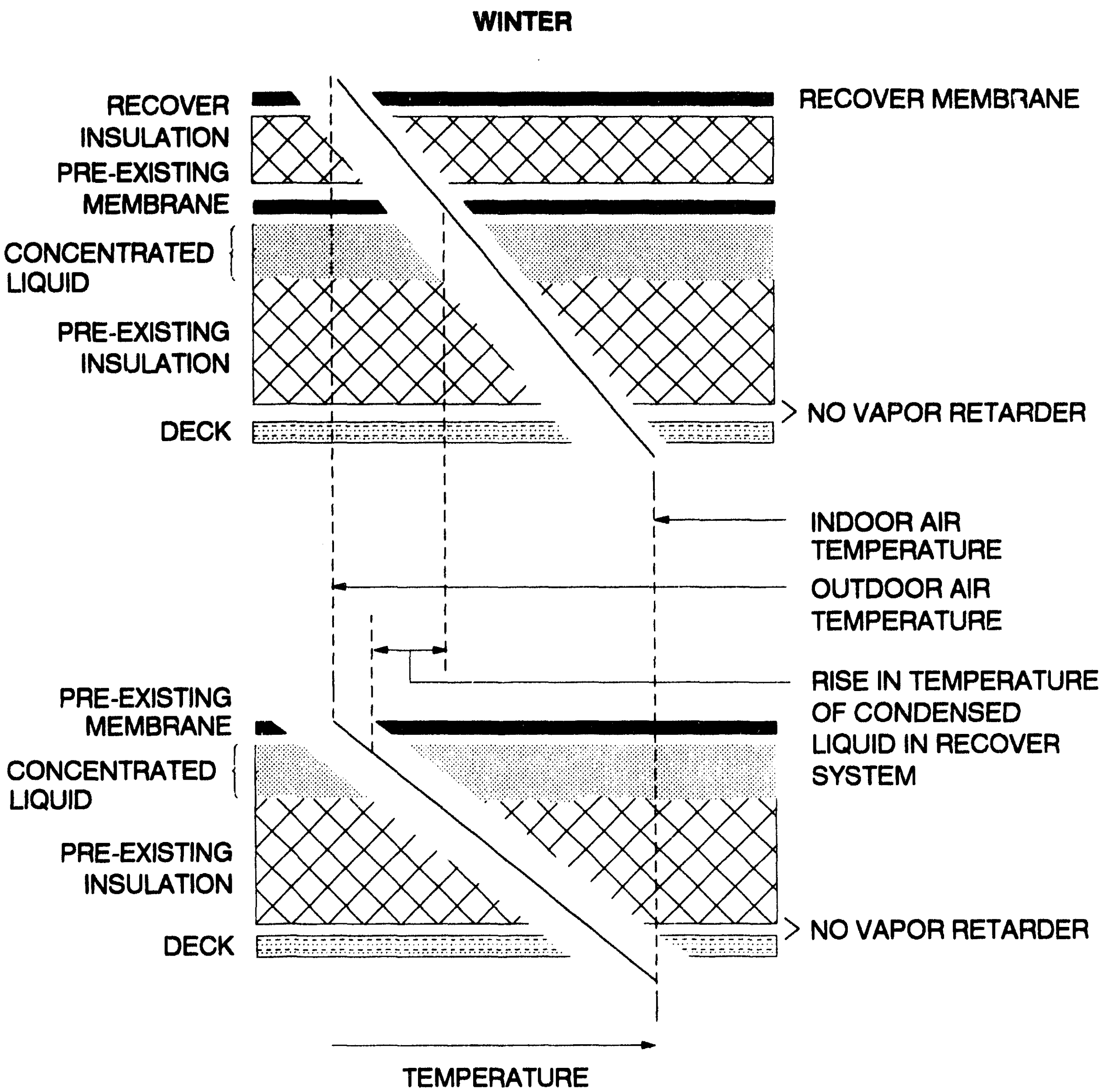

Fig. 4.5. Effect of recover of fibrous insulation on wintertime temperature distribution. The temperature at the top of wet pre-existing insulation determines the wintertime vapor diffusion rate upward through the deck, for the case of relatively permeable insulation. Recover insulation increases this temperature, thus slowing the diffusion rate. Note that the original roof design does not include a vapor retarder.

insulation falls below the temperature near the bottom, and water moves to the top. The drying rate is given by Eq. (4.3). However in the case of recover, Fig. 4.5 shows that *$T_{membrane}$ in Eq. (4.3) is significantly higher for the unrecovered case.* Equation (4.3) predicts that the wintertime wetting rate due to water vapor migrating into the roof system from the building (not leakage) will be less for the case of recover. In fact, if enough insulation is added, $p_{sat}(T_{membrane})$ for the old membrane in Eq. (4.3) can become larger than $p_{v,indoor}$, and drying can occur year around. To summarize, in seasonal climates, the annually averaged drying rate should be faster for a recovered roof if sufficient insulation is added. The amount of insulation to accelerate drying will vary with the climate.

4.5.2 Numerical Results

In Fig. 4.6, the results of hour-by-hour calculations are shown for several recover systems. The initial moisture content and the indoor and outdoor conditions are the same as in Fig. 4.3. The roof assemblies are also the same, except that a recover system has been added. The recover system consists of 19 mm (0.75 in.) of perlite insulation (R_T = 0.37 $m^2 \cdot °C/W$ or 2.1 $h \cdot ft^2 \cdot °F/Btu$) and a black ethylene propylene diene monomer (EPDM) membrane. The vertical axis of Fig. 4.6 is the percentage change in drying time due to adding the recover system.

Fibrous insulation

As predicted in the previous subsection, for Chicago's and Seattle's seasonal climates, the drying time for the fibrous insulation is faster for the recover case. In Miami, the drying time is determined solely by the temperature of the deck (Eq. 4.2). In the case of recover, the deck temperature decreases slightly and the drying time is extended slightly.

Closed-cell insulation

At the start of these calculations, all of the water is at the top of the pre-existing closed-cell insulation. The recover system causes the top membrane temperature to be cooler during the summer. Therefore, $p_{sat}(T_{membrane})$ is reduced, reducing the vapor pressure gradient that drives water downward. It turns out that a permeable deck of 5.7×10^{-8} $g/Pa \cdot s \cdot m^2$ or 1 (English) perm in combination with the high R_v of the closed-cell insulations does not allow water to accumulate at the bottom of the insulation. This issue will be examined carefully in Chapter 6. For now, note that the drying rate in this case is controlled by $[p_{sat}(T_{membrane}) - p_{v,indoor}]$ in accordance with Eq. (4.3). This pressure

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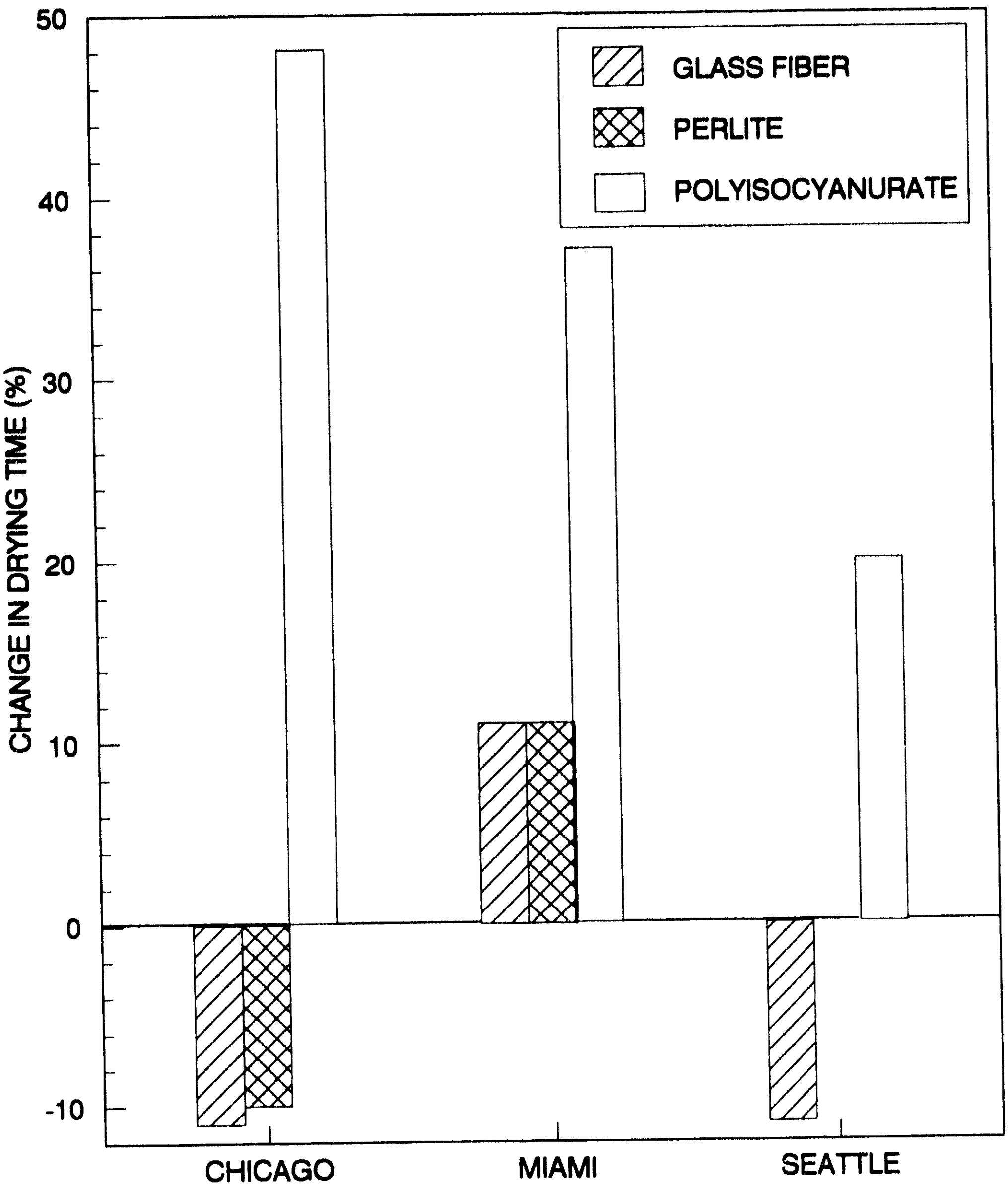

Fig. 4.6. Change in drying time when recover insulation is installed. Data were calculated using a finite-difference computer program [78]. Initial moisture content and boundary conditions are the same as for Fig. 4.3. Construction details are the same as in Fig. 4.3 except for the addition of 19 mm (0.75 in.) of perlite recover insulation and a black ethylene propylene diene monomer membrane. Note that there is a 0% change in water content for perlite insulation in Seattle and that no vapor retarder was included in the original roof system design.

differential is reduced by the recover layer, so drying takes longer. In Fig. 4.6, this effect is observed in all three cities.

4.6 MECHANISMS FOR DRYING BY CONVECTION

Another way for water vapor to move through the deck is by convection. This means that as moist air flows through holes and joints in the deck, water vapor also moves through the opening, in proportion with the humidity level of the air. Convection was not included in the R_v for the preceding calculation because, in the special case of poured concrete, air cannot convect through openings in the metal deck. Sheahan's results [52], which were referred to earlier, were also obtained under conditions where convection was absent. However, Tobiasson [70] points out that in real, installed systems using insulation boards, convection may be a significant vehicle for moisture transfer in compact, low-slope roof assemblies, as water vapor passes through the spaces between insulation boards. On the other hand, convection effects can be significantly reduced by overlapping insulation boards, using closed-cell insulations, using an airtight deck such as poured insulating concrete, and installing vapor or air retarders.

Samuelson [65, 66] has performed extensive studies of metal decking at the University in Lund, Sweden. For the particular assemblies that he studied, he found that in the absence of a vapor/air retarder, convection caused by static pressure differences across the deck is the *primary* mechanism for moisture transport through metal decking joints and holes. We emphasize that this result is very dependent upon construction practices. The air permeability of fibrous glass insulations used in Sweden is much higher than that of insulation products commonly used in the United States. Static pressure differences that drive the air through the deck may be strong for some buildings and absent in others.

Static pressure differences across any type of deck can be caused by wind patterns around the outside of the building which cause a pressure difference between the inner and outer envelope surfaces. Wind flow patterns induce static pressure variations over the exterior surface. Over the *interior* surface of the building envelope, the pressure remains relatively *uniform*, at least when air can flow freely from room to room. Wind can also increase the internal pressure for some buildings, thus increasing the pressure differential across the deck. In addition, exhaust/ventilation practices may induce a pressure differential across the entire building envelope. Now, if the roofing membrane is flawless, and if the membrane is rigid and sealed at each penetration, parapet and curb, then the indoor/outdoor pressure drop will be across the membrane *only*; no pressure differential will be induced across the deck. However, if the membrane was not sealed to the parapet wall during skirting, or if the membrane has separated over time at any location, then the membrane will leak air and a part of the total pressure differential will occur across the metal deck. A membrane that can balloon (i.e., an unreinforced mechanically attached EPDM) is a good example of a membrane that is separated. Even with a sealed membrane, air will flow through the metal deck openings. Note that it is precisely in the corners of the roof where the greatest wind-induced negative pressures occur. The high negative pressures are limited to small areas of the roof; these loads are not transmitted out into the field of the roof.

A second potential cause of air flowing into and out of the metal deck involves adjacent rooms that are sealed from one another or that operate at different static pressures. In many buildings, some interior walls extend up to the bottom of the metal deck. The indoor static pressure may change across such walls because of mechanical ventilation practices, or perhaps wind action, where the pressure in rooms on the windward side is higher than on the leeward side. The air on the high-pressure side of the wall will flow up into the metal deck flutes and along the flutes and exit on the low-pressure side of the wall. If the flutes are parallel to the wall, the air may flow through and around the insulation. In most instances, this phenomenon will equalize very rapidly.

Throughout this report, we ignore the effects of convection. This is primarily because of the lack of published data that would enable us to quantify its effects. Further consideration of convection effects is beyond the scope of this assessment.

5. RETROFIT OPTIONS FOR DRYING EXISTING ROOFS

The retrofit options discussed in this chapter are grouped according to the physical processes that they exploit. These are downward diffusion, downward diffusion with bottom ventilation, upward diffusion, upward diffusion with top ventilation, and ventilation the insulation layer itself. Only options that are already widespread, or that, in our opinion, show commercial potential, have been included.

5.1 DOWNWARD DIFFUSION

5.1.1 Drilling Holes Through Lightweight Insulating Concrete Before Recover

In a period starting in the 1960s and ending in the 1980s, lightweight concrete was most frequently placed over corrugated metal decks that had no openings for evaporation except at the lap joints. The amount of free water left after construction was so great for this type of insulation [48] that even after 10 years, most of it would remain in the roof, contributing to membrane deterioration [47]. Funk outlined a corrective scheme for these roofs that involves drilling holes from above all the way through the metal deck to increase the downward vapor diffusion rate [48].

The technique is shown in Fig. 5.1. The holes may be plugged from above to prevent upward movement of moisture into the recover system. It is our understanding that this procedure is currently being implemented with few adverse short-term secondary effects. Exceptions are cases where two factors occur simultaneously: there is considerable water, and the plugs used to fill the holes were omitted when using a recover system that would warp or blister when wetted. Long-term drying effects have not been documented in the literature.

5.1.2 Drilling Holes Through Insulation Boards and Deck Before Recover: No Pre-Existing Vapor Retarder

The following experiment was carried out at ORNL. Two different 1.2- by 1.8-m (4- by 6-ft) roof specimens were inserted into a climate simulating chamber. One of the panels, called the "real roof panel," was obtained by cutting a section out of an existing 25-year-old roof at the laboratory. It contained a narrow-fluted metal deck including one longitudinal lap joint, a bituminous vapor retarder, 13-mm (0.5-in.) dry glass fiber insulation, and a 4-ply BUR membrane. The other panel, called the control panel, was

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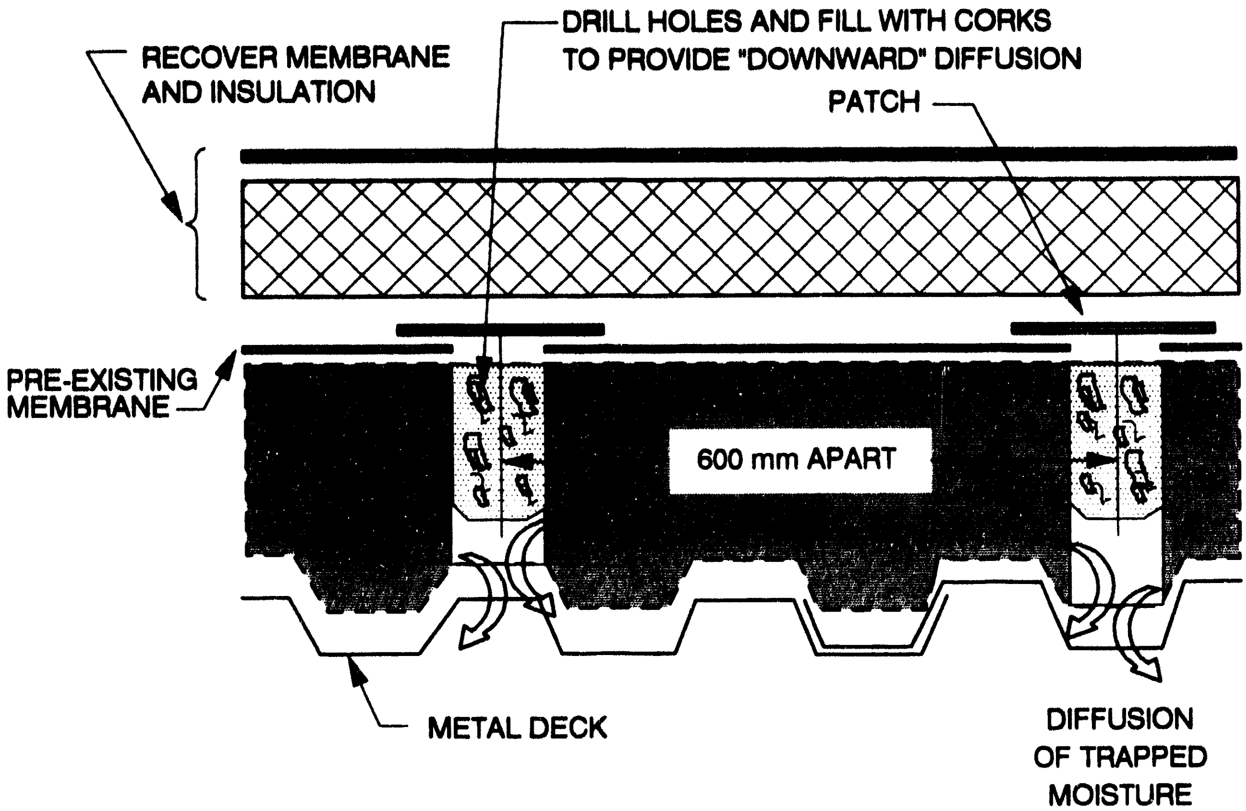

Fig. 5.1. Drilling holes through lightweight insulating concrete to facilitate downward drying. (taken from Funk [48]). After drilling, the roof is recovered. *Source:* Funk [48].

constructed from a flat sheet of 6-mm (0.25-in.) aluminum sheet, 51-mm (2-in.) glass fiber insulation, and a black 1.1-mm (45-mil) EPDM membrane. Both panels were sealed around the perimeter as well as possible with caulk and sealant strips to minimize edge leaks. Before they were inserted into the climate chamber, 10% by volume of water was added to both panels. Inside the climate chamber, the temperature was maintained at a constant 65°C (150°F) above the specimens, and at 26°C (78°F) and 50% rh below the panels. The panels were fully suspended on sensitive load cells for continual gravimetric monitoring. After baseline drying rates were obtained, 33 holes were drilled into the metal decks from below. The holes were 13 mm (0.5 in.) in diameter and were spaced approximately 240 mm (9 in.) on-center.

The results are shown in Fig. 5.2. To eliminate the effects of uncontrolled leaks around the edges of the relatively small panels, the drying rates for the test panels before the drilling of holes were subtracted from the data before calculating the permeance. The data shown in Fig. 5.2 therefore represent increases in permeance that are due solely to drilling the holes. Note that the increases in permeance values are about the same for the two specimens with 33 holes despite the difference in insulation thickness, again indicating the independence of summer drying from insulation permeance. Doubling the number of holes per unit area approximately doubles the permeance effect for the "real" roof specimen.

The error bars show variations in the results as the test progressed. The holes were covered with aluminum tape and uncovered again to obtain several sets of steady drying rates. The variation was not regular, implying that there was ample moisture in the systems throughout the testing. The experimental scatter shows that the measurement of small changes in mass is difficult to accomplish precisely.

If we extrapolate from the data in Fig. 5.2, we find that for 13-mm (1/2-in.) diameter holes spaced 0.6 m (2 ft) apart (2.7 holes/m^2 or 0.25 holes/ft^2), the deck permeance should increase by 0.14 (English) perms. Funk used this spacing in his work [48]. Assuming the estimated permeance of 0.64 calculated previously for metal decks with no holes (Sect. 4.4), we see that drilling holes at this frequency will increase the permeance of metal decks by roughly 22% for glass fiber insulation. We expect similar results for lightweight insulating concrete.

Drilling through insulation boards poses at least three problems not present in the case of lightweight concrete. First, if the insulation is compressible and wet, then water may be displaced by the elastic compression of the insulation and flow out the holes into the building as workers walk in the drilled area. The effect is similar to that of squeezing a wet sponge. Since closed-cell insulation boards are not compressible, they should resist this effect. The second potential problem is that open-cell insulations can hold large amounts of water that will flow out of the insulation simply from the pull of gravity. Hedlin [50] found that high-density mineral wool initially wetted to 80% by volume will drain down to 30% by volume when sloped at 8%, and to 40% by volume when sloped at 2%, within 30 days. Over the first few days of his experiments, the initial drainage rate was extreme. If glass fiber that contains more water than, say, 50% by volume is drilled, then one can expect uncontrollable dripping for the first few days in accordance with Hedlin's results. In fact, a similar process is seen nowadays when lightweight insulating concrete (an open-cell material) is first poured over perforated metal decks [51, 52]. Finally, care should be taken when drilling a coal tar membrane. If an insignificant amount of insulation is added with the recover system, the coal tar could drip through the drilled holes and into the building.

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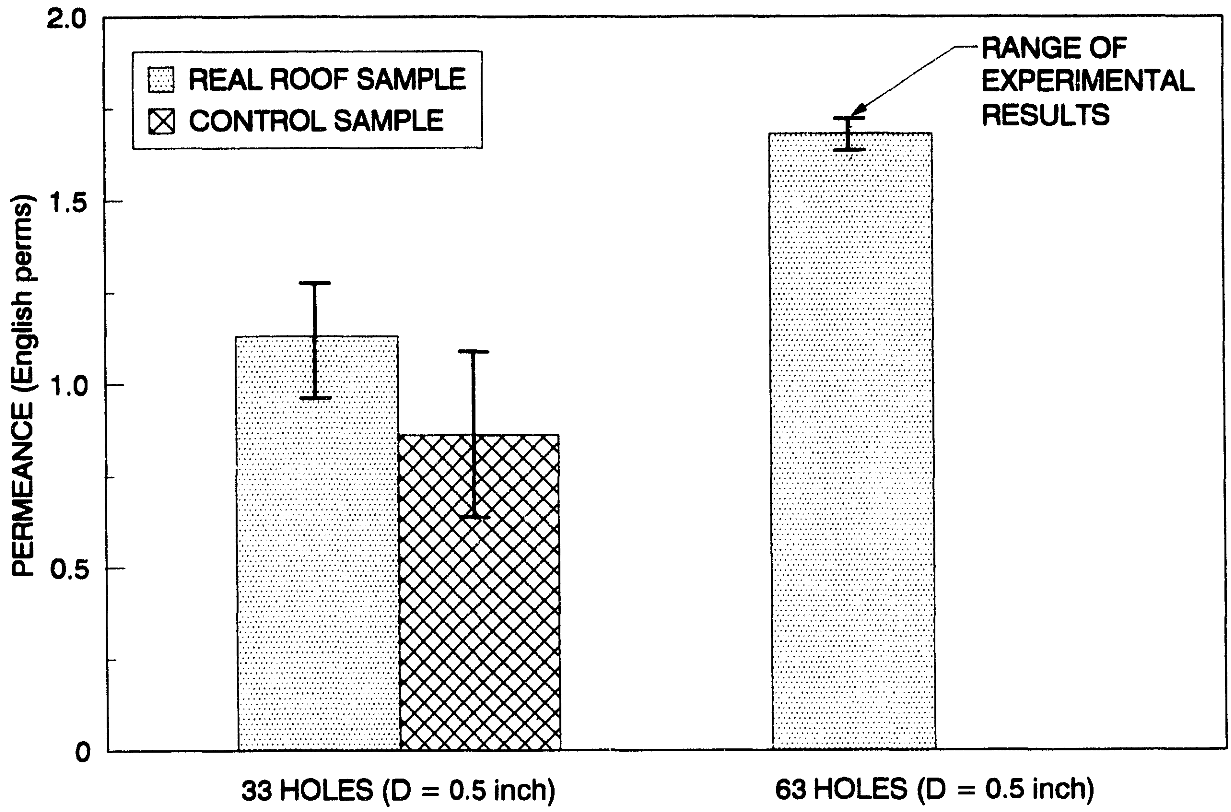

Fig. 5.2. Increase in permeance resulting from perforating a metal deck insulated with rigid fibrous glass insulation. "Control Sample" has 51-mm (2-in.) fibrous glass insulation; "Real Roof Sample" has 13-mm (1/2-in.) fibrous glass insulation. Both samples have approximately 1.9 m^2 (20 ft^2) of area. See text for test conditions.

5.1.3 Drilling Holes Through Insulation Boards and Deck Before Recover: Pre-Existing Vapor Retarder

If the interior is very humid, or if the climate is extremely cold, then the original roof probably has, or should have, a vapor retarder. These are usually installed directly above the deck or over a thin layer of insulation above the deck, followed by an additional insulation layer. After reroofing, a vapor retarder will continue to be necessary. This need is not incompatible with the drilling practice described previously. After holes are drilled through the pre-existing membrane, insulation, vapor retarder, and deck, the pre-existing membrane can be patched using appropriate methods. After the recover insulation and new membrane are installed, the sealed pre-existing membrane constitutes a "sandwiched vapor retarder." Sandwiched vapor retarders offer some advantages over those installed directly above the deck [70]. If excessive wintertime wetting via diffusion from the building interior is feared, now that the deck is more permeable, enough recover insulation should be added to ensure that the vapor retarder (old membrane) temperature will not fall below the dew point temperature of the building interior under design winter conditions [73].

5.2 DOWNWARD DIFFUSION WITH BOTTOM VENTILATION

Hole drilling is essentially a scheme for increasing the surface area for vapor diffusion between the wet insulation and the building interior. Ideally, one would like to expose the *entire* surface of the insulation to the indoor air. This ideal can be approached by ventilating the flutes of metal decks (between the metal deck and the bottom of the insulation). This scheme also has the potential to reduce and possibly arrest drips that might result from abrupt releases of water (e.g. from fast thawing) because it removes water by rapid evaporation at precisely the location in the roof where water must accumulate for dripping to occur (as long as the evaporation rate exceeds the accumulation rate).

5.2.1 When Is Bottom Ventilation Viable?

Under certain circumstances, air recirculating between the metal deck and the building interior can cause *accumulation*—not drying—within the roof assembly. Such circumstances are identified in this subsection and simple means for avoiding them are described. Another potential concern about recirculating air is that, for some types of roofing systems, undesirable contaminants (i.e., glass fibers) may be transported from within the roofing system into the indoor environment.

An alternate scheme for bottom ventilation would be to use outdoor air. This option has the advantage of little or no potential for moisture accumulation for a large portion of the United States. The issue of moisture accumulation with outdoor air ventilation is fully addressed in Sect. 5.4.2. Bottom ventilation with outdoor air imposes a considerable energy burden, however, because unconditioned outdoor air directly contacts the uninsulated top surface of the deck. This burden increases as the flow rate increases and as the indoor-outdoor temperature differential increases. Furthermore, in cold climates, this form of ventilation will cause condensation on the underside of decks if it occurs during the winter, making it not a viable option unless it is undertaken only during favorable conditions.

A third option consists of using indoor air as a ventilation source and exhausting the air to the outdoors. It can be shown that this option imposes the greatest energy burden of all options because of the volume of conditioned makeup air that is needed.

The following discussion assumes that the air used for ventilation is indoor recycled air.

Drying Principles 5.1, 5.2, and 5.3

5.1: No wetting can occur if the dew point of the ventilating air stream is below the lowest temperature of any roof material exposed to the ventilation air.

5.2: Often at night, radiative cooling brings the outer membrane temperature below the dew point of any available air stream (as evidenced by frost and dew). Contact between ventilation air and materials close to the outer membrane may cause wetting at this time.

5.3: The most energy-conserving method of bottom ventilation is to circulate air between the roof assembly and the building interior, under the constraints of Principle 5.1 and Principle 5.2. For metal decks, air is to flow in the deck flutes between the deck and the underside of the insulation.

Air-conditioning season

Drying Principle 5.1 is satisfied whenever the indoor dew point is below the temperature of any portion of the roof. During daylight hours in the air conditioning season, the deck is the coolest point in the roof, the indoor drybulb temperature is less than the deck temperature, and the indoor dew point physically must be less than or equal to indoor dry bulb. It follows that Principle 5.1 is automatically satisfied. A set of circumstances can be contrived which violates this generalization, but if considered on a seasonally averaged basis, it is virtually assured. The ventilation blower should be disabled at night.

Heating season

If the climate is one where solar heating usually raises the membrane temperature above the indoor drybulb temperature during daylight hours in the heating season, then the physical picture is identical to the air-conditioning season described above. In this climate, the roof may be ventilated year around during daylight hours. Again, the ventilation blower should be disabled at night.

If solar heating does *not* usually raise the membrane temperature above the indoor drybulb temperature, then the membrane is usually the coldest point in the roof during the day. Principle 5.1 requires that the membrane temperature exceed the indoor dew point. The indoor dew point is typically 10°C (50°F) in winter [72]. Examination of the U.S. Climatological Data indicates that there are large regions of the United States where the daytime membrane temperature may not rise above 10°C (50°F) during at least a portion of January-March. This is even true if typical membrane solar heating effects of 5-9°C (10-16°F) above winter ambient are considered. Bottom ventilation during such periods should not be considered.

An effective way to optimize wintertime ventilation practices is to control the ventilation blower thermostatically with the membrane temperature. Operate the blower whenever the membrane temperature is above the average indoor dew point. Measure the indoor dew point directly to learn its average wintertime value.

5.2.2 Metal Deck Ventilation: No Pre-Existing Vapor Retarder

Figure 5.3 shows how metal deck flutes might be ventilated. The insulation is exposed directly to the air traveling in the deck flutes, and moisture removal begins when ventilation begins. It may not be necessary to ventilate each flute. This drying technique can be used regardless of whether other reroofing activities are planned. However, if the membrane is leaking, it should be repaired before the ventilation begins.

5.2.3 Metal Deck Ventilation: Drilling Through a Pre-Existing Vapor Retarder Before Recover

If the insulation has an impermeable facer that faces downward, or if a vapor retarder has been installed, these layers must be penetrated to allow vapor to move from the insulation into the ventilation stream. During recover work, holes that are drilled from above can be positioned over the flute. In this case, *the drill does not need to penetrate the metal deck*, only the pre-existing membrane, insulation, and vapor retarder, as shown in Fig. 5.4. If the metal deck is penetrated, the potential problems identified in Sect. 5.1.2 must be addressed. This activity is difficult and time-consuming, especially for narrow rib decks.

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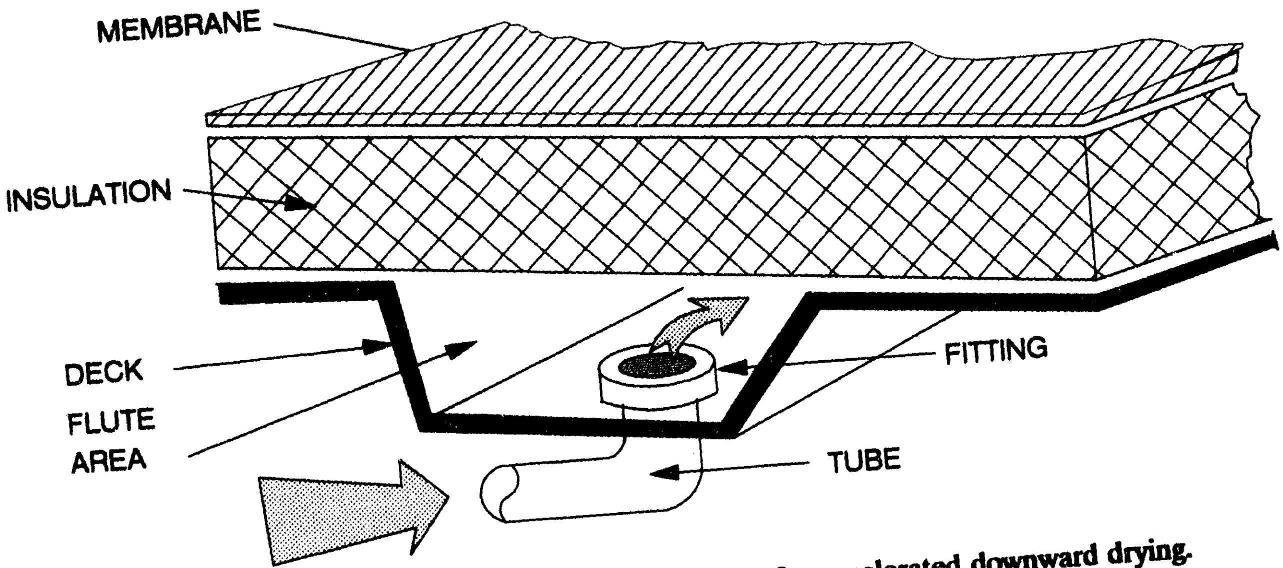

Fig. 5.3. Ventilating metal deck flutes for accelerated downward drying.

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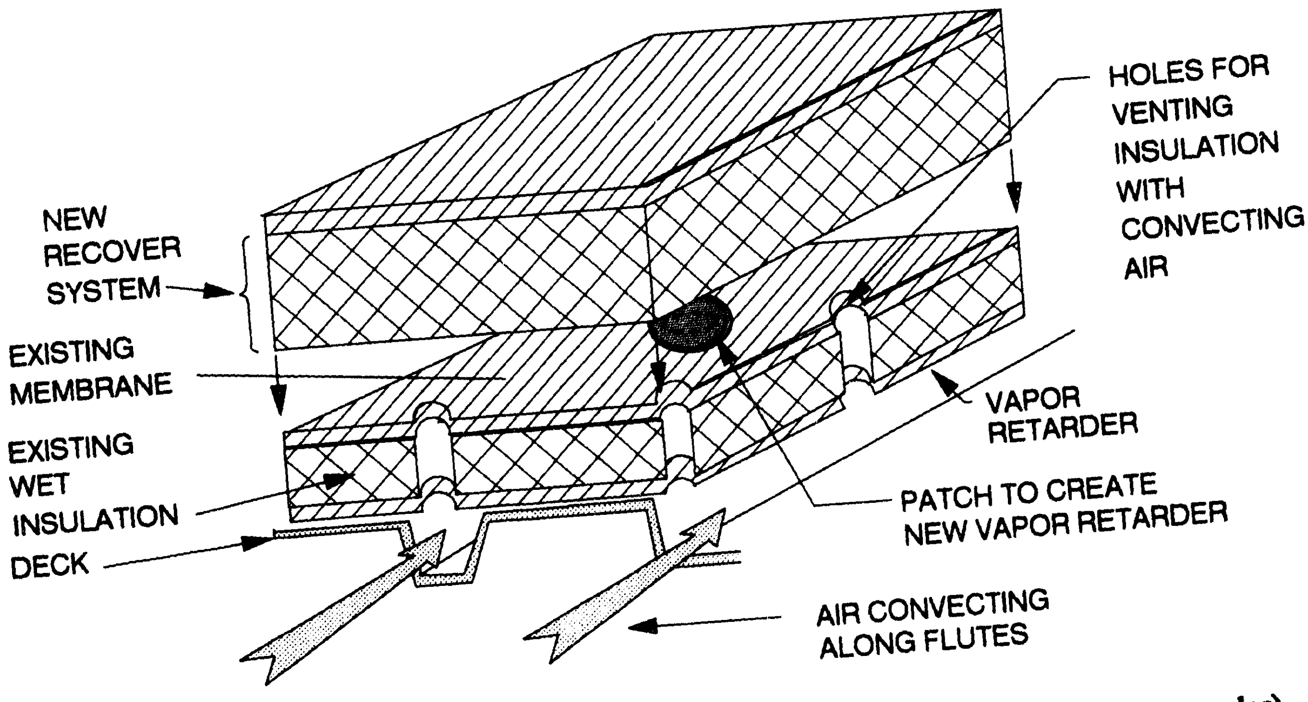

Fig. 5.4. Drilling through to the ventilated flute for recover (pre-existing vapor retarder).

Figure 5.4 depicts how the metal deck flutes act as a duct system for bringing moving air in contact with the opening of each hole. The control panel experiment, some results of which are shown in Fig. 5.2, was continued and has demonstrated that the rate of moisture transfer out of holes drilled through the deck can increase almost tenfold when air is blowing across the openings of the holes. Figure 5.5 presents data from this experiment, along with data already shown in Fig. 5.2 obtained with nominally still air. The blowing data were obtained by positioning two portable fans 0.6–1.0 m (2-3 ft) outside the perimeter of the 1.2 by 1.8 m (4 by 6 ft) test section. The fans blew air across the bottom surface of the metal deck. We conjecture that, in addition to diffusion, disturbance of the air layer below the deck caused water vapor to convect out of the holes.

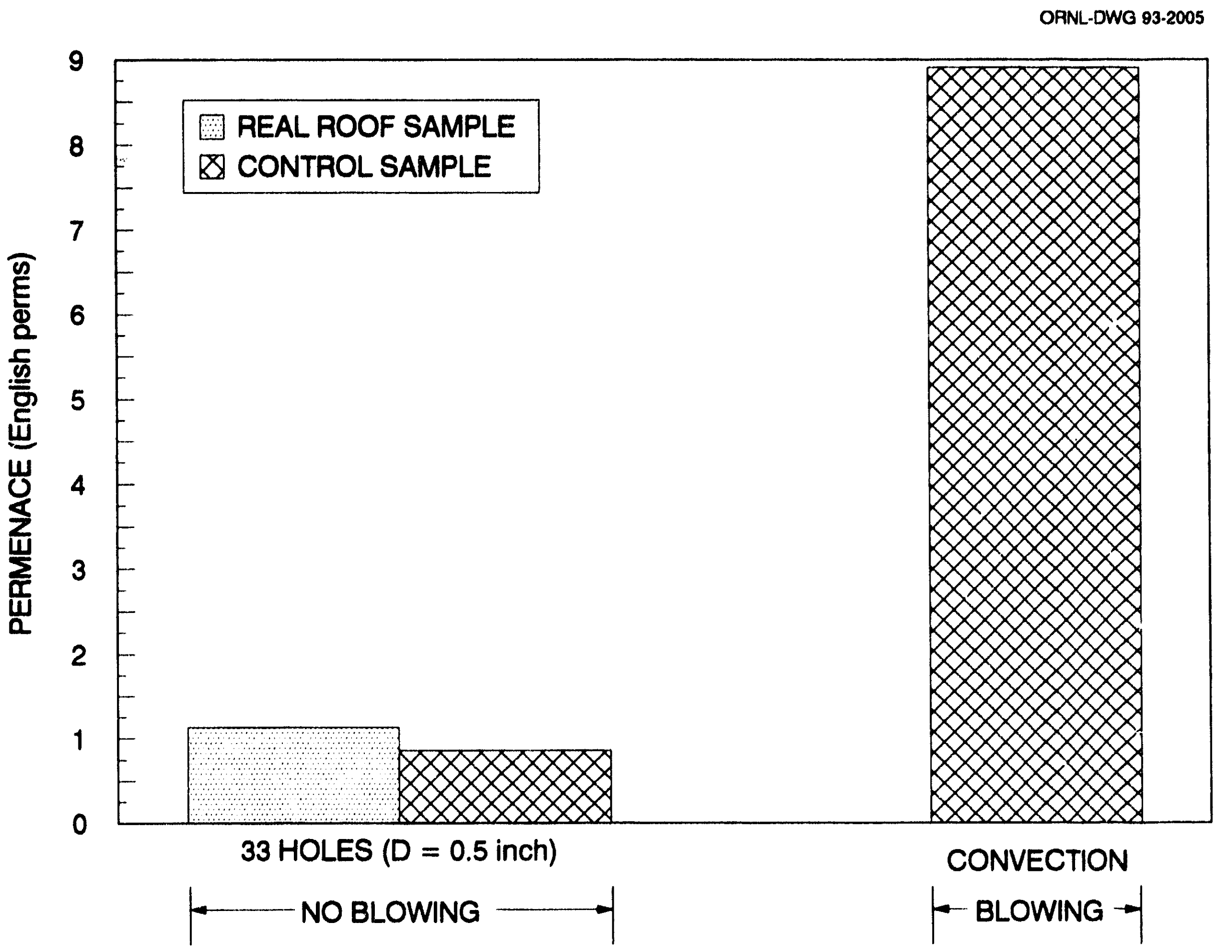

Fig. 5.5. Increase in apparent permeance caused by blowing air across openings in the metal deck. Data shown for no blowing were already presented in Fig. 5.2. No change occurred in the experimental arrangement or boundary conditions for the case with moving air.

5.3 UPWARD DIFFUSION

When there is condensed liquid inside a wet roof assembly, the vapor pressure below the top membrane is usually higher than the vapor pressure of the outdoor air. It is therefore reasonable to speculate that the process of upward vapor diffusion alone may be used to dry out a wet roof.

5.3.1 Experimental Results

For vapor to diffuse from inside the roof to the outdoor air, a diffusion path is required. Either edge vents or vents positioned directly over openings in the membrane must be installed. The latter configuration has been examined experimentally both at ORNL [64] and in well-controlled field experiments [44, 56]. A typical moisture relief vent is shown schematically in Fig. 5.6. In one test panel, Baker and Hedlin wetted 51-mm (2-in.) glass fiber insulation boards to 44% by volume [44]. A single vent allowed 0.605 kg/year (1.3 lb/year) of water to escape. Tobiasson wetted 51-mm (2-in.) panels of perlite and glass fiber to 66% by volume [56]. Annually, 1.3 kg (2.9 lb) of water escaped from the glass fiber panel, or twice the rate observed by Baker and Hedlin.

5.3.2 Simplified Analysis

Tobiasson's experiments were conducted in New Hampshire, while Baker and Hedlin's were in Saskatoon, Saskatchewan. Both regions have long, cold winters. Let us assume that for very wet glass fiber insulation in cold climates, roughly 1 kg/year (2.2 lb/year) of water will leave one moisture relief vent. On a percentage by volume basis,

assuming

92.9 m^2 (1000 ft^2) of roof area per vent,
a 1000 kg/m^3 (62.4 lb/ft^3) density of water,
a 51-mm (2-in.) insulation thickness, and
removal of 1 kg/year (2.2 lb/year) of moisture per vent,

then the moisture removal rate on a percentage by volume basis is:

$$1 \text{ kg/year} \div 1000 \text{ kg/m}^3 \div 92.9 \text{ m}^2 \div 0.051 \text{ m} = 0.00021 \text{ /year} = 0.021 \text{ \%/year} .$$

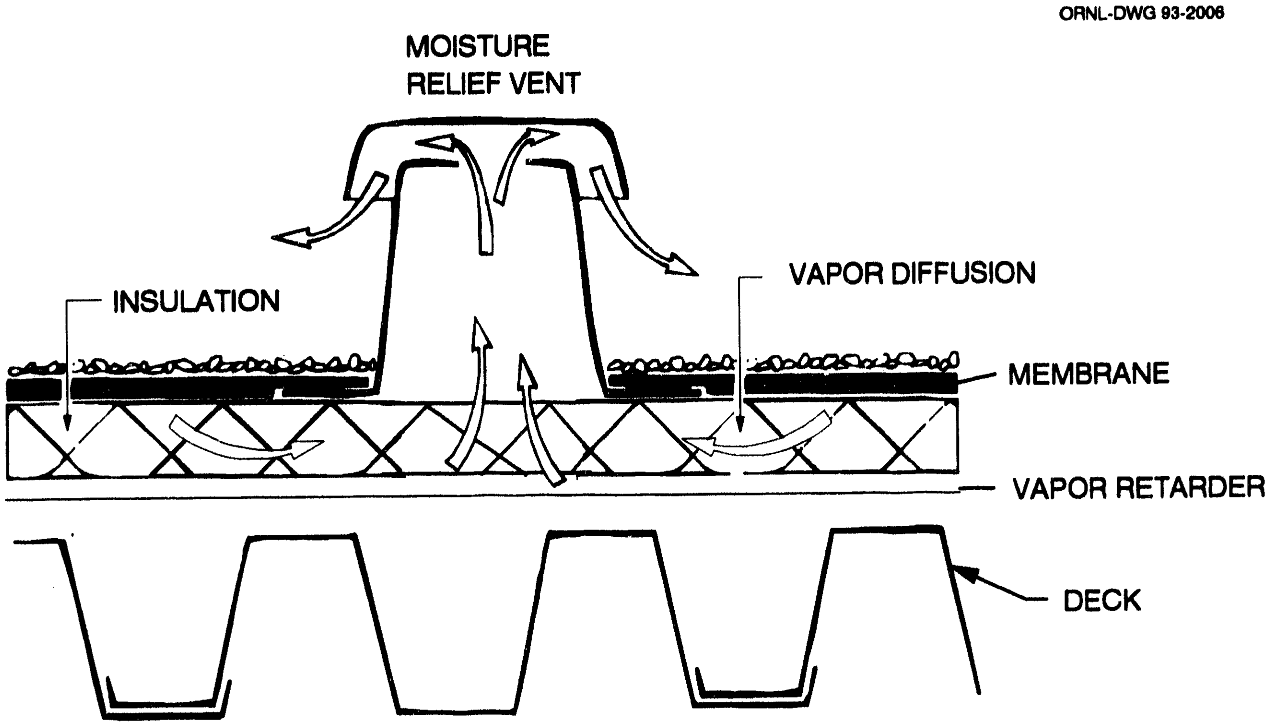

Fig. 5.6. Moisture relief vent to allow vapor to diffuse to the outdoors.

We believe that this quantity of water removal would not be measurable, except by extremely well-controlled experiments like those cited in this report or those performed at ORNL and presented in Figs. 4.3 and 5.5.

Technical Note 5.1: Vapor Diffusion to the Outdoors Through Vents

The process by which water exits through a moisture relief vent can be thought of in two parts: (1) migration of water to the base of the vent body and (2) removal of water from within the vent body. To crudely estimate the moisture removal rate requires two major assumptions about these processes. Regarding (1), we note that the vapor concentration cannot exceed saturation. We shall assume that at the exposed insulation surface beneath the vent, $p_v = p_{sat}(T_{membrane})$. This assumption may be quite good in very wet roofs. Regarding (2), we consider only transport by vapor diffusion. Convection by small eddies, which may be induced by wind circulating around the outside of the vent casing, is ignored.

The vapor transfer rate up through the vent can now be evaluated using

$$m = \frac{\mu A}{l} \left(p_{sat,\ surface} - p_{v,\ outdoor} \right) \times time \,, \tag{T5.1-1}$$

where m is mass transfer (kg or lbm), μ is the vapor permeability of air, A is the cross-sectional area of the housing, and l is its length. Using a computer model, we have evaluated the annually averaged pressure difference appearing in the parentheses in Eq. (T5.1-1), ΔP_{vapor}, for Miami, Chicago, Seattle, and Concord, New Hampshire. The model is one-dimensional and cannot model an opening in the membrane. We have simply assumed a continuous membrane, and used the saturation pressure directly under the membrane in place of $p_{sat,surface}$ in Eq. (T5.1-1). Concord was included so that the calculations can be directly compared with Tobiasson's measurements.

Assuming

$\mu = 1.74 \times 10^{-10}$ kg/s·m·Pa (12 perm·in.),
$A = 5 \times 10^{-2}$ m^2 (0.5 ft^2),
$l = 0.2$ m (0.7 ft),
31.536×10^6 s/year, and
ΔP_{vapor} = Seattle, 930 Pa; Miami, 1900 Pa; Chicago, 1200 Pa; Concord, 920 Pa, (Seattle, 0.28 in. Hg; Miami, 0.56 in. Hg; Chicago, 0.36 in. Hg; Concord, 0.27 in. Hg),

the annual vapor transfer is

1.74×10^{-10} kg/s·m·Pa $\times\ 5 \times 10^{-2}$ m^2 $\div$ 0.2 m $\times\ 31.536 \times 10^6$ s/year $\times\ \Delta P_{vapor}$
= 1.3 kg/year (0.59 lbm/year): Seattle,
= 2.6 kg/year (1.2 lbm/year): Miami,
= 1.7 kg/year (0.77 lbm/year): Chicago, and
= 1.3 kg/year (0.59 lbm/year): Concord.

The exact match with Tobiasson's measurements in New Hampshire is obviously fortuitous. All that is claimed is that the prediction is of the same order of magnitude as his experimental data. The assumption that the vapor pressure at the base of the vent equals $p_{sat}(T_{membrane})$ may be appropriate. Note that these results may be regarded as the maximum transfer rate that is theoretically possible in the absence of convection.

In Technical Note 5.1 we predicted the rate of vapor transfer in a moisture relief vent using several simplifying assumptions. Perhaps the most significant assumption is that air does not circulate inside the body of the vent. This may be reasonable, but it depends upon how the vent is situated and its construction. The results obtained in Technical Note 5.1 may be interpreted as *the maximum possible transfer rate, in the absence of convection.* It is the maximum in the sense that the vapor pressure at the base of the vent is as high as possible—the saturation vapor pressure at the membrane temperature. This is probably accurate in cases where the insulation is extremely wet. In fact, calculations that assume the same weather conditions as in Tobiasson's experiments, and which assume the same degree of moisture contamination, yield evaporation rates similar to his measurements. The conclusion based upon careful measurements in cold climates and on a rough calculation of the maximum possible drying potential in a variety of climates, is that moisture relief vents alone are not an effective means of drying a wet roof.

Tobiasson noted that moisture relief vents only impacted a small area around the roof vent [56]. This is consistent with Hedlin's observations that the driving forces for horizontal water transfer are extremely low [50].

5.4 UPWARD DIFFUSION WITH TOP VENTILATION

Installing vents is essentially a scheme for creating a small amount of surface area in which vapor diffusion can occur between the wet insulation and the outdoor air. Ideally, one would like to expose the *entire* top surface of the insulation to the outdoor air. This ideal can be approached by installing a ventilation layer as a part of the recover system, after perforating or removing the pre-existing membrane. The concept has been addressed directly by Jackson [60] and has been broadly studied by Korsgaard [61]. In addition, insights from several related fields of research can be applied directly to designing ventilated recover systems. Low-slope roofs with ventilated spaces are often built, perhaps most frequently in Europe. Tobiasson examined moisture issues that are related to these designs very comprehensively [70, and references cited therein]. Hedlin measured the drying rates of insulations when outdoor air is allowed to flow over the insulation surface as part of his research on protected membrane roofs [11].

5.4.1 Drying Effect of Top Ventilation

If the pre-existing membrane is removed or can be uniformly and densely perforated, then under many climatic conditions, moisture will diffuse into the air stream from areas of condensed liquid located anywhere in the roof. During the heating season, $T_{membrane} \geq$

$T_{db,OD} \geq T_{dewp,OD}$, where these temperatures are considered on a daily averaged basis. $T_{dewp,OD}$ is also the dew point temperature of the ventilation stream where it enters the roof. It follows that the saturation vapor pressure just beneath the membrane, $p_{sat}(T_{membrane})$, is greater than the vapor pressure of the ventilation stream. Water near the membrane will evaporate and diffuse into the stream. Since the temperature everywhere else in the roof is even warmer than at the membrane, it follows that p_{sat} at every location within the roof is greater than p_v of the ventilating stream. Vapor will diffuse into the ventilation stream from all points during winter.[5]

During summer, we usually think of moisture as being driven downward, not upward, in the pre-existing roof. This is because the vapor pressure just under the membrane is roughly equal to the saturation value (high temperature, high pressure) and the vapor pressure just above the deck is also roughly equal to the saturation value (low temperature, low pressure). Thus, vapor diffuses downward. If an outdoor air stream is introduced, the picture changes. The vapor pressure of the outdoor air stream is less than the saturation vapor pressure throughout the insulation, even the insulation near the cool deck (except occasionally in the Southeast as discussed later). As a result, water will evaporate and diffuse into the ventilation stream. Korsgaard has found that roofs with high moisture content can be dried out in this way [61]. The situation is shown schematically in Fig. 5.7.

Drying Principle 5.4: Top Ventilation

Concern for energy conservation requires that for *top* ventilation, we select the outdoor air stream, under the constraints of Principles 5.1 and 5.2.

5.4.2 Controlling Ventilation

Outdoor air

Principle 5.4 can be quite constraining in warm moist climates, such as in the southeastern United States. During much of the year, the outdoor drybulb temperature, $T_{db,OD}$ is higher than the deck temperature T_{deck}, which is the coldest temperature in the roof. Under humid summer conditions, the outdoor dew point is nearly equal to $T_{db,OD}$,

[5] If the upper part of the wetted insulation is frozen, vapor diffusion will cease since ice is relatively impermeable.

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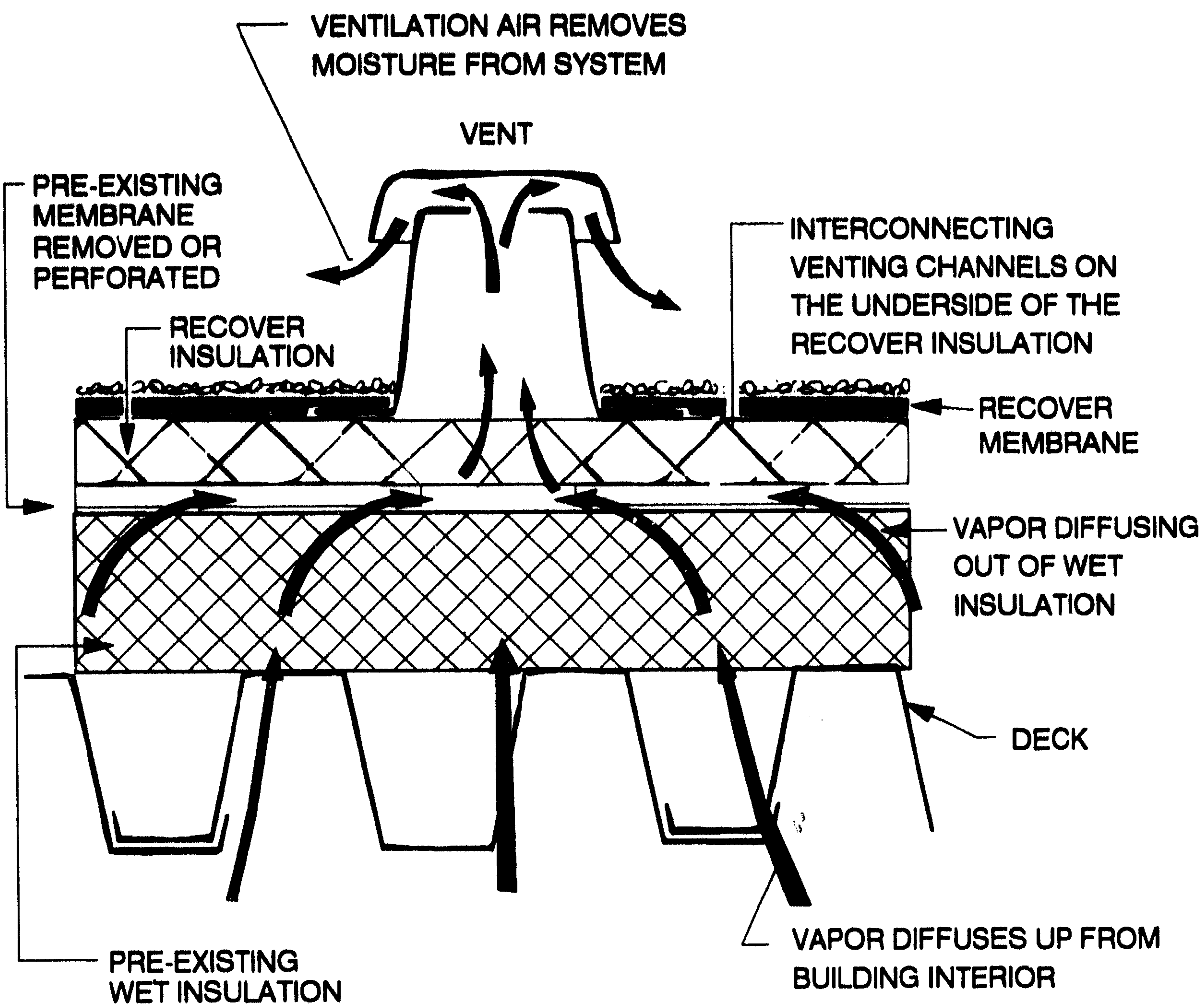

Fig. 5.7. Recover insulation with venting channels. When ventilated with outdoor air, excessive water in any portion of the roof will diffuse toward the ventilation stream and be removed.

and may therefore also be higher than T_{deck} (23–27°C or 73–81°F). In this case, Principle 5.1 would be violated by top ventilation. The vapor pressure of the ventilation stream would exceed p_{sat} above the deck, and vapor would diffuse out of the stream toward the deck. This is shown schematically in Fig. 5.8. Because moisture is accumulating directly onto the deck, even a small amount may cause dripping unless a good vapor retarder has been installed. The problem is obviously a serious one in warm, humid climates such as in the Southeast.

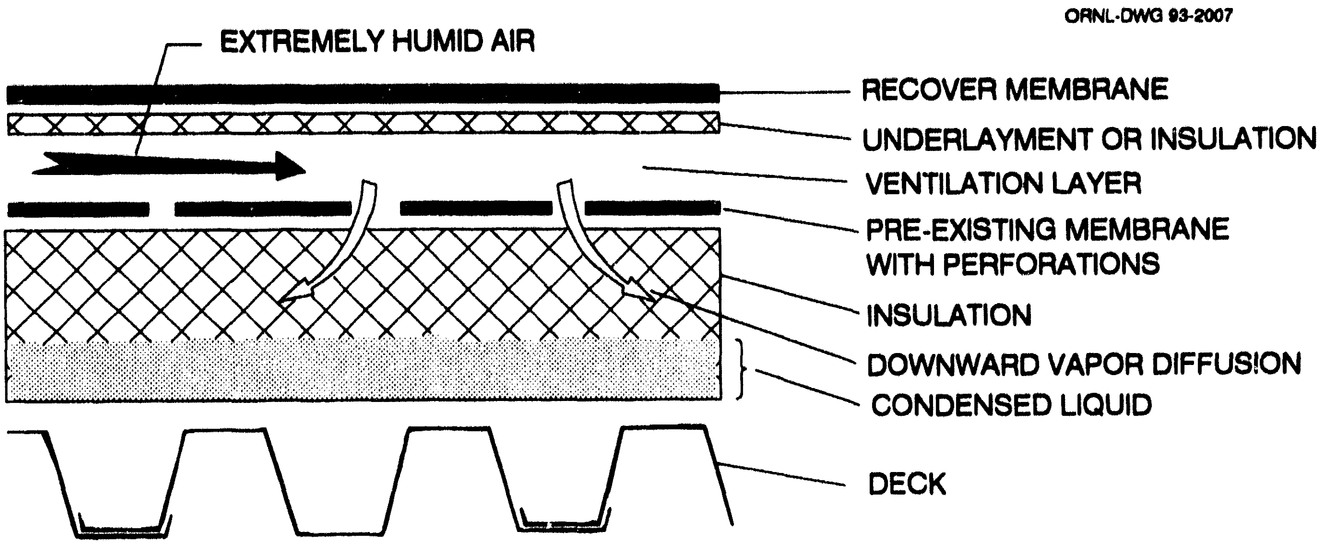

Fig. 5.8. Moisture diffuses out of the ventilation stream toward the cooler deck during extremely humid outdoor conditions.

The U.S. Climatological Data Book lists monthly-averaged dew point temperatures for hundreds of U.S. cities. It shows that in fall, winter, and spring in the Southeast, the outdoor dew point will be below the deck temperature, and drying Principle 5.1 will be satisfied. This is also true year around in nearly every other type of climate in the United States. For these reasons, the practice of ventilating the top with outdoor air could have wide application.

Indoor air leakage into negative gauge pressure systems

Figure 5.9 demonstrates that the air flowing through the ventilation layer *is not the only stream* to which we must apply Principle 5.4. It also must be applied to the air that leaks through joints and other penetrations in the deck. If air is *pulled* through the ventilation layer because a *negative* gauge pressure has been created at the *outlet*, relative to the inside of the building, then this negative gauge pressure will force air leakage from the building interior up into the roof. The leakage rate can be minimized by using a good vapor retarder, certain deck types (i.e., lightweight insulating concrete), or double-layer insulation boards [46, 61, 69].

Unfortunately, even a small air flow can result in significant moisture deposits [61, 70] because convection is a very effective means of moisture transport. The vapor is *carried* to the cold condensing surface within the roof; it no longer needs to diffuse through resistive layers to get there. In addition, deposition from leaks in a compactly constructed deck will

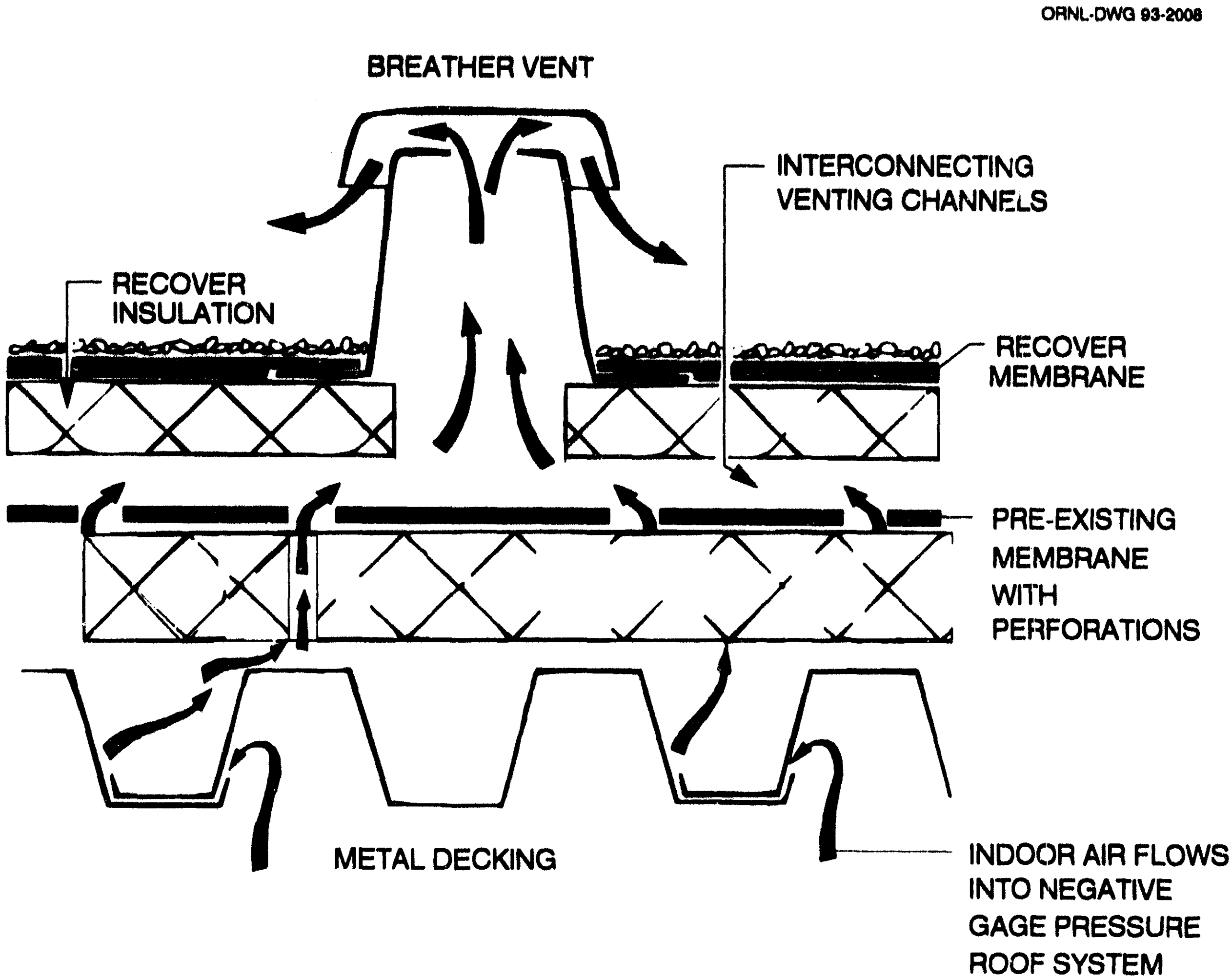

Fig. 5.9. Indoor air leakage into ventilated recover systems operated with negative gauge pressure. During winter, this indoor air stream can come in contact with surfaces whose temperatures are below its dew point and result in condensation.

be localized, not dispersed. Localized concentrations are more conducive to dripping. If deposition occurred in the ventilated recover layer itself, then the moisture would likely be swept away. However, deposition can also occur in the pre-existing assembly or in areas within the recover system that are starved of ventilation air.

Summary of active top ventilation control

Ventilating recover systems that operate under *positive gauge pressure* are safe and effective for drying under all but the most humid conditions found in the United States.

Ventilating recover systems that operate under *negative gauge pressure* are certain to dry the roof only under the following conditions, which relate to *indoor air* effects.

1. Conditions described in Sect. 5.2.1 are satisfied. Thus, if solar heating usually raises the membrane temperature above the indoor drybulb during daylight hours in the heating season, then passively ventilate or operate a blower during the day. If this condition is satisfied on a daily-averaged basis, then passive ventilation (nonmotorized) is safe, as is operating the blowers all day.

2. Solar heating does *not* usually raise the membrane temperature above the indoor dry bulb. In this case, operate the blower only when the membrane temperature is above the average indoor dew point. Measure the indoor dew point directly to learn its average wintertime value. Passive ventilation is hazardous.

3. Decks are sealed against air leakage. Poured decks and systems that incorporate an air retarder generally satisfy this condition.

5.4.3 Configuration

In positive gauge pressure systems, the blowers should be selected or throttled so that the discharge pressure is a very small fraction of the pressure differential used in determining the wind uplift resistance.[6] Also, if the membrane is not adhered, its weight plus the weight of any ballast must exceed the discharge pressure to prevent billowing. The air must move laterally with as little resistance as possible, because for a given fan discharge pressure, higher resistance results in smaller ventilation rates. It is expected that open channels should provide the lowest possible resistance, although fibrous glass may also prove useful. Channels might be cut or molded into closed-cell foam boards.

If parallel channels are used, the air that exits the blower must somehow be distributed among the many channel entrances. In an extended region surrounding the fan and bordering the channel entrances, air would have to flow away from the blower in a widening, 2-dimensional pattern. It would be necessary to use either fibrous glass or foam

[6] Factory Mutual Test FM 4450/4470 is a static test that requires the assembly to resist 60 psf (1436 Pa, 0.208 psi, 5.77 in. H_2O) for one minute to achieve I-60 rating. The same is true for the Underwriter's Laboratories test UL1897. Discharge pressures 1/100th these values should provide ample ventilation rates.

boards with crisscrossing channels. Such boards are currently available, but their performance has not been documented.

Another proposed means of distributing ventilation air within the recover layer is to lay a network of perforated tubes among the insulation boards. If the boards are not fibrous glass, then the method seems to rely upon air flowing along a tortuous route of interconnecting gaps between neighboring boards. These systems are commercially available; again, we were unable to find information on their performance.

5.5 LATERAL CONVECTION THROUGH PRE-EXISTING RIGID FIBROUS GLASS INSULATION: "FORCED DRYING"

5.5.1 Background

If the wet pre-existing insulation is fibrous glass, then it may be possible to achieve some drying by forcing outdoor air to convect laterally through the insulation material itself. This technique, often called "forced drying," will be less effective for other types of insulation that are less permeable to air. As air flows in and around regions of condensed liquid, some of the liquid will evaporate if the air is not already saturated. This liberated vapor is then carried out of the roof, as shown schematically in Fig. 5.10. However, if a base sheet or any other layer was fully mopped to the fibrous glass boards while the roof was being assembled, the hot asphalt probably flowed into the joints between the insulation boards, partially or fully isolating them from one another. Forced drying is ineffective in that case [69].

Tobiasson, et al. have conducted controlled outdoor experiments with 51-mm (2-in.) perlite and glass fiber insulated roof panels in New Hampshire [56]. Each panel received two identical moisture relief vents (no fans) situated roughly 4 m (14 ft.) apart (a rather close spacing for anything but experimental work). A moisture removal rate of 3.5 kg/year (7.7 lb/year) can be attributed to convection in the fibrous glass panel and a rate of 1.3 kg/year (2.9 lb/year) attributed to convection in the perlite panel. Numerous authors have discussed the potential benefits of forced drying [44, 46, 60], but no other quantitative results have been reported.

If the fibrous glass is wetted to 30% by volume or more, Hedlin's laboratory experiments indicate that it may be possible to drain some fraction of this water from the roof [50]. This can be done by locating the exhaust hole at the lowest point in the roof, with the hole opening downward into the building interior. The drainage rate can be

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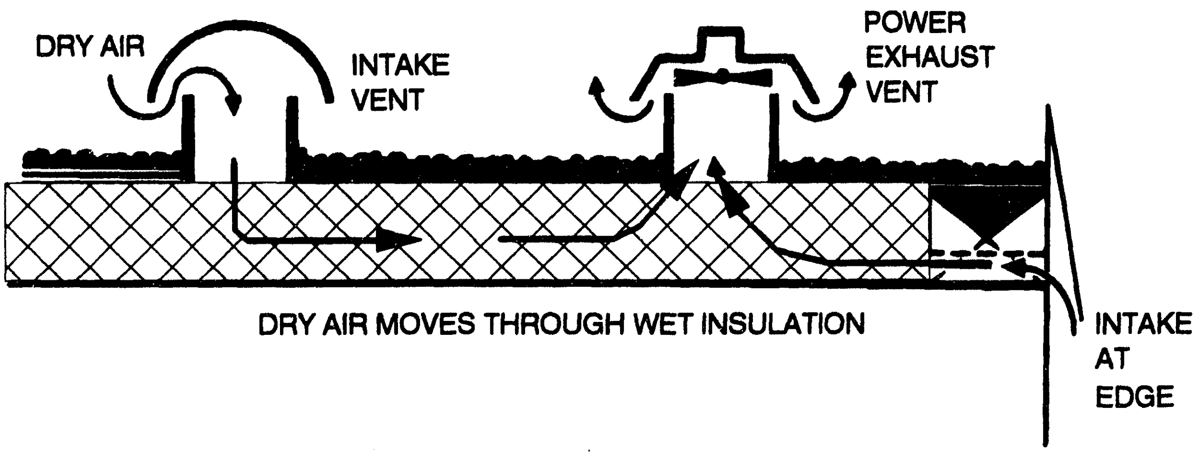

Fig. 5.10. Drying insulation by forcing outdoor air to flow directly through the insulation material.

accelerated by using a blower [56]. Again, this procedure will not be successful if top mopping has isolated the insulation boards from one another.

5.5.2 Sealed Decks: One Vent

If the deck is poured concrete, gypsum, or lightweight insulating concrete, air leakage through the deck will be negligible. Good air retarders can also reduce air leakage to a safe minimum. In either case, air can enter and leave the roof assembly only through the top membrane or along the roof perimeter. In the case of a single installed vent, the principle of mass conservation ensures that no ventilation can occur, regardless of whether the vent is capable of inducing a negative gauge pressure within the roof. Also, the rate of diffusion is unaffected by any sucking action that the vent imposes, because only extremely small fractional changes in vapor pressure will result from the pressure changes imposed by any fan or vent. The diffusion through a single vent was discussed in Sect. 5.3; we concluded that the drying effect is too small to measure.

Roofing systems are currently being marketed which use strategically placed pressure relief vents to maintain a negative or zero gauge pressure on the underside of the loose-laid membrane to prevent wind uplift without using extra ballasting. The concept is valid. However, several of these systems are being marketed with the promise that they also promote moisture removal. In the case of a sealed deck, that claim is false, assuming that the vents are one-way and there is no ventilation layer. The case of unsealed decks is discussed in Sect. 5.5.4.

5.5.3 Sealed Decks: Two Vents

Figure 5.10 depicts the movement of outdoor air in through an inlet vent or fan, through the insulation, and back out through an exhaust vent or fan. This method of ventilation could remove large amounts of moisture from the roof. If the roof is very wet, it is likely that the air exiting the roof will be saturated (rh = 100%) at roughly the outdoor temperature. Then, the drying rate is simply computed using [72]:

$$\dot{m}_v = \dot{m}_a w_s \left(T_{OD}\right) - \dot{m}_a w_{OD} , \tag{5.1}$$

where $\dot{m}_v$ is the mass of water vapor, $\dot{m}_a$ is the mass of dry air that enters and leaves the roof, w_{OD} is the humidity ratio (mass water/mass dry air) of the outdoor air, and $w_s(T_{OD})$ is the saturation humidity ratio at the outdoor air temperature.

It is instructive to consider a specific example. The monthly averaged dew point and drybulb temperatures have been obtained for Chicago from the U.S. Climatological Data Book, and using these data, w_{OD} and $w_s(T_{OD})$ were obtained from the psychrometric chart [72]. For every cubic foot per minute of air flow, 41 kg (91 lb) of water is removed from May through October, and 11 kg (25 lb) of water is removed from November through April. If there is one vent every 90 m^2 (1,000 ft^2) and each pair of vents provides one inlet and one outlet, then water will be removed each summer at a rate of 0.43% by volume per cubic foot per minute of air, and 0.13% is removed each winter for every cubic foot per minute of air. Because of the low air permeability of roofing insulation, even very small flow rates may be difficult to obtain economically. The low air permeability will require that significant pressures be overcome to obtain any type of air flow through the insulation.

5.5.4 Unsealed Decks: One Vent Plus Leaks

In an unsealed deck with leaks, interior air probably will leak into the unsealed roof. If we assume that all the leaking air exits to the outdoors in the saturated state, then the rate of drying/wetting from leaks is given by

$$\dot{m}_v = \dot{m}_a w_s \left(T_{OD}\right) - \dot{m}_a w_{ID} , \tag{5.2}$$

where $\dot{m}_a$ is the mass of dry air that infiltrates from within the building, and w_{ID} is the humidity ratio of the indoor air. Assume that for wintertime indoor conditions, T_{db} = 21°C (70°F) and rh = 35%, and for summertime indoor conditions, T_{db} = 22°C (72°F) and rh = 60%. Assuming a Chicago climate outdoors, for every cubic foot per minute of air flow from leaks, 36 kg (79 lb) of water is removed during May through October, and 13 kg (28 lb) of water is *deposited* from November through April. On an annually averaged basis, air leakage has a net drying effect of 23 kg (51 lb) per cubic foot per minute in Chicago. Note that the accumulations can be locally concentrated. For example, if condensation from just one uncompensated cubic foot per meter of leakage is concentrated in a 1.9-m^2 (20-ft^2) area, then water will occupy 14.5% by volume in that area. Such accumulations are often released suddenly, causing dripping. In climates where the indoor dew point is usually below the exterior membrane temperature during winter, there is minimal danger of condensation.

5.5.5 Unsealed Decks: Two Vents Plus Leaks

In an unsealed deck with two vents plus leaks, two air streams from different sources converge in the same insulation material. These are (1) the intended cross flow described in Sect. 5.5.3 and (2) the indoor air leakage described in Sect. 5.5.4. If the volume flow rate for leakage exceeds the flow rate for ventilation in any given area of the roof, the air leakage can result in considerable moisture accumulation during winter. Otherwise, this case yields the combination of effects described in Sects. 5.5.3 and 5.5.4.

6. SELF-DRYING DESIGNS FOR NEW ROOFS

6.1 INTRODUCTION

This chapter describes a method for designing self-drying roofs. Virtually all of the concepts to be discussed originate from the work of Powell and Robinson [64], whose experimental investigations at the National Institute of Standards and Technology spanned 6 years and used 27 roof specimens for the purpose of understanding the factors which influence the self-drying performance of insulated low-slope roofs. The goal of this chapter is to show how easily and economically Powell and Robinson's ideas can be implemented using today's materials and modern computational methods. Many of concepts introduced by Powell and Robinson are echoed by Griffin [82].

6.2 THE MODERN SELF-DRYING ROOF ASSEMBLY

Figure 6.1 shows one example of a self-drying roof assembly constructed with modern materials. From the bottom up it consists of a metal deck that is perforated to make it permeable to water vapor, a possible wicking layer of paper or polyester fabric that will laterally disperse any liquid flow that reaches it, insulation board that is relatively permeable to vapor (low R_v value) and possibly absorptive, a wicking layer, insulation board that is relatively impermeable to vapor (high R_v value), and the membrane.[7] The role that the components play within the overall assembly, including the importance of their positions within the assembly, will now be described in light of Powell and Robinson's experimental results.

Omission of the vapor retarder or impermeable layers such as an asphalt mopping to adhere two insulation layers together is a key to a self-drying roof. In situations where a vapor retarder is deemed essential, self-drying roof principles are violated.

[7] If the top insulation layer is a plastic foam and the membrane is either a BUR or modified bitumen, NRCA Bulletin 9 recommends the use a cover board to reduce the possibility of blistering. This is consistent with a self-drying roof, as long as the addition of the cover board does not also introduce an impermeable layer into the roof system.

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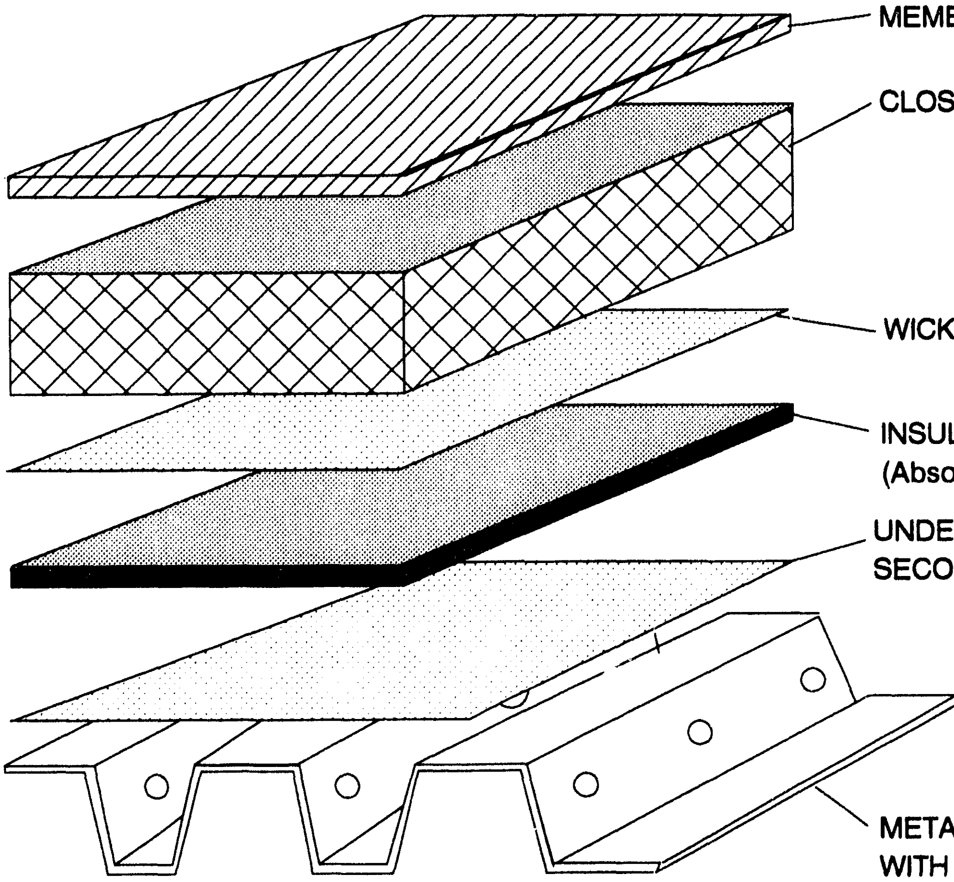

Fig. 6.1. Self-drying roof assembly. See text for explanation.

6.2.1 Perforated Metal Deck

Drying times

Powell and Robinson found that roof specimens whose undersurfaces were moderately vapor-permeable (>5.7 × 10^{-7} g/Pa·s·m^2 or 10 English perms) would generally dry out (reach equilibrium moisture content) during simulated summer conditions, even after initial moisture contents of 10% by volume. Their roof specimens included no vapor retarder, no membrane between the wet insulation and the deck, and no asphalt moppings between layers of the roof specimen. Their results are consistent with the data shown in Fig. 6.2, which were calculated using Rode's finite difference program [78]. The roof assemblies used for these calculations comprised a BUR roof, 51 mm (2 in.) of unfaced glass fiber, perlite, or PIR insulation boards, and a deck having zero resistance to vapor diffusion (R_v = 0). The choice of zero vapor resistance was meant to simulate the behavior of perforated (slotted) metal decks currently available for acoustical applications and for lightweight insulating concrete construction. An initial moisture concentration of 10% by volume overall was assumed, which was placed entirely in the top 10 mm (0.38 in.) to simulate a leak into the roofing system. The closed cell insulation (PIR) required 2–3 years of simulated time to dry, while the permeable insulations (glass fiber and perlite) required less than 0.5 year to dry in all three cities.

Compare these times with the drying times shown previously in Fig. 4.3 for the same cities and constructions, but with different deck R_v values. The presence of a deck with a permeance of 1 (English) perm doubles the drying time for 51 mm (2 in.) of PIR and increases the drying time by an order of magnitude for the permeable insulations. The data shown previously in Fig. 4.3 are consistent with Powell and Robinson's experimental results for expanded shale concrete decks (permeance of 4.8 × 10^{-8} g/Pa·s·m^2 or 0.84 English perms) and EPS-filled insulating concrete decks (permeance of 6.9 × 10^{-8} g/Pa·s·m^2 or 1.2 English perms).

Dripping and deck corrosion

In order for dripping to occur, water must reside on the top surface of the deck. This is also a precondition for corrosion of metal decks, dry rotting of wood decks, and mechanical deterioration of other types of decks. Downward vapor diffusion is one process that can lead to the presence of water on the top surface of the deck, if the deck is relatively impermeable. This process is shown schematically in Fig. 6.3 by unfilled arrows. During the cooling season, water that is trapped near the solar-heated roof

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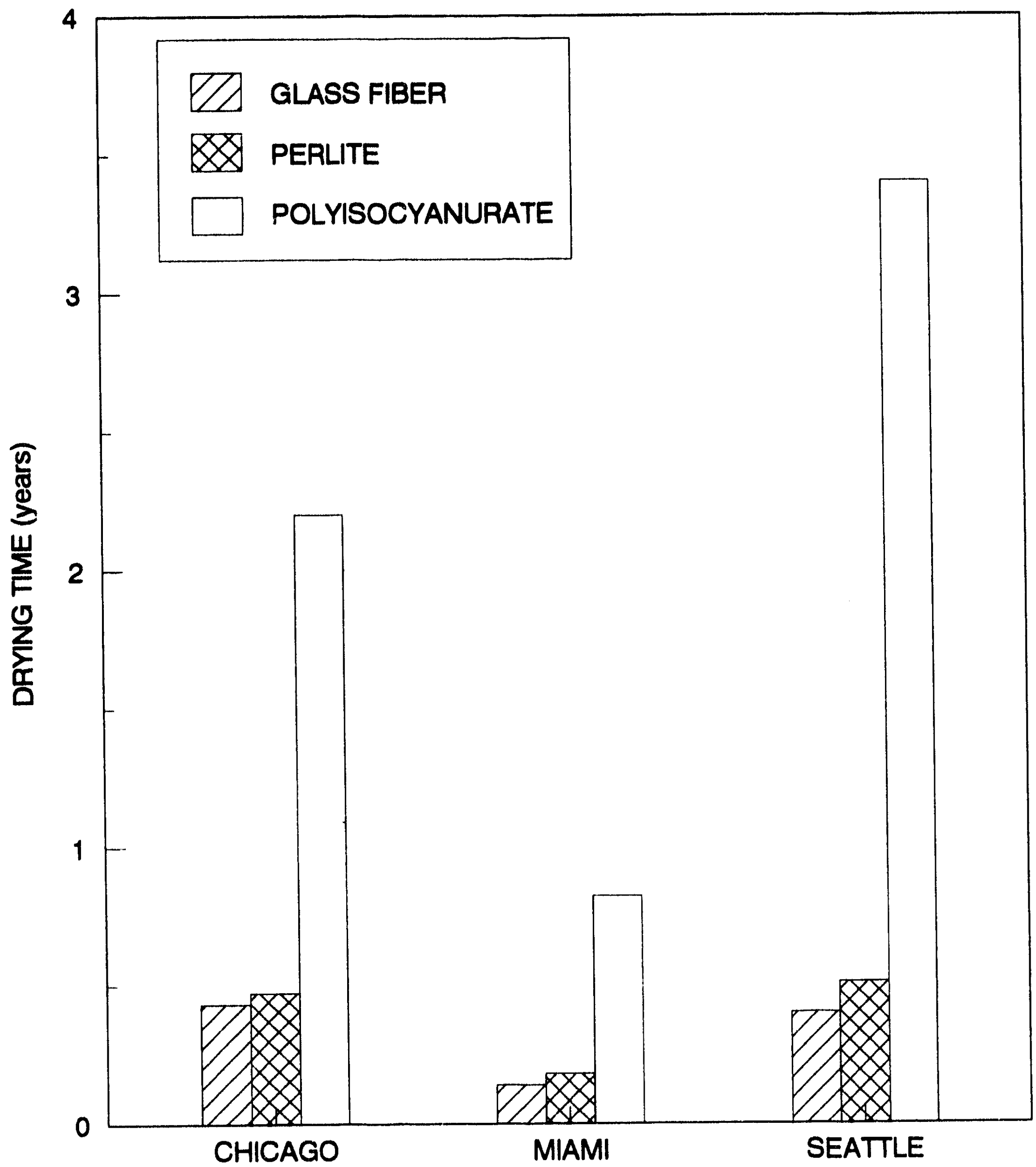

Fig. 6.2. Drying times for roof systems incorporating very permeable decking. Data were calculated using a finite-difference computer program [78]. Initial conditions, boundary conditions, and assembly configurations are the same as for Fig. 4.3, except here $R_{v,deck}$ = 0.0. Again, the drying time is defined as the time required for the insulation material to achieve an equilibrium moisture content.

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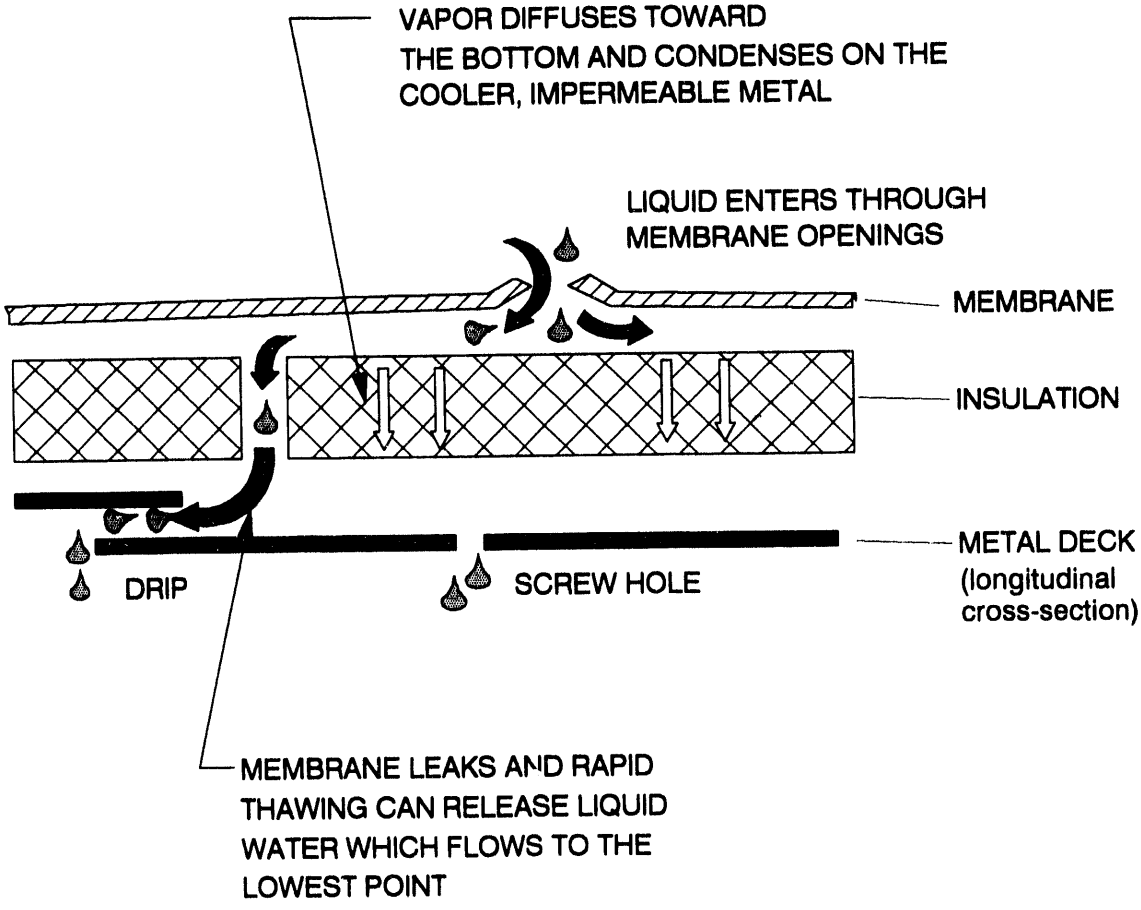

Fig. 6.3. Two processes leading to water on the top surface of the deck, a required precondition for dripping.

membrane will tend to vaporize and diffuse downward toward the cooler deck. Conventional metal decks (as well as some other deck types) inhibit the vapor from passing on into the building interior. The vapor pressure therefore continually builds up at the bottom of the insulation, and a layer of condensation develops. The development of this liquid layer has already been depicted in Fig. 3.2 for the case of an impermeable deck with several different insulations. If that deck is replaced by one with a permeance of 5.7 $\times 10^{-8}$ g/Pa·s·m^2 or 1.0 English perms, the calculated moisture distributions look virtually the same as the data shown in Fig. 3.2, if the same moisture content is present at the start of the year. Figure 3.2 shows that concentrated water accumulates on the deck for at least part of the year in most U.S. climates when the insulation is wet.

If the metal deck is perforated so that it becomes highly permeable or if another type of permeable deck is used, then vapor is not significantly impeded from passing into the building interior. Speaking very crudely, the gaseous water molecules arriving at the bottom of the insulation during the cooling season respond to the low vapor pressures in the building interior and continue to diffuse. They are impeded only by a relatively permeable "boundary layer." In Technical Note 6.1 we present a more quantitative evaluation of conditions immediately above the deck. We show that even in a worst-case scenario, water vapor will not accumulate above a perforated deck during the summer unless there is a major leak that saturates the assembly.

Drying Principle 6.1: Condensation Resulting from Downward Vapor Diffusion

If the deck is very permeable (very low R_v), then a layer of concentrated liquid will seldom form at the bottom of the insulation as a result of downward vapor diffusion.

By eliminating condensation resulting from downward diffusion and repairing major leaks, dripping should be less frequent with permeable decks. This conjecture is supported by an NRCA survey [2] of 41 problem low-slope roofs. In this study, 44% of the roofs had metal decks, whereas of those reporting chronic dripping, a disproportionate 75% had metal decks. Of course, other problems may have plagued these metal decks as well. Once condensation resulting from downward diffusion is eliminated, metal deck corrosion should also be reduced overall.

Technical Note 6.1: Calculation of Vapor Pressure at the Deck

We consider steady-state conditions with the maximum conceivable diffusion rate. This vapor flux intensity exceeds realistic transient situations and may be considered a worst case. If the calculated vapor pressure at the bottom of the insulation is less than $p_{sat}(T_{bottom})$, then we know that condensation at the deck is avoided. The governing equation is

$$\left(\frac{p_{sat}(T_{membrane}) - p_{v,indoor}}{\sum R_v}\right) = \frac{p_{v,bottom} - p_{v,indoor}}{R_{bl}} , \qquad \text{(T6.1-1)}$$

where we have used the fact that for steady-state, the mass flux across any horizontal plane is the same. $R_{v,bl}$ is the vapor diffusion resistance of the boundary layer of air along the bottom of the deck. Solving for $p_{v,bottom}$,

$$p_{v,bottom} = \left(\frac{p_{sat}(T_{membrane}) - p_{v,indoor}}{\sum R_v}\right) \times R_{v,bl} + p_{v,indoor} , \qquad \text{(T6.1-2)}$$

Through similar arguments, we have for the steady-state temperature at the bottom of the insulation:

$$T_{bottom} = \left(\frac{T_{membrane} - T_{indoor}}{\sum R_T}\right) \times R_{T,bl} + T_{indoor} . \qquad \text{(T6.1-3)}$$

Examining Eq. (T6.1-2) we see that the maximum $p_{v,bottom}$ occurs when the membrane temperature is high and the vapor resistance of the insulation is low.

Assuming

$R_{v,bl}$ = 5.1×10^7 Pa·m²·s/kg (0.22 Rep) [72, 76],
R_v = 4.5×10^8 kg/Pa·m²·s (2.5×10^{-2} Rep) for 0.051-m (2-in.) glass fiber [72],
R_T = 0.134 m²·°C/W (0.76 h ft² °F/Btu) for the boundary layer [72],
R_T = 1.55 m²·°C/W (8.77 h·ft²·°F/Btu) for 0.051-m (2-in.) glass fiber [72],
T_{indoor} = 23°C (73°F), and
$T_{membrane}$ = 60°C (140°F).

According to Eq. (T6.1-3), the temperature at the bottom of the insulation is 26.3°C (79.4°F). According to the steam tables, the vapor pressures are

$$p_{sat}(T_{membrane}) = 25.0 \text{ kPa } (7.4 \text{ in. Hg}),$$
$$p_{v,\,indoor} = 0.60 \times 2.81 \text{ kPa} = 1.7 \text{ kPa } (0.50 \text{ in. Hg}), \text{ and}$$
$$p_{sat}(T_{bottom}) = 3.40 \text{ kPa } (1.0 \text{ in. Hg}).$$

From Eq. (T6.1-2), $p_{v,\,bottom}$ = 1.96 kPa (0.58 in. Hg). Since this is less than $p_{sat}(T_{bottom})$ = 3.40 kPa (1.0 in. Hg), no condensation occurs for these conditions.

Thermal performance

The self-drying roof system requires that the roof assembly be free of impermeable layers and surfacings. This requirement will prohibit the use of asphalt to fully adhere the individual layers of the roof system together, and mechanical fastening will be required. The use of mechanical fasteners will degrade the thermal performance of the roof by introducing thermal bridges through the insulation. However, the self-drying design will keep the insulation material significantly drier, enhancing the system's thermal performance.

6.2.2 Low R_v and Absorptive Lower Insulation Layer

Low R_v

The optimum total R_v of the assembly for a particular climate is defined in the next section. In most cases, the optimum can be achieved by combining two different types of insulation boards. Powell and Robinson configured several of their specimens for the specific purpose of learning how best to arrange different insulation types. They advise, "If more than one material is used, locate the material of lowest permeance [highest R_v] just under the roofing [membrane]." This has the advantage that if *either* insulation layer becomes wet, the moisture is readily transferred to the building interior. On the other hand, if a relatively impermeable layer lies just below the permeable layer, then large amounts of moisture can be trapped above this layer for a very long time. As Fig. 6.2 indicates, the use of high R_v insulations *alone* can also greatly extend the drying time in seasonal climates.

Absorption

Powell and Robinson note that "it appears advantageous to provide [at least one material with] some moisture absorption capacity to prevent inundation of the occupied space should the membrane leak during a hard rain storm. Also, some moisture absorption capacity appears advantageous to retain the much smaller quantity of vapor transferred and condensed during winter." [64]

Regardless of how it was introduced, water residing beneath the membrane may flow, under the influence of gravity, along some route within the roof assembly, eventually arriving at the deck. This is shown schematically in Fig. 6.3 by the dark arrows. If there is absolutely no absorptive component in the roof assembly, then even the sudden thawing of very small wintertime accumulations may cause dripping. If this flow is absorbed by the lower insulation layer and dispersed, then it will quickly dry downward through this permeable layer, thus preventing dripping.

6.2.3 Wicking Layer

Some buildings may require greater insurance against dripping than that afforded by the absorptive bottom insulation layer alone. In that case, a highly permeable wicking layer can be sandwiched between insulation layers. Sheets of light polyester fabric, cotton, or fiberglass are very efficient wicking layers in roofing applications [64, 68]. Blotting paper should also be effective. If wicking sheets are overlapped when laid, then any liquid stream will be intercepted and widely dispersed. Alternatively, consumers could demand new insulation facers that have wicking capability. Whether wicking material is installed as a facer or as a separate sheet, water will disperse and subsequently dry by evaporation through the permeable bottom insulation layer. If the liquid flow driven by gravity is so intense that dripping continues despite the dispersal action of a wicking sheet, there is a massive membrane leak in need of immediate repair.

Powell and Robinson examined the effect of adding a cotton "scrim" to the top and bottom surface of a poured lightweight concrete slab. They observed a slight decrease in the drying rate. They conjectured that because the water is more locally concentrated without the wicking action of the scrim, the vapor pressure drive for drying was greater than with the scrim.

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6.2.4 High R_v Upper Insulation Layer

Powell and Robinson configured several of their specimens for the specific purpose of determining the most desirable material properties of insulations in a self-drying roof. From their experimental results, they advise not using an insulation with high water vapor permeance by itself. This advice stems from their observation that large quantities of vapor can diffuse upward from the building interior during winter if the entire assembly is made of low-resistance components. They assume the use of a very permeable deck (deck permeance in excess of 5.7×10^{-7} g/Pa·s·m^2 or 10 English perms). Although the moisture dried back out during the simulated summer conditions in every specimen, Powell and Robinson judged that the maximum accumulation needed to be limited. A high R_v insulation layer provides this function. As stated in Sect. 6.2.2, the higher R_v layer should be positioned above the more permeable layer. Usually there is no need to install a high R_v layer in climates where there is no heating season and therefore no winter condensation.

7. REQUIRED RESEARCH AND DEVELOPMENT

In 1971, Powell and Robinson concluded that it was necessary to rely upon laboratory and field experiments to determine the suitability of any self-drying roof assembly. They believed that, at that time, the theoretical basis for understanding combined heat and mass transfer processes was not developed sufficiently and that, therefore, quantitative analytical tools such as computer programs could not be developed. The 1989 *NRCA Roofing and Waterproofing Manual* [77] currently echoes Powell and Robinson's conclusion about self-drying roof assemblies, stating that "conditions should be established by lab tests" alone.

Lack of confidence in the theory of combined heat and moisture transfer, and in the availability of computer programs to implement it is no longer warranted. The theory is more or less complete [24, 76]. Many computer programs that are available worldwide are capable of analyzing heat and moisture movement in low-slope roofs. Organized efforts to validate many of these programs are well under way [76]. Some of these programs are in the public domain or are licensed for sale, while more closely guarded programs are owned by institutions that are often anxious to work with others. Hour-by-hour weather data are available in digital format from numerous weather stations. In short, it is now possible to calculate the heat and moisture movement within any roof assembly located anywhere in the United States, given the material properties of the roofing components where sufficient weather data is available. These databases of material properties are now expanding.

In this chapter, we present one possible way of using these computer programs, in conjunction with limited experimental research, to develop a simple methodology for designing self-drying roofs.

7.1 REQUIRED RESEARCH

7.1.1 Seasonally Averaged Vapor Pressures

As part of the methodology that we are suggesting, the roof specifier (architect, etc.) is required to know the average summertime saturation vapor pressure immediately below the membrane, $p_{sat,summer}$,[8] and the average wintertime saturation pressure immediately below the membrane, $p_{sat,winter}$. These should be provided by researchers, who can calculate

[8]Since a self-drying roof will not allow water vapor to condense at the deck during summer, we use $P_{sat,summer}$ instead of $P_{sat,deck}$ to compute summer drying.

typical values using the computational tools described above for a range of building interior conditions. The vapor pressure immediately below the membrane depends strongly upon the local climate and should therefore be calculated separately for each region of the country. It also depends upon the membrane type and color (subject to change over time), which establish the radiative heat transfer properties, and upon the total R_T value of the roof. In summary, the specifier will need a table pertaining to one geographic region that presents $p_{sat,summer}$ as a function of the membrane type and roof R_T. Another such table should present $p_{sat,winter}$.

7.1.2 Moisture Limits

Condren [58] has suggested that the most rational approach to specifying the amount of vapor resistance to be installed in a roof assembly begins with identifying the maximum allowable winter accumulation, or "moisture limit." We agree with Condren. Moisture limits may be dependent upon the type of insulation, the type of membrane, and the technology used for fastening the membrane. These choices affect the degradation in thermal resistance due to moisture and the potential for structural damage from freeze-thaw action, delamination, metal corrosion, and decay of organic fibers (see Sect. 2.2). With all this in mind, researchers must establish a set of moisture limits with a reasonable safety factor by means of well-controlled experiments.

Several researchers have recommended moisture limits in the past [32, 58, 64]. Recommendations range from 1.5 to 5.0% by volume, based on 51 mm (2 in.) of insulation. The median moisture content of currently installed roofs has been observed to be about 1.5% by volume for polyurethane foam, and 4.4% for perlite [1]. The large majority of these installed roofs function adequately throughout most of their service life [69]. Note that Fig. 2.3 suggests that these moisture contamination levels are probably not due *primarily* to upward vapor diffusion from the building interior. Other potential sources include trapped construction moisture, membrane leaks, and convection of indoor air within the roof assembly. Regardless of the source, the self-drying roof should allow the moisture to promptly dry downward (see Fig. 6.2), resulting in a lower median moisture content than that observed in currently installed roofs.

7.2 SUGGESTED ROOF DESIGN PROCEDURE

The designer's job is to design a reliable roof system which has the maximum total R_T that is economically justifiable and the optimum total R_v value. The optimum total R_v is defined in the following principle.

Drying Principle 7.1: Optimum total R_v

The total vapor diffusion resistance, R_v, is at its optimum value when the expected wintertime moisture accumulation is equal to the maximum allowable accumulation with a reasonable factor of safety. Installing less resistance than this optimum value would cause excessive moisture accumulation during the winter; installing more resistance than this would result in unnecessarily long drying times.

Note that the optimum R_v is not determined by economic considerations. This is because in most cases, the incremental increase in cost for the design modifications described in Sect. 6.2 appears to be insignificant compared with the total savings accrued from drying out the roof. Recall from Sect. 2.2 that in Chicago, heating savings alone justify roughly a \$0.16/ft^2 per year increase in construction costs. This is in addition to electrical demand savings in summer (see Fig. 2.2 and Table 2.3) and reductions in amortized construction costs associated with the presumed longer service life of self-drying roofs (Fig. 2.4).

We suggest a four-step procedure for specifying the optimum total R_v:

1. Calculate the expected wintertime moisture accumulation for a proposed design.

2. Compare the calculated accumulation with the "moisture limits."

3. If the moisture limits are exceeded, increase the vapor diffusion resistance of the design. If the calculated accumulation is far less than the moisture limits, then reduce the vapor diffusion resistance of the design.

4. Finally, calculate the summertime drying. This should exceed winter accumulations in nearly all continental U.S. climates. If drying does not exceed wetting, then self-drying roofs are not viable in the geographic region of interest.

7.2.1. Calculation of Moisture Accumulation

The physical situation during winter condensation is shown in Fig. 7.1a. Vapor originating within the building must pass through all elements in the assembly to arrive at the underside of the membrane. The equation is

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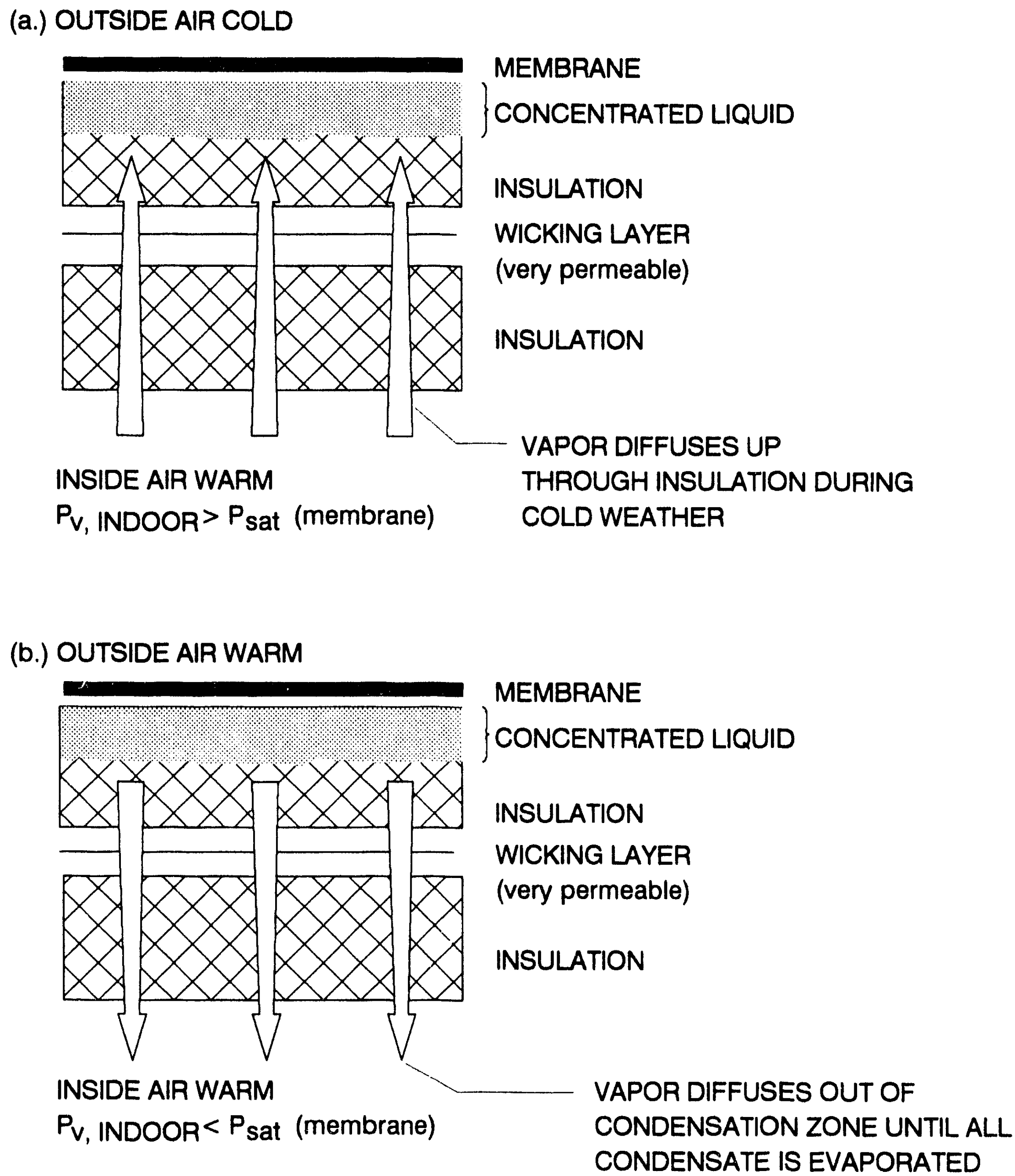

Fig. 7.1. Winter condensation and summer drying in self-drying roofs. On self-drying roofs, unlike relatively impermeable metal decks, water never accumulates anywhere inside the roof except immediately below the membrane, unless there is a major leak.

$$m_{H2O} = [p_{interior} - p_{sat,winter}] \; / \; \sum R_v \; X \; time \, , \tag{7.1}$$

where

m_{H2O} = the total accumulation (kg/m^2 or lbm/ft^2) during winter,

$p_{interior}$ = the vapor pressure (Pa or in. Hg) inside the building,

$p_{sat,winter}$ = the average wintertime saturation pressure (Pa or in. Hg) immediately below the membrane (provided to the specifier in a table, as described above),

R_v = the vapor diffusion resistance (m^2·s·Pa/Kg or Rep) of any roofing element (see, e.g., ASHRAE Fundamentals [72], the new ASTM manual [70], or any of a number of other references), and

$time$ = the length of the winter wetting season (indicated on the $p_{sat,winter}$ tables).

The designer must determine $p_{interior}$ for each building. The procedure is to determine the daily average interior temperature and relative humidity during winter. In the case of roof replacement, this is best accomplished by direct measurement; ASHRAE's tables of standard values can also be used. From steam tables, or from tables in the "Psychrometrics" chapter of ASHRAE Fundamentals, find the "saturation vapor pressure" corresponding to the interior temperature. Multiply this by the relative humidity to obtain $p_{interior}$.

7.2.2 Calculation of Summer Drying

After adjusting the roof design to obtain the optimum total R_v, the designer must calculate the summertime drying to ensure that the roof self-dries. The physical situation during summer drying is shown in Fig. 7.1(b). Vapor originating at the underside of the membrane must pass through all elements in the assembly to arrive at the building interior. The equation is

$$m_{H2O} = [p_{sat,summer} - p_{interior}] \; / \; \sum R_v \; X \; time \, , \tag{7.2}$$

where $p_{sat,summer}$ is the average summertime saturation vapor pressure immediately below the membrane and is provided to the specifier in a table, as described above. Again, the specifier must determine $p_{interior}$ from the daily average interior temperature and relative humidity during summer by measurement or estimation. In a modern air-conditioned building, both are likely to be higher than the winter values.

7.3 INDUSTRY NEEDS

The advent of self-drying roofing practices represents an opportunity for manufacturers to develop and market new self-drying roofing systems. Perhaps component and system manufacturers, as well as system trade associations, should also take on the task of determining moisture limits. There is also the need to generate reliable moisture properties data for input into the modeling programs. Some industry-standard measure of freeze-thaw durability, moisture absorption, and permeance would be helpful. This would require developing new test procedures, as current ASTM freeze-thaw tests are inappropriate (Sect. 2.2.1), and test methods for moisture absorption and permeance do not require that these properties be measured over the complete range of conditions to which materials in the roof will be subjected.

In warmer climates, high R_v insulations will not be required for achieving optimum total R_v values. On the other hand, some high R_v materials like PIR also offer high ratios of R-value per dollar and will therefore remain economically attractive for reducing energy costs. One simple solution may be to make the foam more permeable by introducing narrow vertical holes into the material, as illustrated in Fig. 7.2. The holes, or channels, could be made small enough (d = 1-3 mm, or 0.04-0.12 in.) so that convection through the holes is suppressed. In this case, the thermal insulating value would be virtually unaffected. Vapor would readily diffuse through each channel, so that if enough holes are introduced, the permeance of the board could be quite high, as long as the holes are free of debris.

7.4 TECHNOLOGY TRANSFER

Additional laboratory research, field experiments, and full-scale demonstration projects are needed to validate many of the concepts brought forward in this assessment. Appropriate design and application guidelines need to be written; these should include reroofing issues such as the evaluation of existing buildings so that designers and contractors have the necessary tools and information to confidently design and construct self-drying roof systems.

Better statistical data regarding the existing roofing inventory are sorely needed. The databases that are maintained today do not provide the critical information that is needed to justify the necessary research. Consequently, we cannot confidently answer simple

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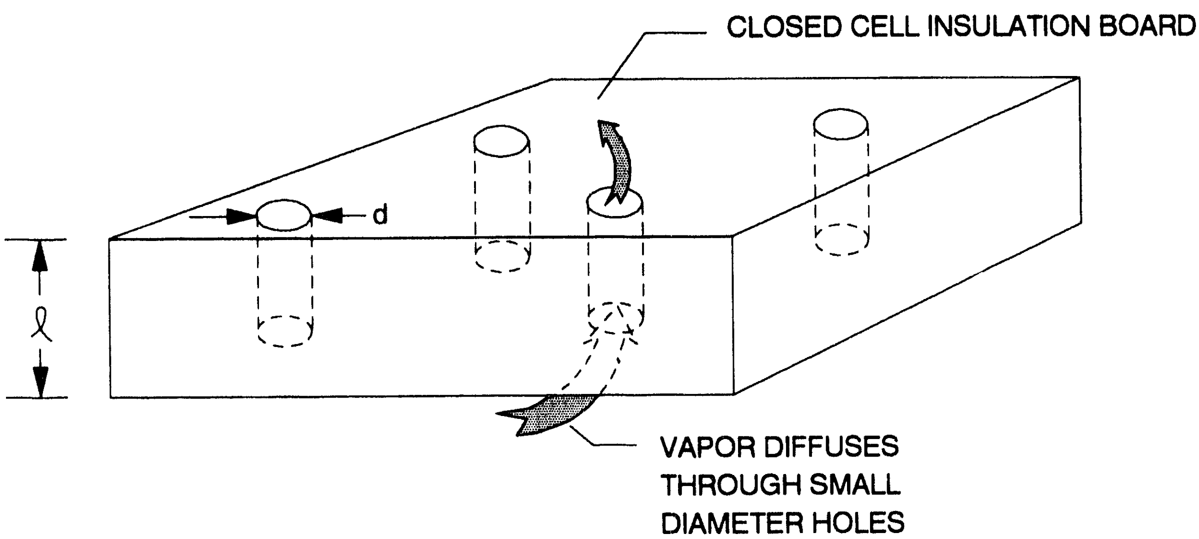

Fig. 7.2. Small-diameter holes can make closed-cell insulation more permeable while retaining high thermal resistance values.

to justify the necessary research. Consequently, we cannot confidently answer simple questions such as what is the average service life of today's roofing stock, what is the average thermal resistance applied in low-slope roofing, and what is the level of moisture contamination.

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APPENDIX A

AVERAGED HEAT FLUX EQUATIONS

APPENDIX A: AVERAGED HEAT FLUX EQUATIONS

In the absence of convection, the energy flux is given by [24]

$$\dot{Q} = k\frac{\partial T}{\partial x} + h_v\, j_v + h_l\, j_l\,, \qquad \text{(A.1)}$$

where

$\dot{Q}(x,t)$	=	the energy flux ($Jm^{-2}s^{-1}$),
$k = k(w,T)$	=	the thermal conductivity as a function of moisture content, w, and temperature, T,
$h_v = h_v(T)$	=	the enthalpy of water vapor,
j_v	=	the mass flux of vapor (kg $m^{-2}s^{-1}$),
$h_l = h_l(T)$	=	the enthalpy of water, and
j_l	=	the mass flux of liquid (kg $m^{-2}s^{-1}$).

Note that $T = T(x,t)$ and $w = w(x,t)$. For moisture gradients that are typical in installed roofs [1], j_l is small relative to j_v [68]. Furthermore, h_v/h_l is on the order of 20. Therefore, the liquid diffusion term, $h_l\, j_l$, is considered negligibly small. As a further simplification in this discussion, we ignore the temperature dependence of k, i.e., $k = k(w_{alone})$.

To make (A.1) more useful, it is desirable to cast it into an approximate form involving time-averaged terms, and involving surface temperatures, not temperature gradients. To ensure the validity of any approximating procedure, it will be necessary first to determine the time scales that characterize the evolution of each of the distributed "field" variables: temperature, water vapor, and, in a system with a large amount of water, the liquid distribution.

Characteristic Time Scale for the Temperature Field

The time over which the temperature experiences substantial change can be deduced from the energy equation for dry materials:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\alpha_T \frac{\partial T}{\partial x}\right), \qquad \text{(A.2)}$$

where α_T is the thermal diffusivity and is equal to $k/\rho c_p$. Thermal diffusivities may be temperature dependent and can be estimated for roofing materials from data in [72]. Let a significant change in the temperature differential be imposed across the specimen of thickness Δx. It follows from Eq. (A.2) that the time required for substantial change in the temperature distribution, using some average value of α_T, is of the order

$$\tau_T \sim \frac{(\Delta x)^2}{\alpha_T} . \tag{A.3}$$

Characteristic Time Scale for Water Vapor

In building materials, the mass flux of vapor is usually evaluated using

$$j_v = -\mu\left(\frac{\partial p_v}{\partial x}\right) , \tag{A.4}$$

where μ is the permeability, and p_v is the partial pressure of water vapor (Pa). The permeability of roofing materials varies greatly [72]. The principle of mass conservation requires

$$\frac{\partial \rho_v}{\partial t} = -\frac{\partial}{\partial x}(j_v) = \frac{\partial}{\partial x}\left(\mu\frac{\partial p_v}{\partial x}\right) , \tag{A.5}$$

where ρ_v is the mass of vapor per unit volume. Now, let a significant change in the vapor pressure differential suddenly be imposed across the insulation thickness Δx. It follows from Eq. (A.5) that the time required for substantial change in the vapor distribution (and therefore j_v) is of the order

$$\tau_v \sim \frac{\Delta\rho_v(\Delta x)^2}{\mu(\Delta p_v)} . \tag{A.6}$$

Let us try to cast Eq. (A.6) in a more useful form. We do not know $\Delta\rho_v$, but we note that $\Delta\rho_v = \rho_{dry}\ (\Delta w_{mass})$, where ρ_{dry} is the density of dry insulation and w_{mass} is the mass fraction of water. To estimate Δw_{mass}, we can use the sorption curves for a given material, which give Δw_{mass} for that material as a unique function of $p_v/p_{v,sat}$, the relative humidity.

For the present order-of-magnitude estimate, we have approximated this function by drawing a straight line on the sorption curves from the origin (rh = 0, w_{mass} = 0) to the point (rh = 0.9, w_{mass} = 0.9). The slope of this line, m, characterizes the ratio $\Delta w_{mass}/\Delta rh$ for the material.

Making the substitution $\Delta \rho_v = \rho_{dry} (\Delta w_{mass})$ in Eq. (A.6) and using m = $\Delta w_{mass}/\Delta rh$, we obtain

$$\tau_v = \frac{\rho_{dry} m (\Delta x)^2}{\mu \left(\frac{\Delta p_v}{\Delta rh} \right)} . \tag{A.7}$$

But

$$\left(\frac{\Delta p_v}{\Delta rh} \right) \approx \frac{\partial p_v}{\partial (p_v \ / \ p_{v,sat})} = p_{v,sat} . \tag{A.8}$$

Substituting (A.8) into (A.7), and choosing $p_{v,sat}$ at a representative location, we can write finally

$$\tau_v \sim \frac{\rho_{dry} m (\Delta x)^2}{\mu p_{v,sat}} = \frac{(\Delta x)^2}{\alpha_v} , \tag{A.9}$$

where, by examining (A.3), we define (by analogy with the thermal diffusivity) a vapor diffusivity,

$$\alpha_v = \frac{p_{v,sat} \ \mu}{m \rho_{dry}} . \tag{A.10}$$

Characteristic Time Scale for Liquid

On a microscopic scale, water is deposited (adsorbed) on the pore surfaces at all values of rh < 1.00, as described by the sorption curves. Near rh = 1.00, the moisture content can increase precipitously until the pores are completely filled [24]. It is in this range of a large percentage by volume of water, w_{vol}, that the thermal conductivity starts to increase significantly [17, 31]. The extent of this increase will depend upon the distribution of concentrated liquid. For this reason, we are interested in how quickly the distribution of concentrated liquid changes because of a change in the boundary conditions.

The characteristic time for significant change in the concentrated liquid distribution, τ_l, can be approximated by the use of an example. We start with an amount of water that we know can significantly increase the overall thermal conductivity. According to a study by Tobiasson and Ricard [31], lightweight concrete loses 20% of its insulating ability when w_{vol} = 0.037. For EPS and fibrous glass, 20% degradation occurs at w_{vol} = 0.061 and 0.062, respectively. We shall assume a rough average of w_{vol} = 0.050 [5.0% by volume, or 2.55 kg/m^2 based on a Δx = 0.051 m (2 in.)]. We ask, "How much time is required for this amount of water to diffuse through a plane that is adjacent to the region of concentration?" The time is found by solving an approximate form of Eq. (A.4) for τ_l:

$$j_l \sim \frac{2.55 kg/m^2}{\tau_l} \sim \mu \left[\frac{p_{v,sat}(T_{top}) - p_{v,sat}(T_{bottom})}{\Delta x} \right] . \tag{A.11}$$

Summary of Characteristic Times

Typical values for permeability and density, along with all thermal properties, were obtained from ASHRAE [72], while the sorption curves were obtained from Tye [67]. Calculated values are shown in Table A.1.

Table A.1. Diffusivities and characteristic time scales for temperature, vapor, and concentrated liquid distributions in common insulations

Insulation	α_T (m^2/s)	τ_T (hours)	α_v (m^2/s)	τ_v (hours)	τ_l (hours)
Polyisocyanurate	0.67 10^{-6}	1.1	1.2 10^{-8} (sum) 3.5 10^{-9} (win)	57 (sum) 204 (win)	2800
Expanded polystyrene	1.2 10^{-6}	0.60	3.8 10^{-8} (sum) 9.6 10^{-9} (win)	19 (sum) 75 (win)	1800
Fibrous glass	0.34 10^{-6}	2.1	7.4 10^{-7} (sum) 1.8 10^{-7} (win)	1.0 (sum) 3.9 (win)	77
Perlite	0.25 10^{-6}	2.8	2.5 10^{-8} (sum) 7.0 10^{-9} (win)	23 (sum) 102 (win)	270
Insulating concrete	0.30 10^{-6}	5.4	3.9 10^{-9} (sum) 9.8 10^{-10} (win)	183 (sum) 732 (win)	440

Time Averaging

Integrating (A.1) with respect to time over some finite interval Δt gives

$$\bar{Q}(x) = \int_0^{\Delta t} k(w) \frac{\partial T(x,t)}{\partial x} dt + \int_0^{\Delta t} h_v(T)\ j_v\ (w,T)\ dt\ , \tag{A.12}$$

where ($\bar{\ }$) represents averaging over Δt. It is understood that averaged quantities still depend on time, but on scales larger than Δt, and that Δt differs for different insulation materials.

Knowing the characteristic time scales for the variables in Eq. (A.12), we can justify certain approximate forms of (A.12). For example, it is possible to choose Δt so large that $\bar{Q}(x)$ may then be considered relatively independent of position—that is, $\bar{Q}(x) = \bar{Q}$. This assumption is valid whenever the characteristic time associated with the temperature or mass flow of vapor on the right side of (A.12) is short compared with the averaging interval, Δt. It is also required that $\bar{Q}$ not be very close to zero. Under all these conditions, the heat stored in any layer is small compared with the time-integrated flux. It suffices that $\Delta t >> \tau_v, \tau_T, \tau_l$.

One useful result presents itself immediately. At any impermeable layer, $j_v = 0$, so the second integral on the right side of (A.12) must vanish. For $\Delta t >> \tau_v, \tau_T, \tau_l$ we are left with

$$\bar{Q} = \int_0^{\Delta t} k(w) \frac{\partial T(x_{imperm},t)}{\partial x} dt\ , \tag{A.13}$$

where the derivative $\partial T/\partial x$ and $w(x,t)$ must be evaluated at the impermeable boundary. The integrand in (A.13) could be evaluated on, say, an hourly basis by using a two-point measure of $\partial T/\partial x$ directly adjacent to a membrane, while simultaneously measuring w there also. The total heat flux could then be determined from

$$\bar{Q} = \sum_0^n \delta t \left[k(w) \frac{\delta T}{\delta x} \right]_{membrane}\ ,\quad n\delta t >> \tau_v, \tau_T, \tau_l\ . \tag{A.14}$$

A second useful simplification of (A.12) can be obtained for long averaging periods if the roof is not too wet. The second integral in (A.12) is the total latent heat transferred over the period Δt through a plane at position x. Under certain conditions, the total latent heat term may be negligible (say, less than 5%) when compared with the total conducted heat. The latent term is limited by one of two factors. If all of the water can move from top to bottom during Δt, then the mass of water in the roof limits the latent transfer. On the other hand, the latent transfer may be limited by the diffusion rate. Mathematically, the latent heat transfer must be bounded by

$$\int_0^{\Delta t} h_v \, j_v dt \leq | h_{v,max} | \, | j_{v,max} | \, \Delta t \, , \qquad \text{(rate limited)(A.15a)}$$

$$\int_0^{\Delta t} h_v \, j_v dt \leq | h_{v,max} | \, M_{H_2O} \, , \qquad \text{(mass limited)(A.15b)}$$

where m_{H2O} is the total mass of water per unit area within the roof. The smaller of (A.15a, b) determines the magnitude of the second integral in (A.12).

For clarification, consider the example of a 51-mm (2-in.) fibrous glass roof in Chicago. First, let us estimate the total heat conducted for the Δt of concern. The average membrane temperature during summer on a black EPDM roof should be around 34°C (93°F). A typical summer deck temperature is 26°C (78°F). If the R-value is 1.5 $m^2/W\cdot°C$ (8.5 $h\cdot ft^2\cdot°F/Btu$), then over three summer months, the heat *conducted* is $\approx 4\,(10^7)$ J. Now we use (A.15a) to see if a comparable amount of latent heat could diffuse down in that time. Using saturated vapor pressures at the above temperatures to calculate the pressure gradient, we use Eq. (A.4) to calculate $j_{v,max}$. Then (A.15a) yields a total latent heat transfer of 5.4 (10^6) J—about 10% of the conducted heat. Using (A.15b), we find that 5% of the conduction term corresponds to m_{H2O} = 1.5% by volume. Unfortunately, many roofs in Chicago may be this wet [1]. The conclusion for this example is that we cannot automatically ignore the latent heat integral in (A.12). (Note that if the insulation were PIR, then the total latent heat transfer would be limited to 0.4% of the conduction term by the slow diffusion rate, regardless of how wet the roof was. This result will be exploited in the next subsection.)

To summarize, for the latent heat term in (A.12) to be considered negligibly small for the Δt of concern, two latent heat quantities must be estimated. One is the amount that could potentially diffuse during Δt (Eq. A.15a), and the other is the total amount of latent heat stored in the roof (Eq. A.15b). The *smaller* of the two should be used as an order-of-magnitude estimate for the second integral in (A.12). If this is less than, say, 5% of the estimated conduction heat load, then a simplified form of (A.12) can be used for calculating the total heat load during Δt:

$$\bar{Q} = \int_0^{\Delta t} k(w) \frac{\partial T(x,t)}{\partial x} dt \,, \tag{A.16}$$

or, in a more practical form:

$$\bar{Q} = \sum_0^n k(w) \frac{\delta T}{\delta x} \delta t \,, \quad n\delta t \gg \tau_v, \tau_T, \tau_l \,, \tag{A.17}$$

where now $w(x,t)$ and $\partial T(x,t)/\partial x$ are measured at the same location *anywhere* in the insulation.

Closed-Cell Foam Insulations

Eq. (A.12) can be simplified for closed-cell foams in several significant ways. From Table A.1 we note that for the plastic foams, $\tau_l \gg \tau_v$. Physically, the permeability is so low that the concentrated water distribution changes very slowly. The foams have such low density and low water retention for rh < 1.00 that a vapor pressure wave front will travel quickly through them—that is, their moisture diffusivities are large (see Eq. A.10). As a result, it is easy to find time averaging intervals Δt which satisfy

$$\tau_l > \Delta t > \tau_v, \ \tau_T \,. \tag{A.18}$$

When (A.18) is satisfied, we may consider $w(x,t)$ to be frozen in time insofar as its effects on the conductivity, $k(w)$, are concerned. We now write $w = \bar{w}(x)$, where again, ($\bar{}$) represents averaging over Δt. The term $k(\bar{w})$ may be moved outside the first integral in (A.12). The argument that $\bar{Q}(x) = \bar{Q}$ is constant still holds, since, with average $\bar{w}$, all of the fields on the right side of (A.12) that now change are changing quickly. Eq. (A.12) can be written as

$$\bar{Q} = k(\bar{w}(x)) \frac{\partial \bar{T}(x)}{\partial x} + \overline{h_v(T) \ j_v(\bar{w},T)} \,. \tag{A.19}$$

A second simplification has already been discussed in the previous subsection. For the relatively impermeable foams, the total latent heat transfer term in (A.19) for U.S.

climates is nearly always one or two orders of magnitude less than the conduction term, so that the latent term is negligible.

Now, the conductivity, $k[\bar{w}(x)]$ can be expressed as a linear function of $\bar{w}$:

$$k[\bar{w}(x)] = \lambda_{dry} + a\bar{w}(x) \ , \tag{A.20}$$

where λ_{dry} and a are regarded as constants [24]. Substituting (A.20) into (A.19) and omitting the latent heat term, we obtain simply

$$\bar{Q} = [\lambda_{dry} + a\bar{w}(x)]\frac{\partial\bar{T}(x)}{\partial x} \ . \tag{A.21}$$

Again note that (A.21) is valid only when (A.18) is satisfied; for example, Table A.1 shows that for EPS, Δt must be of the order of 1 to 3 weeks.

Eq. (A.21) is readily integrated in the vertical direction:

$$\bar{Q}\Delta x = \lambda_{dry}\Delta T + a\int_0^{\Delta x}\bar{w}(x)\frac{\partial\bar{T}(x)}{\partial x}\,dx \ . \tag{A.22}$$

Solving (A.21) for $\partial\bar{T}/\partial x$ and substituting into (A.22), we obtain, after some algebra,

$$\bar{Q} = \frac{\lambda_{dry}\Delta\bar{T}}{\Delta x - \left[\int_0^{\Delta x}\frac{\bar{w}}{\lambda/a+\bar{w}}\,dx\right]} \ . \tag{A.23}$$

Eq. (A.23) has two useful features. First, it involves only surface temperatures; there is no thermal gradient term. Secondly, it shows clearly the importance of the distribution of concentrated liquid. Two different shapes for the function $\bar{w}(x)$ are compared next in Appendix B. Finally, we note that the total seasonal heat flux is found by

$$\sum_0^n\bar{Q} = \sum_0^n\frac{\lambda_{dry}\Delta\bar{T}}{\Delta x - \left[\int_0^{\Delta x}\frac{\bar{w}(x)}{\lambda/a+\bar{w}(x)}\,dx\right]} \ . \tag{A.24}$$

APPENDIX B

INFLUENCE OF MOISTURE DISTRIBUTION ON SEASONALLY AVERAGED WET R-VALUES

APPENDIX B: INFLUENCE OF MOISTURE DISTRIBUTION ON SEASONALLY AVERAGED WET R-VALUES

One important criterion for choosing the amount and type of insulation is how the choice will influence the seasonal heating and cooling loads of the building. If the insulation is dry (which is typically assumed), then traditionally, the following simple formula is used to calculate the heat flow through the roof:

$$\bar{Q} = (\bar{T}_{top} - \bar{T}_{bottom}) \times \left(\frac{1}{R_{dry\ insulation} + \Sigma R_{other\ layers}} \right) . \qquad (B.1)$$

Here, $\bar{Q}$ is the time-averaged heating or cooling load, $\bar{T}$ is the time-averaged temperature, $\bar{R}_{dry\ insulation}$ is the thermal resistance of the insulation, and $\bar{R}_{other\ layers}$ are the thermal resistances of other layers in the assembly. Fortunately, the dry R-values are essentially constants; once they are measured in a laboratory [71], then Eq. (B.1) can be used to determine the heat flow through roofs installed in virtually any climatic region.

R-values for damp or wet insulation are not constant. In Appendix A, we have analyzed issues related to deriving time-averaged equations similar to (B.1) for moist insulation. It turns out that when we replace $\bar{R}_{dry\ insulation}$ in Eq. (B.1) with $\bar{R}_{wet\ insulation}$, $\bar{R}_{wet\ insulation}$ does not have a constant value. For most cases, knowing $\bar{R}_{wet\ insulation}$ requires knowing (1) how much moisture is in the insulation overall, and (2) how the moisture is distributed within the insulation layer. In very wet, porous insulations in which a large amount of water is expected to move up and down each season, even more information is required (see Appendix A).

It is a burden to periodically measure the moisture distribution in a roof. If we chose instead to ignore moisture issues altogether and used Eq. (B.1), what error would result in our load calculations? We examine this question in Fig. B.1, where we compare the calculated heat flux for four common insulations. In each case, calculations were made assuming no moisture, uniformly distributed moisture, and moisture only within a thin layer within the insulation. The calculations are described in Technical Note B.1.

As the figure shows, for closed-cell foams that we modeled, heat lost through the roof will increase by about 20% for w_{vol} values, on the order of 0.05. The degradation of the fibrous insulations is more severe for the same 5% moisture content. Regarding distribution effects, uniformity in the distribution increases the heat loss compared with the thin-layer case. For the foams, this increase is on the order of 10% for 5% moisture content, and is 20–30% for 10% moisture content by volume. For the fibrous insulations, the effects are more pronounced; uniformity enhances heat loss by 35-60% for 10% moisture content by volume. Note that these are moderate contamination levels. From a collection of 1600 coring samples, Anderson [1] observed that 83% of the closed-cell insulation samples were in the range $w_{vol} \leq 0.10$, while the rest were wetter. For perlite, he found 66% with $w_{vol} \leq 0.10$, while the rest were wetter.

Drying Principle B.1: Effect of Moisture Distribution on R-Value

At moderate moisture content levels, the dry R-value of insulation is significantly degraded. The degradation is more severe when water is evenly distributed than when the water is collected in a thin layer near the top or the bottom of the insulation.

TECHNICAL NOTE B.1

In Appendix A, we show that the total heat flux through closed-cell insulations can be evaluated using the formula

$$\bar{Q} = \frac{\lambda_{dry} \Delta \bar{T}}{\Delta x - \left[\int_0^{\Delta x} \frac{\bar{w}}{\lambda / a + \bar{w}} dx \right]} . \qquad \text{(B.1-1)}$$

Here, $\bar{Q}$ is the time-integrated heat flux and is not dependent upon the vertical position, x. The term $\Delta \bar{T}$ is the time-averaged surface temperature difference, and $\bar{w}(x)$ is the "quasi-stationary" moisture distribution. Eq. (B.1-1) is strictly valid only under certain conditions (see Appendix A). The thermal conductivity, $k[\bar{w}(x)]$ is expressed as a linear function of $\bar{w}$:

$$k[\bar{w}(x)] = \lambda_{dry} + a\bar{w}(x) . \qquad \text{(B.1-2)}$$

Certain restrictions are placed on the averaging period used in (B.1-1), as described in Appendix A.

In form, Eq. (B.1-1) is just a generalization of Eq. (T2.1-1), with R replaced by $R = \Delta x/k$, and k expressed using (B.1-2). For example, if the moisture is uniformly distributed with a constant moisture content w_0, then the thermal conductivity is also a constant, having a value $k = \lambda_{dry} + a\, w_0$. Eq. (B.1-1) takes the form

$$\bar{Q}_{uniform} = \frac{\Delta\bar{T}}{\left[\dfrac{\Delta x}{\lambda_{dry}+aw_0}\right]} . \tag{B.1-3}$$

This result may be compared with a different case using the same total amount of water, $w_0\Delta x$, but one in which the water is mostly confined to a thin layer with thickness $\Delta x/10$. If 0.9 of the water is distributed uniformly within this layer, then the concentration in the layer is $9w_0$, while the uniform concentration outside the layer is $w_0/9$. For the thin-layer case, Eq. (B.1-1) becomes

$$\bar{Q}_{layer} = \frac{\Delta\bar{T}}{\left[\dfrac{(0.1\Delta x)}{\lambda_{dry}+a(9w_0)}\right] + \left[\dfrac{(0.9\Delta x)}{\lambda_{dry}+a(w_0/9)}\right]} . \tag{B.1-4}$$

Eqs. (B.1-3) and (B.1-4) have been evaluated for PIR, fibrous glass, and EPS. The results are shown in Fig. B.1.

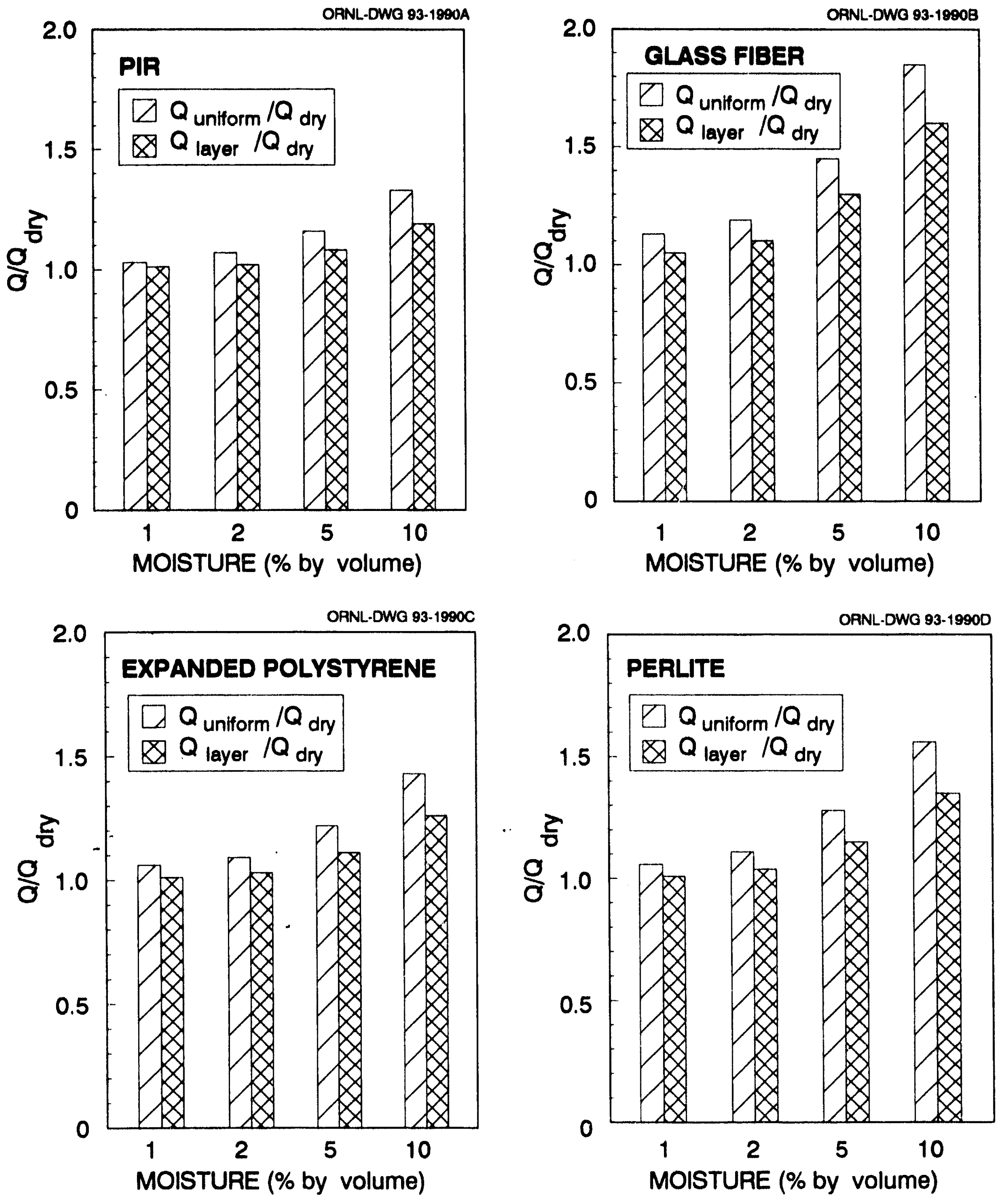

Fig. B.1. Comparison of heat conduction rates for various insulations and moisture distributions. $Q_{uniform}$ is the seasonally averaged heat conduction if moisture is distributed uniformly over the insulation thickness; Q_{layer} is the seasonally averaged heat conduction if all moisture is confined to a thin layer. Data were calculated using Eq. (B.1-4) in Technical Note B.1.

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