IEA ANNEX 19
LOW-SLOPE ROOF SYSTEMS

**A Guidebook for
Insulated Low-Slope
Roof Systems**

February 1994

International Energy Agency
Energy Conservation in Buildings
and Community Systems Programme

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ACRONYMS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BBA	British Board of Agreement
BRE	British Research Establishment
BUR	built-up roof, built-up roofing
CFC	chlorofluorocarbon
CSPE	chlorosulfonated polyethylene
DOE	U.S. Department of Energy
EPDM	ethylene propylene diene monomer
EPS	molded expanded polystyrene
FM	Factory Mutual Research Corporation
HCFC	hydrochlorofluorocarbon
HVAC	heating, ventilating, and air conditioning
IC	installation costs
IEA	International Energy Agency
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NRCA	National Roofing Contractors Association
OC	operating costs
ODP	ozone depletion potential
ORNL	Oak Ridge National Laboratory
PIR	polyisocyanurate
PUR	polyurethane
PVC	polyvinyl chloride
PVF ₂	polyvinylidene fluoride
RMA	Rubber Manufacturers Association
SPI	Society for the Plastics Industry
TC	total present cost
XPS	extruded expanded polystyrene

PREFACE

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Cooperation and Development to implement an international energy program. A basic aim of the IEA is to foster cooperation among the 21 IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, and energy research development and demonstration (RD&D). This aim is achieved in part through a program of collaborative RD&D consisting of 42 implementing agreements, containing a total of more than 80 separate energy RD&D projects. This publication forms one element of this program.

Energy Conservation

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, monitoring of buildings, comparison of calculation methods, as well as air quality and studies of occupancy. Seventeen countries have elected to participate in this area and have designated contracting parties to the implementing agreement covering collaborative research. The designation by governments of a number of private organizations, as well as universities and government laboratories, as contracting parties has provided a broader range of expertise to tackle the projects in the different technology areas than would have been the case if participation were restricted to governments. The importance of associating industry with government-sponsored energy research development is recognized in the IEA, and every effort is made to encourage this trend.

The Executive Committee

Overall control of the program is maintained by an executive committee, which not only monitors existing projects, but also identifies new areas where collaborative effort may be beneficial. The executive committee ensures that all projects fit into a predetermined strategy, without unnecessary overlap or duplication but with effective liaison and communication. The executive committee has initiated the following projects to date (completed projects are identified by an asterisk).

Annex 1:	Load energy determination of buildings (*)
Annex 2:	Ekistics and advanced community energy systems (*)
Annex 3:	Energy conservation in residential buildings (*)
Annex 4:	Glasgow commercial building monitoring (*)
Annex 5:	Air infiltration and ventilation center
Annex 6:	Energy systems and design of communities (*)
Annex 7:	Local government energy planning (*)
Annex 8:	Inhabitants' behavior with regard to ventilation (*)
Annex 9:	Minimum ventilation rates (*)

Annex 10:	Building heating, ventilating, and air conditioning system simulation (*)
Annex 11:	Energy auditing (*)
Annex 12:	Windows and fenestration (*)
Annex 13:	Energy management in hospitals (*)
Annex 14:	Condensation and energy (*)
Annex 15:	Energy efficiency of schools (*)
Annex 16:	BEMS 1—User interfaces and system integration
Annex 17:	BEMS 2—Evaluation and emulation techniques
Annex 18:	Demand-controlled ventilating systems
Annex 19:	Low-slope roof systems
Annex 20:	Air flow patterns within buildings
Annex 21:	Calculation of energy and environmental performance of buildings
Annex 22:	Energy-efficient communities
Annex 23:	Multizone air flow modeling
Annex 24:	Heat, air, and moisture transport in new and retrofitted insulated envelope parts
Annex 25:	Real-time simulation of heating, ventilating, and air conditioning systems and fault detection
Annex 26:	Energy-efficient ventilation of large enclosures
Annex 27:	Evaluation and demonstration of domestic ventilation systems
Annex 28:	Low-energy cooling systems.

FOREWORD

This document has been developed by Annex 19 on Low-Slope Roof Systems of the Buildings and Community Systems Committee of the International Energy Agency. Participating countries were Denmark, Sweden, the United Kingdom, and the United States.

The objective of the document is to describe available information and good practices when working with low-slope roofs with significant insulation—highly energy-efficient roof systems. An extensive listing of relevant literature is included in the document.

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INTRODUCTION

1.1 OVERVIEW

Low-slope roof systems are common on commercial and industrial buildings and, to a lesser extent, on residential buildings. Although insulating materials have nearly always been a component of low-slope roofs, the amount of insulation used has increased in the past two decades because of escalation of heating and cooling costs and increased awareness of the need for energy conservation. As the amount of insulation has increased, the demand has intensified for design, installation, and maintenance information specifically for well-insulated roofs.

Existing practices for design, installation, and maintenance of insulated roofs have evolved from experience. Typically, these practices feature compromises due to the different properties of materials making up a given roof system. Therefore, they should be examined from time to time to ensure that they are appropriate as new materials continue to enter the market and as the data base on existing systems expands. A primary purpose of this International Energy Agency (IEA) study is to assess current roofing insulation practices

in the context of an accumulating data base on performance.

Many design and installation issues arising from the use of insulation in low-slope roofs have already been addressed adequately by the industry. Insulation is now being used routinely in roofs in all industrialized countries, especially those with significant winter heating loads. Yet, some contractors and building owners still perceive correlations, realistically or unrealistically, between roofing problems and the addition of insulation. As a result, they may be reluctant to add insulation to roofs, they might add the wrong amount for the situation, or they might adopt poor practices for design and installation. Therefore, another purpose of this IEA study is to identify perceived correlations between roofing problems and the addition of insulation, to examine their factual basis, to discuss remedial measures, and to define the research needed to resolve significant outstanding issues. Performance information and illustrative roof systems from all the countries participating in the study are used.

A roof, as an integral part of a building, has several basic functions. It must prevent

water entry to the building below it, and it must thermally isolate the building from the environment. In doing so, it also must accommodate motion of the building, foot traffic, and penetrations for equipment. It must resist high wind loads, and it must not contribute to the spread of fire occurring inside the building or spreading from an adjoining roof. Because no single material can perform all these functions, a roof is a composite of several materials, each with particular properties, all of which must perform together as a system.

The basic components of a low-slope roof are a membrane for waterproofing, insulation for thermal protection, and a deck for physical support of the entire system. Each component must provide a level and compatible substrate for the components above it. The component that is exposed to the weather must be sufficiently durable to withstand continual environmental abuse. Additional components may be added for specific reasons. For example, vapor retarders may be needed to limit vapor transport upward. Ballast may be added to prevent the wind from lifting some membranes and to protect them from ultraviolet radiation. All components acting together must allow the whole system to meet its performance criteria. A major contribution of roofing studies within the past 10 years has been to stress the importance of the roof as a system. That is, whatever a particular component's primary function, its suitability must be judged by a more complex set of criteria. Consistent with this notion, this IEA study not only provides information on insulation as a roofing material, but also emphasizes insulation as a component of roof systems.

The primary function of insulation in a roof is to reduce heat transfer to the outdoors in the winter and to reduce demand on the building cooling system during the

summer. With a properly designed roof, the most noticeable benefits of increasing the insulation are reduced operating costs because energy exchange between the building and the outdoors is reduced, and improved occupant comfort because the amplitudes of diurnal temperature swings are diminished. The effect on thermal performance of adding roof insulation is greatest on one-story buildings, because they have the largest ratio of roof area to total building area. But even for a three-story building as small as 4000 m² (43,100 ft²) or 36.5 m by 36.5 m (120 ft by 120 ft), the ratio is more than 50% (Fig. 1.1).

Insulation also provides a level and uniform substrate for waterproofing membranes and decreases the vulnerability of

Fig. 1.1. Roofing as a percentage of building total floor area. Source: Chang, T. and Busching 1983. *Energy Savings Potential of Roofing Research*, ORNL/Sub-82/22293/1, Oak Ridge National Laboratory, USA.

membranes to sustained or repetitive localized shearing forces. In fact, use of high-density fibrous materials as leveling surfaces over metal decks was common practice in the United States well before the thermal insulating quality of these boards became important. Insulation also is a primary material for acoustical damping in buildings.

Currently, most nations have recommended minimum levels of insulation for low-slope roofs. Often these are backed up by specific regulations. However, while minimum levels are thus clear, the optimum levels are less well understood. Financially, the optimum level results from a trade-off between the added first costs for insulation and the savings in future operating costs. Techniques for determining this trade-off range from "simple payback," which forecasts the number of years of average operating-cost savings required to equal the first cost of the investment, to more sophisticated "life cycle cost" procedures. The latter typically compare added first costs and the present worth of future energy savings and maintenance charges. These calculations are sensitive to energy cost escalation estimates and estimates of the future cost of money. Smaller amounts of insulation are justified when conservative estimates are used. For harsh climate zones in the United States, life cycle costing suggests using a mineral wool thickness of about 80 mm. In Scandinavia, the thickness is about 200 mm; in the United Kingdom, the suggested thickness is between these two values.

An alternate, more absolute method is to conduct a pure energy balance, that is, to compare the total lifetime operating energy saved with the energy used to produce, deliver, and install the insulation. This method, of course, leads to much higher levels of insulation. To make this

comparison, it is necessary to calculate or estimate the energy consumption for all materials and activities involved in insulating the roof. An estimate for the allowable thickness of mineral wool in a Danish climate is near 1 m. Taking into account the uncertainty in energy estimates and the diminishing savings for very thick insulations, a more practical limit is about 400 mm. This suggests that current Danish economic practice, 200 mm, is about half-way to this practical technical limit.

Calculating the heating and cooling costs attributable to the roof should always be part of the building design process. Simple techniques are available to calculate the total roof energy load (ASHRAE 1989; Wilkes 1989). However, these techniques provide only the heat transfer through the roof. They do not allow consideration of the effect this transfer has on the whole-building energy balance. If a roof allows heat gain to the building during a few afternoon hours in the winter while the walls are still cold and are causing heat loss, then the roof reduces the heating bill. On the other hand, the building may have such a high lighting and equipment heat load that it more than compensates for wall heat loss. Then, even in winter, the internal load and any heat gain through the roof have to be removed by cooling equipment. Complex mathematical models of whole-building performance are available that account for these load interactions (DOE 1989; BLAST 1991), but the input models are tedious to formulate and the programs do not readily allow separation of the contributions of individual components for a particular building envelope (e.g., the roof). A simpler way to use these whole-building models is in parametric studies [e.g., to estimate the differences in operating costs for different roof systems on otherwise identical buildings (Courville 1984;

Walukas 1985; Griggs 1989)]. These differences in operating costs can then be used in a life-cycle cost calculation to determine the benefits of insulation thickness subject to particular assumptions about thermal properties and about fuel and material costs and escalation rates.

In one study, based on life-cycle costing for the range of weather conditions in the United States (Courville 1984), the economically optimum R-values of several types of insulation under built-up roofing (BUR) ranged from $2.6 \text{ (K} \cdot \text{m}^2\text{)W}^{-1}$ to $4.4 \text{ (K} \cdot \text{m}^2\text{)W}^{-1}$ [$15 \text{ (}^\circ\text{F} \cdot \text{ft}^2 \cdot \text{h)Btu}^{-1}$ to $25 \text{ (}^\circ\text{F} \cdot \text{ft}^2 \cdot \text{h)Btu}^{-1}$] with high-thermal-performance foam insulations recommended to achieve the higher values. This study used idealized thermal properties of dry, protected insulations. In many cases, field performance differs from idealized performance. For example, Petersson (1986) and others have shown that in-service R-values of extruded polystyrene foam insulation in a protected membrane system should be decreased to account for moisture effects. Performance standards are used to convey this information in Swedish building codes. The thermal drift of chlorofluorocarbon (CFC)- or hydrochlorofluorocarbon (HCFC)-blown foam insulations and the effect on heat transfer of moisture movement through porous insulations are additional examples of cases where laboratory data may not reflect in-service performance.

Adding insulation to a roof system may place the system at increased risk for mechanical failure. Insulation added between the deck and the membrane tends to isolate the membrane from the deck. One consequence of this is that mechanical stresses applied to the membrane, for example from the perimeter wall, are not as readily transferred to the deck. Thus, the membrane will move more when ther-

mally stressed, which ultimately increases the potential for membrane fatigue. Severe temperature fluctuations will increase thermal stressing. In northern U.S. climates, mean surface temperatures for dark-colored roofs (with high solar absorptance) can range from -20 to 80°C (-4 to 176°F) over the year, with rates of change as high as 25°C/h (45°F/h) (Griggs 1989). However, the solar absorptance of the membrane surface is more a factor than is the insulation level. In Fig. 1.2, a computer model (Wilkes 1989) is used to predict changes in surface temperature for increasing amounts of insulation and varying solar absorptance under early summer conditions. Once the thermal resistance reaches a value of about $0.7 \text{ (K} \cdot \text{m}^2\text{)W}^{-1}$ [$4 \text{ (}^\circ\text{F} \cdot \text{ft}^2 \cdot \text{h)Btu}^{-1}$], equivalent to the R-value of a few cm (about an inch) of min-

Fig. 1.2. Changes in roof membrane temperature for different amounts of insulation. Results for three different surface solar absorption coefficients are shown. *Source:* Wilkes, K. E., 1989. "A Model to Predict Heat Flows and Temperatures in Roofs," pp. 85-98 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, ORNL/CONF-890976, Oak Ridge National Laboratory, USA.

eral wool insulation, there is little additional change in the surface temperature as more insulation is added. Thus, membrane temperature fluctuations and thermal stressing are not significantly enhanced by thick insulation.

Other mechanical concerns include the possibility that layers of insulation will separate because of their low cohesive strengths. In systems where the membrane adheres to an insulation substrate, low adhesive strength at the boundary also may lead to separations. In systems where the membrane is mechanically attached, fasteners may fatigue and fail. All these mechanical failures contribute to a lack of resistance to wind loads, the most catastrophic example of which is tear-off of all or part of the roof.

Moisture problems can also be exacerbated by insulation. The likelihood of increased membrane movement caused by adding insulation increases the risk that leaks will develop, particularly at edges or penetrations. In addition, moisture can move laterally for some distance within insulation, and the amount of water entering the leak can be quite large before a problem is noticed inside the building.

Despite the potential mechanical and moisture problems brought on by insulation, a well insulated roof system is an important way to achieve significant savings in operating costs, albeit at an increased capital investment for the building owner. The increased investment value should increase the likelihood that owners will support improved design, installation, and maintenance programs. Another likely consequence of the increased investment in insulation will be that the practice of reroofing over old roofs will become more common. Reroofing raises another set of issues regarding when it is necessary to discard all or part of the old roof. These

issues will be addressed in more detail in subsequent sections of this report.

1.2 REFERENCES

ASHRAE 1989

1989 ASHRAE *Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA, p. 22.10.

BLAST 1991

BLAST: *The Building Loads Analysis and System Thermodynamics Program, User Reference*, BLAST Support Office, University of Illinois, Champaign, Ill., USA.

Courville 1984

Courville, G. E. and Kolb, J. O., *Economic Analysis of Insulation Materials Used in Low-Slope, Built-Up Roof Systems*, ORNL/TM-9004, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

DOE 1989

DOE-2 *Reference Manual, Version 2.1A* and *DOE-2 Supplement, Version 2.1D*, LBL-8706, rev. 2 and LBL-8706, Supp. 5, rev. 5, Lawrence Berkeley Laboratory, Berkeley, Calif., USA.

Griggs 1989

Griggs, E. I. and Courville, G. E., *Changes in the Heating and Cooling Energy Use in Buildings Due to Lowering the Surface Absorptance of Roofs*, ORNL/TM-10339, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Petersson 1986

Petersson, B.-Å., *The Moisture and Thermal Insulation Conditions in the Duo-Roof* (in Swedish), Bygg & Teknik Report 4, Stockholm, Sweden.

Walukas 1985

Walukas, D. J. and Courville, G. E.,
Decision Guide for Roof Insulation R-Value, ORNL-6172, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Wilkes 1989

Wilkes, K. E., "A Model to Predict Heat Flows and Temperatures in Roofs," pp. 85-98 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, ORNL-CONF-890976, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

2

DATA BASE ON INSULATIONS, COVERINGS, AND SYSTEMS

2.1 INTRODUCTION

Before describing good roofing practices and issues in relation to insulated roof systems, it is worthwhile to introduce briefly the materials and systems that will be discussed in this document. Table 2.1 indicates the relative importance of different materials and systems in the participating countries. Three cautionary notes need to be given concerning Table 2.1. First, no country was able to provide reliable, nonambiguous data. Second, even the relative importance of specific entries can change rapidly (within a few years). Third, the categories listed are not exactly descriptive. For example, about 10% of U.K. waterproof coverings are mastic asphalt. These are included under the heading "bituminous." Another example is that both lightweight and normal weight poured concrete, as well as prefabricated concrete panels, are included under the heading of "concrete" decks. Given these caveats, some general observations are possible. Mineral wool is the insulation of choice in Europe, polyisocyanurate (PIR) in the United States. Bituminous systems [built-

up roofs (BURs) and modified bitumens] are common everywhere; single plies, especially ethylene propylene diene monomer (EPDM), are used more extensively in the United States. Metal is the preferred deck material, except in Denmark where concrete still dominates. Metal roofing is becoming more popular, especially in the United Kingdom and Sweden.

This section provides information about common insulation types, waterproof coverings, and insulated roof systems. The descriptions rely heavily upon materials from the *1989 ASHRAE Handbook of Fundamentals* and *The National Roofing Contractors Association Roofing Materials Guide*.

2.2 GENERIC INSULATION TYPES

2.2.1 Introduction

Table 2.2 shows typical relative material property values for most common roof insulations. Where available, the information is quantitative (in SI units). Many of these properties are subject to standardized test procedures. Insulations are

Table 2.1. Relative importance of various roof materials and use of various systems^a

	Denmark	Sweden	United Kingdom	United States
Insulation types				
PIR or PUR ^b	2		6	6
Mineral wool	1	1		2
High density	6	6	2	3
Low density	3	1		2
Polystyrene				
Expanded	4	3	2	3
Extruded	1	2	1	2
Fiberboard	1		1	3
Perlitic foam	1		1	3
Corkboard	1		2	1
Cellulosic	1	1	1	1
Foam glass	2	1		2
Lightweight expanded Clay (zonolite)	1			1
Waterproof coverings				
Bituminous				
Built-up	6	6	5	6
Modified	6	3	6	4
Elastoplastic/single ply				
EPDM ^b	2	1	1	5
PVC ^b	3	3	3	2
CSPE ^b	1	1		2
Metal roofing	1	3	5	3
Spray applied	1		1	2
Roof systems				
Warm deck				
Metal	3	6	6	6
Concrete	6	4	2	3
Wood	2	2	1	2
Cold deck	3	1	1	2
Metal roof	2	4	6	3
Protected membrane system	1	2	4	2
Spray polyurethane	1	1	1	2

^aRankings and nominal percentage ranges:

6 Very high (>40%) 3 Medium (5-15%)

5 High (25-40%) 2 Low (1-5%)

4 Medium high (15-25%) 1 Small (<1%)

^bPIR = polyisocyanurate, PUR = polyurethane, EPDM = ethylene propylene diene monomer, PVC = polyvinyl chloride, CSPE = chlorosulfonated polyethylene.

Table 2.2. Material properties of common roof insulations

Property	Mineral wool low density	Mineral wool high density	Perlitic	Wood fiberboard	Polyiso- cyanurate	Extruded polystyrene	Expanded polystyrene	Phenolic foam	Cellular glass
Fire resistance	Yes	Yes	Yes	Yes	Yes	Qualified	Qualified	Yes	Yes
Closed cell content (%)	0	0	0	0	90-95%	90-95%	90-95%	90-95%	100%
Compressive strenght (kPa)	Low	70	170-210	NA	120-140	90-690	80	170	690
Damage from freeze/thaw (visual)	NF	NF	NF	NF	NF	NF	NF	NF	Low
Damage from heat (visual)	NF	NF	NF	NF	Slight	High	High	Slight	NF
Damage from water soak (visual)	Low	Mod.	High	High	Low	Slight	Low	Low	NF
Density (may include facer) (kg/m ³)	10-25	110-160	130-160	240-320	32	18-48	16	40	136
Dimensional stability	NF	NF	NF	NF	Good	Good	Good	Good	NF
Flexural strength (kPa)	Low	Low	310-380	NA	NA	210-690	170-210	NA	450-520
Friability	NF	NF	High	Slight	NF	Slight	Slight	Low	High
Interlaminar strength	Low	Low	Low	Mod.	High	High	High	High	High
Moisture expansion	Slight	Slight	Slight	High	Low	Low	Low	Low	NF
Solvent resistance (visual)	NF	NF	NF	NF	NF	Low	Low	NF	NF
Specific heat [kJ/(kg·K) ⁻¹]	0.84	0.84	1.05	1.38	1.59	1.13	1.13	NA	0.75
Thermal aging	NF	NF	NF	NF	Low	NF	NF	Slight	NF
Thermal conductivity [W(m·K) ⁻¹]	0.039	0.036	0.052	0.052	0.020-0.025 ^a	0.029	0.038	0.017	0.055
Thermal expansion coefficient (10 ⁻⁶ ·C ⁻¹)	9-14	9-14	NA	5	54-140	63	63	90	8
Thermal resistance (per m) [M(K·w) ⁻¹]	25	28	19	19	41	26-35	26	NA	18
Water vapor permeability [kg (Pa·K·m) ⁻¹]	High	110	30-35	30-35	3	2-5	NA	3	0
Water absorption	High	High	High	High	Low	Low	Low	Low	NF

Key to entries: NF—not a factor

NA—not available

Slight—less than low but not negligible

Qualified—acceptable with conditions (see manufacturer's literature)

^aAged thermal conductivity of polyisocyanurate foam depends upon facers. ASHRAE 1989, p. 22.7, shows 0.020 W(m·K)⁻¹ for gas-impermeable facers and 0.25 W(m·K)⁻¹ for no facer.

discussed in more detail in subsequent sections.

2.2.2 Polyisocyanurate or Polyurethane Foam

Polyisocyanurate (PIR) and polyurethane (PUR) foam roof insulations are closed-cell foams blown currently with CFC gas. The chemicals used for PIR and PUR foam are almost identical except for chemical ratios and catalyst types. The catalyst chemistry and processing temperature differences produce polymers that resist fire differently, affecting fire performance. The chemistry of PIR foam makes it much more suitable for use directly over a steel roof deck without any fire barrier separation. If PUR foam were used over a steel deck, relatively expensive fire barrier protection in the form of gypsum or perlite board would need to be installed between the foam and the steel deck. Consequently, PIR is used predominantly today. The current blowing agent in PIR is CFC-11. This chemical has a high ozone depletion potential (ODP), which signifies that it has the potential to contribute significantly to the destruction of the ozone layer. The most likely near-term alternative to CFC-11 is the closely related HCFC 141b, which has a lower ODP. Long term projections call for alternatives having no ODP. As shown in Table 2.2, CFC-blown rigid board stock foams provide the best thermal resistance per unit thickness of all major commercial roof insulations. The diffusion of air into the foam, and CFC gas out of it, reduces the thermal performance as the foam ages. That process, known as thermal drift, is discussed more thoroughly in Sect. 4.4.2.

2.2.3 Mineral Wool—High Density

Mineral wool roof insulation is a rigid, insulating material in board form composed of mineral wool and a thermosetting binder. The fibers are formed by spinning from either molten glass (sand, limestone, and soda ash) or molten rock (basalt and limestone). The binder is usually a phenolic resin. The mineral wools have a wide range of lengths and diameters. Boards are made by depositing the fibers as a fluffy blanket, compressing them to a density of about 110 to 145 kg/m³ (7 to 9 lb/ft³) and curing the board. This product can be unfaced or, to allow asphalt mopping for BUR systems, it can have a top surface treatment. Asphalt-impregnated kraft paper is a common facer. Facing materials are added during production. The term "mineral wool" as used here refers to both rock wool and fibrous glass products.

The inorganic, fibrous nature of this product provides fire resistance, good dimensional stability, and conformance to roof-deck irregularities. Because it is the most porous of all commercial roof insulations, it vents moisture readily and acts as a good divorcement for reroofing over an old membrane. However, long-term water exposure usually causes enough deterioration of the insulation that it must be replaced during roof repair or reroofing.

A limitation of mineral wool insulation is its low compressive strength. On thick, high-thermal-performance roofs, roof traffic can produce large deflections that subject a membrane to stress, particularly at insulation joints. In some instances, taping the insulation joints before application of a BUR can minimize stress. Specialty products (e.g., boards with vertically oriented fibers or composite boards with high-density veneer layers) can be used to improve compressive strength characteristics.

2.2.4 Mineral Wool—Low Density

Low-density mineral wool blankets and batts are made similarly to high-density materials, but the final product has a density from about 10 to 25 kg/m³ (0.6 to 1.6 lb/ft³). The exact range of available density will vary from country to country. These products can be used for roof insulation if installed below a roof deck. Low-density material does not have sufficient compressive strength to serve as a leveling course over a corrugated metal deck or as a substrate for a roof membrane. Systems have been designed for attaching the insulation between structural supports under a roof deck.

Mineral wool blankets and batts generally have the advantage of lower cost per unit of insulation R-value than above-deck roof insulation when open, accessible deck framing is available. They are sometimes used as the only roof insulation on light framed, plywood roof decks, which are well suited for BUR application directly to the deck.

In climates where condensation is an issue, a vapor retarder is sometimes used. The vapor retarder should be continuous to afford protection. Vapor retarders are thin and easily damaged, subject both to accidental puncture and to deliberate cuts for utility openings.

2.2.5 Polystyrene

Polystyrene foam roof insulation is a rigid, closed-cell foam supplied in board form. Two distinctly different types are commercially available: Molded expanded polystyrene (EPS), also simply called expanded polystyrene or bead board, is manufactured by molding EPS beads. Extruded expanded polystyrene (XPS), also simply called extruded polystyrene, is directly foamed in an extrusion process. Both

types are produced as homogeneous, unfaced products, but flexible or rigid facers are sometimes factory-applied in a separate process.

The two types of polystyrene foam insulation have significantly different properties and costs, which affect the way they are used in roof systems. In situations where insulation costs must be low, EPS is preferred because it costs roughly half as much as XPS does. Both types are used in a wide variety of applications other than roof insulation, such as for sheathing material under exterior siding and for foundation insulation. It is important that a product specifically manufactured for roofs be used.

2.2.5.1 Molded expanded polystyrene

This product normally has a nominal density of 16 kg/m³ to 20 kg/m³ (1 lb/ft³ to 1.25 lb/ft³) when used in roofs. EPS generally has the lowest cost per unit of insulating value of any above-deck insulation, but the installed cost depends on the need for a fire retarder as a top or bottom board for some deck and membrane systems. The thermal conductivity of EPS does not change with age because it does not contain CFC gas. Its ease of handling and good economics make it well suited for tapered roof systems.

The combustibility of EPS is a significant limitation, even though it is manufactured with a fire-retardant additive. Top and bottom fire barrier protection is required. For steel deck roof systems, mineral wool or perlite boards provide this protection. Sensitivity to hot asphalt is another significant limitation. EPS will melt if attempts are made to embed it into hot bitumen. The recommended upper limit is generally considered to be 80°C (175°F). The fire protection board also provides protection against hot asphalt. If the top

fire barrier is a gravel surface, a less expensive coverboard can be used. This board layer can be applied by back-mopping it with asphalt or by mechanically fastening it into the roof deck. The need for a coverboard increases the installed cost. However, the use of a coverboard also reduces membrane stress due to temperature gradients that might otherwise occur because of the relatively high coefficient of thermal expansion of polystyrene foam.

2.2.5.2 Extruded expanded polystyrene

Extrusion provides XPS with significantly better water resistance than EPS. The insulating value per unit thickness of XPS can be as much as 20% better than that of EPS because XPS is blown with low-conductivity CFC gas. Until recently, the blowing agent for XPS was CFC-12, a chemical with a high ODP whose use will soon be banned. Foam manufacturers have already taken steps to introduce alternatives (e.g., HCFC-142b).

XPS has some of the same limitations as EPS, including sensitivity to hot asphalt and a need for fire barrier protection. Extrusion technology limits this product to a minimum density of about 18 kg/m³ (1.1 lb/ft³). The higher material costs associated with this density generally prevent XPS from competing with EPS in conventional BUR systems. XPS is used primarily in protected membrane roofs, where the insulation is installed above the membrane. A density greater than 32 kg/m³ (2 lb/ft³) is required for this use.

2.2.6 Fiberboard

Fiberboard roof insulation has been used for many years in the United States. It is a rigid, cellulosic board product, composed of interlocking wood or cane fibers

and water resistant binders deposited from a water slurry and dried. On low-thermal-performance roofs, fiberboard has a price advantage over mineral wool or perlite insulation of equal thickness or equal R-value. Fiberboard is not suited for high-thermal-performance roofs because of its high thermal conductivity. The thickness required would make for high perimeter walls and high, expensive curbing for HVAC equipment clearance.

Fiberboard has a relatively high density of about 270 kg/m³ (17 lb/ft³) that provides good compressive strength for all types of roof loads and little handling damage during application. Its good compressive strength makes it ideal for use as an edge taper. Moisture-induced expansion and retention of water are its primary limitations. Moisture-induced dimensional changes cause membrane ridging. This in turn leads to roof leaks that eventually cause the cellulosic fibers to rot. The use of fiberboard as a primary insulation material has decreased during the past 10 years, but its use as a low-cost coverboard insulation over organic foams has increased.

2.2.7 Perlite Board

Perlite board roof insulation is a homogeneous, rigid, insulating material composed of expanded volcanic mineral particles (perlite), some recycled organic fiber, and a waterproofing additive. The product is manufactured from an aqueous slurry, which is deposited on a wire paper-making screen and then compressed and dried to a density of 130 to 160 kg/m³ (8 to 10 lb/ft³). The maximum thickness produced without lamination is 2.5 to 3.8 cm (1 to 1.5 in.) The high perlite content of this product provides good fire resistance and good dimensional stability.

Relatively low interlaminar and peel strengths are undesirable characteristics of

perlite board. These low strengths increase its susceptibility to wind damage, but they make the board well suited for field or factory taper. Water resistance is poor. Long-term contact with water causes permanent structural and thermal degradation. The relatively low strengths increase handling damage, which is recovered as an application cost by the installation contractor.

The relatively thin thicknesses of perlite board that are available and the relatively high thermal conductivity of the material limit its use to low-thermal-performance roofs if it is used alone. However, perlite board frequently can be used in combination with organic foam insulations on high-thermal-performance roofs. It is used underneath some organic foams to meet fire resistance requirements. Its relatively high vapor permeability makes it suitable for application over organic foams to minimize the risk of roof blisters. Perlite board is often used as a factory laminate (composite board) with organic foam insulation, but it can also be field laminated.

2.2.8 Corkboard

Corkboard insulation is a natural material that can be either bitumen bonded or mechanically fixed with screws and washers to the roof deck. It is suitable for metal and other decks. It is manufactured by steam-baking granules of cork into blocks under heat and pressure. No CFC gases are used during this process. The natural resins present in cork are sufficient to bind the granules together into a single unit. The blocks are then cured and finally cut to size and thickness. They are shrink-wrapped before delivery to a site. Corkboard used as roof insulation has a density of 110 to 140 kg/m³ (6.8 to 8.6 lb/ft³) and a thermal conductivity of 0.042 W(m·K)⁻¹ [0.29 Btu·

in. (F·h·ft²)⁻¹]. The boards are supplied in 1000 mm lengths × 500 mm sizes (3.28 ft × 1.64 ft) and in thicknesses of 25 mm to 110 mm. Tapered boards are also available for adjustments to the roof slopes, and corkboard can be bonded to other insulation materials (e.g. polyurethane foam) to give better thermal resistance values. This material is dimensionally stable and will accept bitumen at all working temperatures. It is friable and therefore liable to damage from rough handling. It has good laminar and compressive strengths. Corkboard, when used with appropriate decks and finishes, has unrestricted use with respect to fire regulations in the United Kingdom.

2.2.9 Cellular Glass

Cellular glass is the only inorganic, closed-cell roof insulation in the marketplace. It is produced by foaming molten glass at approximately 950°F with an inert gas. The finished molded product is available either with or without kraft paper facers.

The inorganic nature of cellular glass makes it durable, dimensionally stable, and highly fire resistant. Its closed cell structure makes it highly water resistant. It has a thermal conductivity of 0.055 W(m·K)⁻¹ [0.38 Btu·in. (F·h·ft²)⁻¹], which is relatively poor compared with closed-cell CFC-blown organic foam insulations. It is also relatively costly for equivalent thermal performance compared with other roof insulation products. Cost has greatly limited its commercial use in the last decade, in spite of the inherent advantages associated with its inorganic composition.

Cellular glass has good compressive strength and is compatible with all types of membrane systems. However, it is somewhat brittle and cannot be attached to a

roof deck using nails without being shattered. It can be mechanically fastened with screw-type fasteners or fully adhered with hot asphalt or adhesives.

2.2.10 Lightweight Insulating Concrete Deck and Fill

Lightweight insulating concrete is a cementitious deck insulation and roofing substrate produced by combining lightweight insulating aggregates, such as perlite, vermiculite, or expanded clay clinker, with portland cement and water. Some types are made simply by blending pre-generated foam with portland cement and water. All of these are applied in a liquid form and are screeded to provide a smooth roofing substrate. This system of application is well suited to achieving a good slope for drainage. Cured lightweight insulating concrete should have an oven-dry density of 320 to 640 kg/m³ (20 to 40 lb/ft³) and should attain a compressive strength of 7 to 35 kg/cm² (100 to 500 lb/in²). Lightweight insulating concrete should not be confused with lightweight structural concrete, which has a density of 1600 to 3200 kg/m³ (100 to 200 lb/ft³). The installation of lightweight insulating concrete requires large quantities of water, and some moisture will remain in the concrete even after the surface is dry. Adequate venting must be provided to allow drying and avoid the buildup of water vapor pressure under a roof membrane. Underside venting, either through formboards or through special slotted corrugated metal decking, is required to remove excess water from the product as it cures in place.

The relatively poor insulating value of lightweight insulating concrete makes it necessary to incorporate additional insulation for high thermal performance. This is done in the United States by incorporating foam polystyrene board insulation into the

wet lightweight insulating concrete when it is being poured. Additional roof insulation should not be installed directly over lightweight insulating concrete, because it will inhibit the drying of the concrete.

Special mechanical fasteners designed for use with lightweight insulating concrete and capable of providing fastener withdrawal resistance of 180 N/m (40 lb) per fastener should be used for membrane attachment. These are normally installed through a coated base sheet. The National Roofing Contractors Association (NRCA) recommends that the base ply of a membrane never be attached to lightweight insulating concrete with hot asphalt or adhesives in order to avoid localized stress transfer that could cause membrane splitting.

2.3 WATERPROOF COVERINGS

The primary function of waterproof coverings is to provide a durable, watertight barrier for the top of a building. This function includes a permanent water seal around all projections through the roof surface, long-term resistance to all weather and climate exposure conditions, and accommodation of movement by the building's structure without rupture. Generic types of waterproof coverings include

- bituminous membranes,
- mastic asphalt,
- elastoplastic polymer membranes,
- metal roofing, and
- liquid, spray-applied membranes.

Detailed descriptions and performance standards for these generic waterproof coverings are available in manufacturers' printed literature and in government and industry standards pub-

lished by the American Society for Testing and Materials (ASTM), the Canadian General Standards Board, European Union of Agrément, and other international standards organizations.

The characteristics and quality of waterproof coverings have changed drastically since the energy crisis of the mid-1970s in response to added roof insulation. Initially, roof insulation was simply inserted under existing waterproof coverings without considering any consequences on roof durability. Subsequently, it has been well established that introducing or increasing the thickness of insulation materials imposed stresses in existing designs that the traditional membranes could not withstand without rupturing. Improved reinforcement materials, polymer-modified bitumens, and new synthetic membranes were developed for building construction with current insulation amounts. It should be noted, however, that there is no perfect or indestructible material that can fix a bad roof design. The attributes of all materials used in any system must be matched to achieve satisfactory, long-term roof performance.

2.3.1 Bituminous Membranes

Bituminous membranes are composed of layers of waterproofing bitumen (asphalt or coal tar pitch) reinforced with one or more layers of felt. Traditionally, these membranes have been called BUR because they are fabricated on the roof by adhering layers of factory-impregnated felts with hot bitumen. The completed membranes are approximately 4 mm (3/16 in.) thick and commonly surfaced with 10 to 13 mm (about 1/2 in.) of gravel or stone chippings embedded in hot bitumen or with small mineral granules that can be either factory- or field-applied. Surfacing is used to improve resistance to fire, roof traffic, hail,

and ultraviolet light. Nonaggregate surface coatings, such as solvent or emulsion bituminous coatings, are increasingly popular because they make roof maintenance and repair easier.

BUR historically consisted of oxidized bitumens and organic- or asbestos-fiber felt reinforcements. These reinforcements provided good roof performance until the introduction of roof insulation. The insulation produced thermal and fatigue stressing that frequently exceeded the membrane's performance capabilities. Over the past 20 years, evolutionary improvements have been made to both the reinforcing felts and the waterproofing bitumens.

High performance felts were introduced first, without altering the oxidized bitumen composition. High performance felts can be high strength fiberglass felt, stretchable polyester fiber mat, or a combination. Their substitution for the old organic- and asbestos-felts greatly increased the ability of BUR membranes to accommodate stresses on the roof system. High performance felts also have significantly better rot resistance and make insulated BUR very durable.

Waterproofing bitumens with improved elasticity to accommodate roof stress have been developed by adding synthetic polymers such as atactic polypropylene, styrene-butadiene-styrene or styrene-ethylene-butylene-styrene to the bitumen. It is common to incorporate these more flexible, polymer-modified bitumens with very tough reinforcing felts at the factory to achieve essentially complete, prefabricated membranes called modified bituminous membranes. These modified membranes are installed on roofs either with roof-applied hot asphalt or with open torch or hot air melting of the relatively thick, factory-applied bitumen on the

modified membrane roofing product. The use of an open torch on roofs is decreasing and, in fact, is prohibited in many countries.

2.3.2 Mastic Asphalt (Asphaltic Cement)

The United Kingdom has a well established and successful history of the use of mastic asphalt as a roof covering. This material is a mixture of suitably graded aggregates bound with refined bitumen. The combination results in a dense coating with no voids that is spread out over a roof in two or three coats to a final thickness of 20 to 25 mm (0.75 to 1 in.). The result is a membrane that is fully waterproof and very durable.

Historically, mastic asphalts were produced from naturally occurring rock asphalts or lake asphalt. Rock asphalt is a limestone rock naturally impregnated with bitumen found in Italy, Germany, Switzerland, and France. It is crushed to form fine aggregates and blended with bitumen to constitute the mastic asphalt. Lake asphalt is principally imported into the United Kingdom from the asphalt lake in Trinidad. It is composed of approximately two-thirds bitumen and one-third finely divided clay. It is used to produce "T" grade asphalt, which is now recommended as the only basic asphalt to be used on roofs. The clay gives the mixture a thixotropic quality. The high proportion of bitumen in lake asphalt requires the addition of more aggregate to produce mastic asphalt. Lake asphalt, although generally regarded as being of better quality than rock asphalt because of improved laying characteristics, forms a small proportion of the total asphalt market. Most mastics are bitumen derived.

Examples of mastic asphalt roofs are available that have survived for 50 to

100 years with little maintenance. These good, old roofs are all uninsulated. Mastic asphalt is subject to "thermal shock" failure during springtime and "brittle fracture" during sub-zero winter conditions. Recently, polymer-modified mastic asphalt has been developed to resist thermal stress and to improve durability. This product is used successfully with insulation in the United Kingdom.

2.3.3 Elastoplastic Polymer Membranes

These membranes are factory produced from plastic or elastic polymeric compositions. They are highly durable under the stresses of insulated roof conditions because of long-term flexibility at low temperatures and stability at elevated roof temperatures. Some are manufactured with reinforcements and some contain no reinforcement. The generic types include vulcanized elastomers, nonvulcanized elastomers, and thermoplastics. A feature of these membranes is that they can be produced with a range of colors from highly reflective white to highly absorbing black.

Polymeric membranes are relatively thin (1.0 to 1.5 mm or 40 to 60 mil) and are normally applied as a single ply, which can be installed quickly and is lighter in weight than most alternative systems. Although these membranes can be fully adhered to a substrate, it is more common to provide mechanical attachment or leave them loosely-laid with ballast added for wind resistance. Extra fasteners or ballast is often required at the building perimeter to resist stronger wind uplift there.

In single-ply systems, the lap seal is critical and very dependent on proper application. Some types of polymeric membranes are manufactured in very large sheet sizes that keep job-site seaming to a

minimum. Customized sheet sizes and shapes are sometimes factory-jointed for small roof applications to minimize the need for sensitive job-site seaming.

The most commonly used vulcanized elastomer is EPDM, typically used without reinforcement. Its elongation capability and elasticity allow outstanding joint service. Vulcanization restricts seam fabrication on a roof to adhesive-type seals that demand careful application for permanent water-tightness, especially in cold damp climates. Butyl rubber membranes have properties similar to those of EPDM.

The most commonly used nonvulcanized elastomer is chlorosulfonated polyethylene (CSPE), which generally has a strong reinforcing fabric in the membrane. This material progressively crosslinks (vulcanizes) during roof exposure. The absence of vulcanization allows seams to be sealed by strong solvent or heat welding during original roof application. Special seaming techniques must be used to make subsequent roof repair patches.

The most commonly used thermoplastic membrane is polyvinyl chloride (PVC). It has good flame resistance, and the thermoplastic nature of PVC permits the fabrication of strong solvent- or heat-welded seams both during original roof construction and during subsequent roof repairs. PVC membranes are produced both with and without reinforcements. Because PVC gradually shrinks and embrittles with weathering, unreinforced PVC membranes have experienced serious splitting failure after about 10 years of roof service. This has produced a trend toward reinforced and plasticizer modified formulations. Most PVC membranes are chemically incompatible with bituminous materials and must be carefully isolated from bitumen contamination in roof service. Chlorinated polyethylene membranes

have properties similar to PVC, but they are much more resistant to oils, bitumens, and chemicals, and they are less subject to weather shrinkage. Other uncured polymeric membranes with thermoplastic properties are polyisobutylene and ethylene copolymer. A fleece backing allows both to be used as overlays on existing bituminous roofs.

2.3.4 Metal Roofing

Panels made from sheet metal are frequently used for the waterproof covering on both steep and low-slope roofs. They are available in a variety of colors and protective coatings. Copper, typically 0.6 mm (0.024 in.) thick, has been known as a durable roof covering for many years. Steel, with a variety of protective finishes, has the largest share of the metal roofing market. It is typically 0.6 mm (0.024 in.) thick but can be supplied as thin as 0.4 mm (0.016 in.). Aluminum, typically 0.8 mm (0.032 in.) is used on a substantial number of roofs. Stainless steel with no applied coating has some use, and lead-coated stainless steel is offered as a decorative choice.

Metal roof systems are traditionally divided into fully supported and spanning systems. The fully supported systems include lead, copper, or zinc sheet. They are applied on a solid deck, generally in short lengths, to minimize thermal movement. They were laid originally on a base felt and are now given a geotextile underlay to aid sliding over the deck as the temperature changes. They are generally installed with a minimum roof slope of 15° (3 in./ft) and shed water similarly to tiled or shingled roofs. The cross joints do not require sealant but can be either cross welded or simply overlapped. These sheet coverings can also be on low roof slopes (minimum

1° or 0.25 in./ft) with appropriate joint details.

Structural systems are self-supporting and span across intermediate supports to which they are fixed. They are also laid on slopes as low as 1° (1/4 in./ft) and rely similarly on overlaps to shed water at the higher slopes and fully sealed cross joints on flatter angles. Standing seams, which are designed to remove penetrations through the sheets and effectively raise the joint above the level of draining water, can be used at any slope. Some standing seam systems rely totally on the depth of the edge profiles and anti-capillary grooves to prevent water penetration, but others employ either factory- or site-applied sealants as an additional barrier. The use of concealed clips with a two-piece design anchored (fixed) to purlins or substructures accommodates thermal movement of the metal panels without any penetration through the metal sheet. The structural characteristics of such an attachment design obviously do not include diaphragm strength. Hence, resistance to wind and racking must be accomplished by other means, such as diagonal bracing.

Successful leak-free performance of metal roofing on low slopes is critically dependent on the design and application quality of all seam (jointing) details, flashings at roof penetrations (fixing holes), and substructure attachment to accommodate substantial thermal expansion and contraction.

The original metal decks were simply corrugated metal sheets spanning over timber roof purlins or metal angles and shedding rainfall into a surrounding gutter. They have now developed into a variety of systems incorporating vapor barriers, breather membranes, and insulation materials. The complexity of fixing and jointing details has progressed in con-

junction with the increasing number of layers in each particular system. This limited range of simple corrugated sheets has now been superseded and expanded to over 100 profiles for steel sheeting in the United Kingdom. Aluminum sheets with their own range of profiles provide a further choice not available 30 years ago.

The coatings applied to the majority of the above systems were originally for corrosion and weather protection but have been developed in a variety of colors giving the designer many attractive choices. Steel sheet is generally treated by acid pickling followed by a zinc bath, which leaves a total weight of zinc (half on each face) of 0.275 kg/m² (0.9 oz/ft²) alloy bonded to the steel and providing good long-term corrosion protection. Fluorocarbon is the most common top coating in the United States, but some silicon modified polyester coatings are also used. The coatings used in Europe are PVC and polyvinylidene fluoride (PVF₂). PVC coatings have been used extensively but have suffered some coating peel-off in service. Present experience suggests that field application of maintenance coatings is expedient to protect areas of PVC peel-off. The recommended time for applying maintenance coating previously associated with the vague term "life to first maintenance" has been clearly defined as the occurrence of 5% coating peel-off. The panels should be repainted at this stage, in order to retain long-term durability. Improved performance has also been achieved by increasing the original factory-applied PVC coatings from 25 to 200 µm thick.

The PVF₂ coating is very durable and colorfast, but it is softer and therefore more easily damaged by site handling. The underside is often supplied with paint finishes which should not be subjected to

aggressive conditions. Alternative underside specifications are available up to the same standard as the external face.

2.3.5 Liquid, Spray-Applied Membranes

Spray-applied membranes employ fluid asphaltic or elastomeric waterproofing compositions and are installed at ambient temperature. They are commonly classified as cold-applied membranes.

The asphaltic membranes always contain reinforcing fabrics, which are either asphalt-coated glass fiber felts or nonasphaltic polyester fiber mats. One type of cold-applied asphaltic membrane consists of solvent-based asphaltic mastic spray-applied between the bottom reinforcement and the membrane substrate, as well as between each layer of reinforcement. The mastic is applied at approximately 1 L/m² (2.5 gal per 100 ft²) per coat. A final application of spray-applied mastic over the top reinforcement layer serves as the adhesive for mineral granule surfacing.

Another type of cold-applied asphaltic membrane consists of two or more layers of asphalt-coated cellulosic or glass fiber felts adhered with either hot asphalt or solvent-based asphaltic mastic, over which a heavy layer of asphalt emulsion containing glass fibers is spray-applied with specialized spray equipment. The top layer usually consists of 34 L (9 gal) of emulsion and 1.4 kg (3 lb) of 19 mm (0.75 in.) long glass fibers per 9.3 m² (100 ft²). This membrane system has been used successfully for more than 20 years in warm climate areas of the United States, but it has had only limited use in cold climates.

Elastomeric spray-applied membranes do not incorporate reinforcing fibers or felts. They are normally installed over spray-applied PUR foam insulation. This system forms a continuous, self-flashing

insulated membrane. Elastomeric membrane coatings are spray-applied in one or more layers to provide a finished, cured coating 0.5 to 1.0 mm (0.020 to 0.040 in.) thick.

2.3.6 Brush- and Roller-Applied Systems

A number of glass-fiber reinforced resin systems are in use in the United Kingdom. They are applied by rolling the base coat onto a prepared plywood deck then embedding the glass-fiber mat into the freshly laid resin by further rolling. The resin is left to cure fully for 60 to 90 min, depending on the temperature before the top coat is applied (this waiting period must not exceed 72 h). Some of these systems have been tested by the British Board of Agreement (BBA) and are giving good service. Similar systems, with no Agreement certificates, have exhibited a number of failures and cast doubts on the resins being used for these "unproven" brands. A similar system uses two coats of brush-applied polyester resin reinforced with polyestee fleece between the coats; it is proving successful.

2.4 COMMON INSULATED ROOF SYSTEMS

The roof systems described in this section are representative of those most commonly used in countries participating in this IEA annex. The descriptions are brief. Performance is characterized in Sect. 5, after the discussion of insulated roofing issues and problems in Sects. 3 and 4, respectively.

All systems described are shown with vapor retarders. Vapor retarders prevent moisture originating inside the building from diffusing up into the roof system.

Note, however, that in warm climates, a vapor retarder may not be necessary.

2.4.1 Warm Deck Systems: Single Type of Insulation

Conventional warm deck systems have insulation installed over the roof deck and under a waterproof covering. Systems employing a single type of insulation are easy to install and economical. The concrete deck system illustrated in Fig. 2.1 is common for new construction and is only

Fig. 2.1. A common warm roof deck system with a single type of insulation

one of many possible combinations of membrane, insulation, and deck type. The warm deck configuration is also well suited to steel roof decks, because the roof insulation provides a leveling course over the deck flutes as well as fulfilling the thermal insulation function.

The application of insulation and a waterproof covering over an old roof, either the warm deck or the cold deck type, reuses the existing insulation and avoids the high cost of tearing off and disposing of the old roof. However, the existing insulation will often be wet or even waterlogged and can represent a potential risk if not removed. It provides most of the features of a totally new warm deck roof system. A common reroofing installation over an old warm deck roof is illustrated in Fig. 2.2. In this example, the new system is mechani-

Fig. 2.2. A common reroofing system over an old warm deck roof.

cally fastened through the old roof into the deck. This is desirable to ensure good wind resistance for the new roof. The new insulation should smooth out irregularities due to the residual gravel on the old roof. It should also provide divorcement to protect the new waterproof membrane from localized stress conditions in the old roof. Additional comments on reroofing over old roofs are provided in Sects. 4.5 and 5.2.2. Reroofing over a cold deck roof, illustrated in Fig. 2.3, has many features in common with reroofing over a warm deck roof. If sufficient new insulation is added, condensation will not occur below the deck.

Fig. 2.3. A common reroofing system over an old cold deck roof.

2.4.2 Warm Deck Systems: Multiple Types of Insulation

Insulation must serve several functions in a roof system, including thermal performance, fire protection, membrane compatibility, and leveling. These functions cannot always be provided by a single type of insulation. Multiple types may be needed.

The system illustrated in Fig. 2.4 has been used successfully for many years in the United Kingdom. It employs a coverboard of fiberboard or cork insulation over the primary mineral wool insulation. The coverboard serves as an acceptable substrate for the mastic asphalt waterproof membrane. The latter is usually spread-applied in two or three coats to a thickness of 20 to 25 mm (0.75 to 1 in.). Mineral wool itself is not a satisfactory substrate for mastic asphalt. A slip sheet is incorporated for stress divorcement of the mastic asphalt. The warm deck system with a layer of high-performance insulation and a coverboard is also used with other types of membranes, insulations, and decks. For example fiberboard, perlite, or mineral

Fig. 2.4. A warm deck roof with two insulations. The coverboard is a more acceptable substrate for mastic asphalt than the mineral wool primary insulation.

wool coverboard insulation is often used over PIR primary insulation under BUR to reduce the incidence of blistering.

The high energy efficiency required of modern roof systems demands the use of high-thermal-performance insulations such as foam boards. However, the material between the deck and the membrane must still protect against fire. For this reason, foam boards are sometimes used in conjunction with other types of insulation in multi-layer systems. The three-layer system illustrated in Fig. 2.5 has a mechanically fastened, perlite bottomboard over a steel deck to provide interior fire protection for the EPS insulation. A fiberboard

Fig. 2.5. A three-insulation warm deck roof system. Some high-thermal performance foam insulations are sensitive to bitumens on the top and cannot meet the fire code over metal decks.

coverboard insulation accommodates hot asphalt application of the BUR over the heat-sensitive EPS insulation. The three-layer system is also used with other types of barrier insulation and other types of membranes. For example, gypsum board can be used for the bottom fire barrier, or a fiberboard coverboard might be used to prevent solvent glue from attacking the EPS insulation when an elastoplastic mem-

brane is laid down. A common alternative is to use foam formulations that satisfy fire and membrane compatibility requirements. In this case, a single (foam) insulation system is possible.

2.4.3 Cold Deck Systems

Cold deck systems are attractive economically, because they allow the use of low-density, low-cost mineral wool insulation. Figure 2.6 shows an example of a cold deck roof system with under-deck insulation. Unvented systems can be used in

Fig. 2.6. A cold deck roof system. Care must be taken to minimize water condensation on the underside of the deck.

warm, dry climates when moisture condensation is not a problem. In situations where moisture condensation is significant, vapor retarders have not been effective because they do not provide continuous protection. Systems with adequate cavity ventilation can be effective. See Sect. 3.2.3 for additional comments. An alternative concept, the water permeable vapor retarder, is discussed in Sect. 3.2.3. Another variation of the cold deck roof, the "raised cold deck" system, involves a membrane-covered wood deck elevated about a meter over a concrete deck. Cavity ventilation is important for this system. It is discussed in Sect. 5.4.2.

2.4.4 Metal Roof Systems

Metal roof systems employ seamed metal panels to form waterproof coverings. Initially these systems were uninsulated, but the increasing demand for thermal efficiency led to the addition of insulation. Insulated systems range from loose-laid, low-density mineral wool hung from the underside of purlins to bonded or unbonded rigid board insulation, either flat or profiled. Metal roof systems may or may not include an over-the-purlin metal panel under the insulation.

Figure 2.7 illustrates a system commonly used today. It shows insulation installed over metal decking (or metal liner

Fig. 2.7. A metal roof system. This example depicts a "structural standing seam" or "secret fix" metal roof.

panels) and a structural standing seam metal roof on top designed to resist water passage on slopes as low as 1:48 (0.25 in./ft). Concealed roof clips used for attachment of the metal roof are designed to accommodate the large thermal movement encountered with metal roofing. Good design and application of all metal seams (jointing) and all metal flashing details around roof penetrations (fixing

holes) is critically important for long-term water-tight performance.

The use of metal roofing to reroof over an existing roof is illustrated in Fig. 2.8. Metal reroofing can be installed over any type of old roof membrane or roof deck type. Reroofing involves the addition of a new framing system over the old roof to support the new metal roof. The new roof is usually designed to provide at least 1 : 48 (0.25 in./ft) slope. Flexible mineral wool insulation blankets are generally installed between the old and new roofs.

2.4.5 Protected Membrane Systems

A protected membrane system is a special warm deck system. It is distinguished from the conventional warm deck insulated system in that the roof insulation is located wholly or partly on the weather side of the waterproof membrane. Consequently, the thermal performance of the insulation must not be affected by roof

service conditions. Figure 2.9 shows a typical protected membrane construction. The insulation commonly used is loose-laid, XPS held in place by some type of heavy ballast (e.g., coarse gravel or paver blocks). A protection sheet or mat is frequently used under the ballast. Instead of XPS, high-density mineral wool insulation has been used successfully on some roofs in Europe.

2.4.6 Spray-Applied Polyurethane Foam Systems

Spray-applied PUR foam roofing is a monolithic, seamless, self-flashing system consisting of foamed-in-place insulation usually covered with a spray-applied elastomeric membrane coating. The system illustrated in Fig. 2.10 is on a concrete deck, but it can also be installed over other types of decks and as reroofing over old roofs. (Also see Sect. 5.7.)

Fig. 2.8. Reroofing with metal over an existing roof. The spacer assembly provides positive slope for the new covering and space for additional insulation over the old system.

Fig. 2.9. A protected membrane roofing system.

Fig. 2.10. A spray-applied polyurethane foam roof. The figure shows foam being sprayed right up to penetrations. The elastomeric protective coating is applied up the side of the penetration.

3

GOOD PRACTICES FOR INSULATED ROOFS

When choosing the type and amount of insulation and the method to incorporate it into a roof system, one should be aware of the implications of this choice on other characteristics of the roof. Problems can result from increased membrane stress, moisture storage, reduced resistance to wind uplift, and increased fire hazard. For most problems, remedies have been identified and are part of standard good practices in the roofing industry. Some aspects of standard good practices as they relate to insulated roofs are discussed in this section. Outstanding problems and research needs are presented in Sect. 4.

3.1 GENERAL GUIDELINES

Above all else, quality roofing is a product of experience. Every nation has documents that capture and, in some instances, codify the best examples of experience from its roofing industry. These documents, prepared by agencies and associations recognized as leaders, are generally accepted as the most appropriate guides to good roofing practices. Examples for countries participating in this IEA An-

nex are shown in Table 3.1. Experience is also conveyed through training programs. Training courses for both designers and roof applicators are provided by roofing material manufacturers, roofing contractor associations, building owner groups, and educational organizations.

3.2 DESIGN ISSUES

3.2.1 Optimum Thermal Efficiency

Insulation in low-slope roofs improves thermal efficiency and reduces the heating and cooling load on a building. This has a direct impact on the cost of operating the building. The performance data for the materials chosen, especially the thermal performance data for the insulation, are important for realistic estimates of the operating costs during design of the building. Data that reflect in-service performance are required and for some systems, they may be different from data obtained under laboratory conditions. Example systems include wetted insulation in protected membrane systems (discussed in the following paragraphs), thermal drift in foam

Table 3.1. Resource documents on good roofing practices

UNITED STATES

- U.S. ASTM *Annual Book of ASTM Standards*, Vol. 04.06, *Thermal Insulation*, American Society of Testing and Materials, 1993.
- NRCA *Roofing and Waterproofing Manual*, National Reroofing Contractors Association, Chicago, 1983.
- C. W. Griffin, Jr., *Manual of Built-up Roof Systems*, McGraw-Hill, New York, 1982.
- Maxwell C. Baker, *Roofs: Design, Application, Maintenance*, Multiscience Publications, Quebec, 1980.
- Manufacturers' Information Booklets for Proper Use of Specific Products.
- Laaly, H., "The Science and Technology of Traditional and Modern Roofing Systems."

DENMARK

- Tagdækning med bitumenprodukter. Teknik, Økonomi* (Roofing with Bituminous Products. Technique, Economics), TOR Anvisning 14, 1985 (in Danish).
- Tagdækning. Renovering og vedligeholdelse* (Roofing. Renovation and Maintenance), TOR Anvisning 16, 1990 (in Danish).
- Tagdækning. Retningslinier, Specifikationer, Detaljer* (Roofing. Directions, Specifications, Details), TOR Anvisning 17, 1990 (in Danish).
- Tagpapbranchens Oplysnings Råd Teknikerbyen, VIRUM DK (Guides from the Council of Danish Roof Membrane Manufacturers (in Danish).
- Bygningers Fugtisolering*, SBI anvisning 139, 1984. (Moisture Protection of Buildings), Guide from the Danish Building Research Institute (in Danish).

SWEDEN

- Hus AMA. *Allmän Material-och Arbetsbeskrivning för husbyggnadsarbeten* (General Material and Performance Guide for House Building), AB Svensk Byggtjänst, 1983 (in Swedish).
- RA. *Råd och Anvisningar till hus AMA* (Advice and Instructions to Hus-AMA), AB Svensk Byggtjänst, 1992, Stockholm (in Swedish).
- AMA-nytt Mark Hus (Regular Publications to Hus-AMA), AB Svensk Byggtjänst, 1992, Stockholm (in Swedish).
- Isolerguiden. En vägledning till Boverkets nybyggnadsregler* (Thermal Insulation Guide from the Swedish Thermal Insulation Manufacturers Association, 1989, Swedisol (in Swedish).
- Manufacturers' handbooks in Sweden (in Swedish).

UNITED KINGDOM

- PSA *Technical Guide to Flat Roofing*, Vols. 1 and 2, March 1987.
- "Asphalt and Built-up Felt Roofings: Durability," *BRE Digest 144*, August 1972.
- NFRC *Profiled Sheet Metal Roofing and Cladding*, September 1991.
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Table 3.1 (continued)

"Flat Roof Design: Waterproof Membranes," *BRE Digest* 372, June 1992.

Flat Roofing: A Guide to Good Practice, Tarmac Building Products, Ltd., distributed by RIBA Publications, Ltd.

British Flat Roofing Council, *Flat Roofing—Design and Good Practice*, to be published May 1993.

Expert System (PC-oriented), Loughborough University (U.K.), "Knowledge-Based Advisor to Diagnose Faults in Flat Roofing Systems," based on Site Inspection Feedback (available 1994).

insulations (discussed in Sect. 4.4.2), and loose-fill attic insulation (Wilkes 1992).

To illustrate derating caused by performance analysis, consider an example using data from the Swedish Building Code (Petersson 1981; Petersson 1990; Petersson 1992). Insulation in a protected membrane system is above the membrane and, depending upon the ballasting, is more or less exposed to weather. Thus, design criteria should require an insulation that is water resistant and/or a system that quickly sheds precipitation. To the extent that this is not the case, the thermal performance of the system is compromised and the system is subject to moisture deterioration. The Swedish Code addresses this concern. For a protected membrane roof using XPS insulation, it specifies

that the design conductance of the roof shall be determined by

$$U_{\text{design}} [W(m^2 \cdot K)^{-1}] = 1/R_L + 0.02 + \Delta U_{PW}.$$

R_L is the thermal resistance of the entire construction. It includes internal and external surface resistances, as well as the resistance of the insulation and the deck. Handbook values are used except for the XPS insulation. Petersson has shown that, depending upon the ballast layer, the XPS will take up moisture over time. This increases its thermal conductivity by $\Delta\lambda_I$. Table 3.2 provides correction factors $\Delta\lambda_I$ to be used depending upon the construction techniques. The value $0.02 W(m^2 \cdot K)^{-1}$ [$0.004 \text{ Btu}(h \cdot ft^2 \cdot F)^{-1}$] is a correction factor

Table 3.2. Correction of thermal conductivity for extruded polystyrene boards due to conditions that increase moisture content. Corrections are for Swedish climate (See reference in text)

Type of construction	Average moisture, volume %	Correction $\Delta\lambda_I, W/mK$
Open topping:		
Gravel		
Single layer of boards	0 to 1	0.001
Two layers of boards	2 to 3	0.003
Sealed topping:		
(One or two layers of boards)		
Paving stones in gravel	6 to 8	0.008
Earth covered roof terrace	6 to 8	0.008
Concrete parking structure	6 to 8	0.008

that accounts for production conditions, estimation methods, etc. The final correction, ΔU_{PW} , accounts for the effect of standing water in the roof system, over and above the effect of water absorption in the XPS. For example, increased precipitation can increase the system conductance, whereas strong average wind velocities will tend to dry a roof more quickly decreasing the impact of precipitation. The value of ΔU_{PW} also depends upon the type of construction. Values for ΔU_{PW} are shown in Table 3.3 for different constructions and for different fractions of insulation above and below the membrane.

To see the magnitude of the correction, consider a BUR membrane directly over a poured gypsum deck. Two layers of XPS insulation are used with a sealed topping of paver blocks. The dimensions of the roof are shown in Fig. 3.1 and the calculations in Table 3.4. For this fairly common system, the Swedish code suggests that one can anticipate a moisture content of 6 to 8% by volume in the XPS and that the λ -factor correction for standing water is 2%. Handbook data (ASHRAE 1989) are used for

Fig. 3.1. A typical protected membrane system roof. See Table 3.4 for design calculations.

other factors needed in the calculation. Box C in Table 3.4 shows that the derated $U_{\text{design}} = 0.41 \text{ W(m}^2 \cdot \text{K)}^{-1}$ while box D gives $U_{\text{design}} = 0.31 \text{ W(m}^2 \cdot \text{K)}^{-1}$ assuming no moisture. In this instance, the correction is 33% of the dry value. Note that this pertains to a specific system and to a specific climate region (Sweden).

Other factors besides material performance data enter into the decision about the amount of insulation to install: (1) material and installation costs, (2) incentive programs to reduce costs, (3) government regulations, (4) a conservation

Table 3.3. Correction ΔU_{PW} for effects of precipitation and wind on a roof with extruded polystyrene insulation above the membrane. Corrections are for Swedish climate (See reference in text)

Type of construction	Correction $\Delta U_{PW} [\text{W(m}^2 \cdot \text{K)}^{-1}]$			
	<20% ^a	20 to 40% ^a	40 to 60% ^a	>60% ^a
Open topping: (One or two layers of boards)				
Gravel	0.05	0.03	0.02	0
Sealed topping: (One or two layers of boards)				
Paving stones in gravel	0.02	0.01	0	0
Earth covered roof terrace	0.02	0.01	0	0
Concrete parking structure	0.01	0	0	0

^aPercentage of total thermal resistance under the membrane.

Table 3.4. Calculation of the design conductance for the roof shown in Fig. 3.1

- (a) Dry thermal conductivity of XPS: $\lambda = 0.029 \text{ W(m} \cdot \text{K)}^{-1}$
 6% average moisture: $\Delta\lambda_I = 0.008$
- $$\lambda_I = \lambda + \Delta\lambda_I = 0.037$$
- $$\frac{1}{\lambda_I} = \frac{0.076 \text{ m}}{0.037 \text{ W(m} \cdot \text{K)}^{-1}} = 2.05 \text{ (m}^2 \cdot \text{K)} \text{W}^{-1}$$
- (b) $R_L = R_{\text{inside}} + R_{\text{deck}} + R_{\text{membrane}} + R_I + R_{\text{paver}}$
R_{inside}	$= 0.11 \text{ (m}^2 \cdot \text{K)} \text{W}^{-1}$
R_{deck}	$= 0.37$
R_{membrane}	$= 0.06$
R_I	$= 2.05$
R_{paver}	$= 0.11$
- $$R_L = 2.70 \text{ (m}^2 \cdot \text{K)} \text{W}^{-1}$$
- (c) $U_{\text{design}} = 1/R_L + 0.02 + \Delta U_{\text{PW}}$
 $\Delta U_{\text{PW}} = 0.02$
 $U_{\text{design}} = (1/2.70) + 0.02 + 0.02$
 $= 0.41 \text{ W(m}^2 \cdot \text{K)}^{-1}$ (with systems corrections)
- (d) R_L (with no systems corrections) $= 0.11 + 0.37 + 0.06 + (.076/.029) + 0.11$
 $U_{\text{design}} = 1/R_L, R_L = 3.27 \text{ (m}^2 \cdot \text{K)} \text{W}^{-1}$
 $U_{\text{design}} = 0.31 \text{ W(m}^2 \cdot \text{K)}^{-1}$ (with no systems corrections)

ethic, and (5) business strategies of the building owner. A simple life-cycle costing procedure based only on material and energy costs illustrates how other factors influence the insulation decision.

According to Fig. 3.2, the present value of the incremental operating cost (OC) for heating and cooling a building decreases inversely as R-value increases. Conversely, the initial material and installation costs (IC) of adding insulation typically increase linearly with the amount of insulation. The total present cost (TC) to the building owner is the sum of the values on the two curves at any particular value of thermal resistance; it passes through a minimum where the two curves cross.

Fig. 3.2. Roof cost per unit area vs insulation R-value.

Thermal resistance at levels below this point means the user is paying too high an energy bill because the roof has too little insulation. At levels above this point, the user has invested too much in insulation and will not recover its costs over the life of the roof.

Even for simple life-cycle cost analyses, many assumptions must be made about such things as weather conditions, the cost of materials and labor, discount rates, the price of fuel and the amount of maintenance. One such analysis, done in 1985, provided a simple worksheet for determining the optimum thickness of mechanically attached insulation under a three-ply BUR over a metal deck for specific building types (Walukas 1985). Assuming that changes in the amount of roof insulation do not affect other building first costs and operating costs, one can write, as shown in Fig. 3.2,

$$OC = C_1/R + C_2$$

and

$$IC = F (C_3 R + C_4),$$

where OC represents building operating costs, C_1/R is the portion of operating

costs attributable to the roof, and C_2 represents other operating costs. Here, the thermal resistance R uses laboratory-measured properties. IC is total first cost, F is a factor accounting for regional differences, $C_3 R$ is the cost of adding insulation to the roof, and C_4 is other building costs. The constants C_1 and C_2 were obtained numerically from DOE 2.1 calculations for specific buildings in specific climates with dry insulation (DOE 1989); and F , C_3 , and C_4 came from analysis of material costs in manuals of published construction costs. Taking the total cost to be the sum of the operating and the first costs, there is a minimum in the curve for total costs. It represents the economically optimum roof insulation for the building, or

$$R_{opt} = (C_1/FC_3)^{1/2}.$$

In DOE 1989, tables are given for the constants pertaining to climates and construction costs in the United States. The results are necessarily site-specific and are based on 1985 data applied over the life of the roof with a constant discount rate (assumed to be 20 years and 8% per year, respectively). R_{opt} can be calculated for popular roof insulations. Typical results are shown in Table 3.5.

Table 3.5. Optimum thermal insulation thicknesses for life-cycle cost minimization

Insulation	Economic optimum thermal insulation thickness (mm) ^a	
	Mild U.S. climates	Harsh U.S. climates (Alaska not included)
Fibrous glass	32	77
Expanded polystyrene	39	99
Polyisocyanurate	32	79

^aThese calculations are typical only of U.S. conditions. In Scandinavia, with harsher climates and higher energy prices, a typical thickness of mineral wool is 200 mm. Mandatory 1981 standards in Scandinavia call for 125 mm in new housing.

In this example, the economic optimum thickness for roof insulation under U.S. conditions varies from about 30 mm to 40 mm (1.2 to 1.6 in.) in mild climates and from about 80 mm to 100 mm (3.1 to 3.9 in.) in harsh climates. The optimum thicknesses for mild or harsh climates show no strong dependence on insulation type. But the R-value per unit thickness at 24°C (75°F) is 28 ($\text{m} \cdot \text{K} \cdot \text{W}^{-1}$ [4.0 ($^{\circ}\text{F} \cdot \text{ft}^2 \cdot \text{h}$)($\text{Btu} \cdot \text{in.})^{-1}$]) for fibrous glass, 35 ($\text{K} \cdot \text{m} \cdot \text{W}^{-1}$ [5.0 ($\text{h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F}$)($\text{Btu} \cdot \text{in.})^{-1}$]) for XPS, and 43 ($\text{K} \cdot \text{m} \cdot \text{W}^{-1}$ [6.5 ($^{\circ}\text{F} \cdot \text{ft}^2 \cdot \text{h}$)($\text{Btu} \cdot \text{in.})^{-1}$]) for PIR (ASHRAE 1989). For each climate, the optimum thicknesses of PIR and XPS give 1.5 to 1.6 times more total R-value than the optimum thickness of fibrous glass does. This analysis suggests that the life-cycle cost per unit R-value of a roof system is lowest when insulation is used with the highest R-value per unit thickness. Purchase cost per unit thickness is higher for these insulations.

3.2.2 Surface Temperatures of Low-Slope Roofs

The solar absorptance of the roof membrane plays a dominant role in determining the daytime temperature of a roof. On a bright summer day, the temperature of a membrane with a solar absorptance of approximately 0.9 can easily exceed 70°C (160°F), and the surface temperature of a membrane with a solar absorptance of approximately 0.5 on a similar roof under similar conditions may not exceed 50°C (120°F) (Griggs 1989). Predictions of a computer model agree with these observations (Fig. 3.3, repeated for convenience from Fig. 1.3). Radiation-sensitive coatings, if they perform according to the claims made for them, yield a low solar absorptance. Although little direct evidence exists to suggest that roofs with low solar absorp-

Fig. 3.3. Changes in roof membrane temperature for different amounts of insulation. Results for three different surface solar absorption coefficients are shown.

tance and resultant lower daytime temperature peaks have a longer life because of the lower temperatures, it is generally felt that higher temperatures will accelerate deterioration and should be avoided.

Computer models can accurately predict roof surface temperatures when the characteristics of the roof and all the conditions imposed on it are known. The following factors affect roof surface temperature:

- roof insulation,
- solar intensity,
- environmental conditions (clouds, rain, wind),
- roof surface color and texture,
- roof surface infrared emittance, and
- roof surface mass.

Roof insulation. Other things being equal, a roof with more insulation will allow less heat to flow from the roof into a

building on a sunny day than will a roof with less insulation. This should cause the roof to have a higher surface temperature. Thus, the magnitude of the surface temperature should depend upon the amount of insulation. As is shown in Fig. 3.3, however, after even a small amount of insulation has been added to a roof, further increases have little effect on the temperature. The reason is that the surface temperature depends upon the net exchange of energy between the roof surface and the outdoor and indoor environments. As the amount of roof insulation is increased, the surface becomes more shielded from energy exchange with the indoor environment (conditioned space) so the surface temperature is controlled by external influences such as absorbed solar energy, sky radiation, wind, rain, and outdoor air temperature. One effect of this is high membrane stresses caused by sudden surface temperature changes during a rain shower on a hot summer day. Note that increased thicknesses of insulation still have a positive impact on fuel bills. That is, if the insulation thickness is doubled, the peak daytime surface temperature may decrease by only a few degrees, but the heat loss or gain (and costs for resulting heating and cooling energy) will still be approximately halved.

Solar intensity. The sun is the primary energy source to heat a roof surface above the ambient air temperature. The amount of direct sunlight reaching the Earth's surface varies with time of year and with location and local weather peculiarities. In general, southern sites and mountainous regions receive more direct sunlight and, therefore, should have higher roof temperatures. In many instances, however, local high cloud cover or high humidity absorb solar radiation and significantly reduce the amount of sunlight reaching the

surface. For example, direct sunlight in February in New Orleans, Louisiana, on the Gulf of Mexico coast is about the same as it is in Laramie, Wyoming, in the Rocky Mountain area. In the summer, direct sunlight in New Orleans is actually about 30% less than in Laramie. This is due to the high water vapor content of the air along the coast compared with that in the clear mountain sky.

Environmental conditions (clouds, rain, wind). Since a roof generally has low mass and therefore cannot store much heat, events such as a quick shower, a cool wind, or even a large cloud can rapidly cool a hot roof. Exact calculations of the effects of these rapid changes on particular roofs are difficult to carry out because conditions are so irregular. For a roof with low solar absorptance, the difference between peak surface temperature and air temperature is smaller than it is for a highly absorbing roof. Therefore, the magnitude of rapid temperature changes caused by sky conditions will be less severe for it. The effect of wind on one particular idealized roof is shown in Fig. 3.4. The peak membrane temperature is predicted for a high-thermal-performance roof [(R-value of $2.8 \text{ (K} \cdot \text{m}^2\text{)W}^{-1}$ or $16 \text{ (}^\circ\text{F} \cdot \text{h} \cdot \text{ft}^2\text{)(Btu)}^{-1}$] with a membrane having high solar absorptance. According to the model, wind with a speed of 32 km/h (20 mph) can lower the peak temperature by more than 15°C (27°F) if it blows directly across the roof.

Roof surface color and texture. The color of a roof surface is the perception that results from reflection of solar radiation. A black color means that little solar radiation is reflected and much is absorbed. A white color means the opposite. Colors between black and white show a variation of solar absorptance from about 0.9 to 0.5. Dark surfaces have high solar absorptance (low reflectance) and light surfaces have low

Fig. 3.4. The effect of wind speed at the surface on maximum membrane surface temperature. The results were obtained from a mathematical simulation. Inputs included a maximum air-temperature of 29.5°C (5°F) and a peak solar intensity of 1 kW/m² [320 Btu(h · ft²)⁻¹].

solar absorptance (high reflectance). Because of the absorbed energy in the visible part of the spectrum, temperatures for a black roof membrane will be higher than for a white one throughout daytime (Fig. 3.5). Peak membrane temperatures as a function of solar absorptance are shown in Fig. 3.3. Texture also is significant in determining the solar reflectance of a surface. Generally, sunlight reflecting from a rough surface has a better chance of striking the surface a second time—and of being absorbed—than does sunlight from a smooth surface. Thus, other things being equal, a rough surface will have a higher solar absorptance and, therefore, will be warmer in sunlight than a smooth surface. Shiny metal roofs can have solar absorptances significantly below 0.5. Aging, either from chemical changes in the membrane or from dirt or contaminants in the air, usually tends to drive roof surfaces

toward the color gray. Thus, initially white roofs with low solar absorptance tend toward higher absorptances and higher temperatures, while initially black roofs with high solar absorptance tend toward a lower absorptance and lower temperatures.

Roof surface infrared emittance. A roof surface radiates infrared energy to the sky and the surroundings. During the day, the incident solar energy in the visible and infrared wavelengths more than makes up for this infrared radiation loss. Therefore, a roof is heated well above the ambient air temperature. During the evening, however, with no incident solar radiation, the loss of radiant energy to the sky can cool a roof below the ambient air temperature. As Fig. 3.5 also shows, evening roof surface temperatures more than 6°C (10°F) below air temperatures are common for well insulated roofs on clear, low-humidity nights. Thus, radiant cooling of a roof can increase the nighttime heat loss slightly.

Roof surface mass. Thermal mass added to the surface of a roof, such as paver blocks or gravel ballast, acts as a

Fig. 3.5. Measured membrane surface temperature for white or black roof membranes during a typical August week at about 40° north latitude in the United States.

thermal flywheel. It smooths out the roof temperature variations from day to night, resulting in lower peak temperatures than would be found with a bare roof. The peak membrane temperature is reduced slightly as the amount of surface mass increases (Fig. 3.6). Unlike increasing roof insulation, adding surface mass has approximately a linear effect on peak temperature.

3.2.3 Interior Moisture

Leaks in the exterior waterproofing are the major source of water in insulated roof systems. While migration of interior building water into (and from) insulated roofs occurs continuously, it is not usually as serious a threat to roof integrity (Tobiasson 1986) except for buildings with unusually high humidities and buildings with cold deck roof systems. For flat, warm deck roofs, both steady-state (Tobiasson 1984; Sheahan 1989) and transient (Pedersen 1990; Pedersen 1991) calculations show that moisture usually diffuses into the roof from below during cold weather (wetting season) and out of the roof during warm weather (drying season) (Fig. 3.7). Whether moisture accumulates in the roof depends upon the length of the wetting season compared with the drying season

Fig. 3.6. The effect on membrane surface temperature of mass, paving, or ballast added to a roof. The calculation pertains to a roof with $R = 2.8 \text{ (K·m}^2\text{) W}^{-1}$.

and upon the strengths of the relative driving forces. For sites with long drying seasons, protection against interior moisture (e.g., a vapor retarder) is most likely not needed. Generally, it is a good practice to examine whether a vapor retarder is needed in every roof design situation.

If a continuous vapor retarder is used, water trapped between two impermeable surfaces, the retarder and the membrane, will have no opportunity to escape. Roof vents, used to relieve high water vapor

Fig. 3.7. The effect of climate on moisture migration in a typical roof.

pressure during hot days, are not considered effective for removing water from roofs (Tobiasson 1983). A novel water-permeable vapor retarder has been developed to alleviate this problem. It allows a wet roof to dry downward, while still providing protection during the wetting season (Korsgaard 1985; Korsgaard 1992). The concept upon which the material is based is illustrated in Fig. 3.8. The product is a layered composite system consisting of a porous synthetic fabric with wide strips of impermeable plastic film alternating with narrow open areas on both sides. The plastic strips are staggered so that an open area on one side is always opposite a plastic strip on the other. Thus, diffusion of water

Fig. 3.8. The water-permeable vapor retarder (hygro diode), a novel concept for moisture management in roof systems.

across the system is kept small because the path length is relatively long compared with flow through the thickness of the fabric. Conversely, water in the roof interior condensing on an open area on the top side readily wicks along the synthetic fabric to the open area on the bottom side, where it evaporates to the room interior.

Problems with interior moisture can be more serious in cold deck systems. Moisture carried by air convection (and to a much lesser extent by diffusion) through the ceiling insulation may condense on the underside of the deck. It is usually wrong to assume that this problem can be entirely

prevented by a vapor retarder or by strong ventilation of the cavity between insulation and deck (Tobiasson 1986). First, it is difficult to achieve a continuous vapor retarder under ceiling insulation; and second, excessive ventilation actually promotes air leakage into the cavity. A practical solution is a combination of a carefully sealed vapor retarder and some cold-side ventilation. Alternately, it has been suggested that an overpressure be maintained in the cavity space by a mechanical venting system, that insulation be added over the deck to eliminate the possibility of condensation under the deck, or that a cold deck system not be used.

3.2.4 Drainage

Water penetration into a roof can cause serious damage. With no insulation, a leak usually shows itself quickly as water entering the interior space directly below the leak source. The effect of the leak is localized and the source of the leak easily pinpointed. With insulation, it is not likely that water will leak through to the interior until long after the leak occurs and after much of the insulation is wet and possibly permanently damaged. Because it is often impractical and expensive to provide frequent surveillance of roofs, it is good practice to design safeguards into them to minimize problems if they do occur. Good rooftop drainage is such a safeguard. If water drains quickly away from probable leak sites with minimal ponding, the volume of water that can enter the roof is minimized. Roofs that chronically pond water require perfection in design details and application quality. Ponding makes a roof much more sensitive to even small defects, such as building movement at flashings or puncture damage from rooftop traffic.

An Oak Ridge National Laboratory (ORNL) study of the effects of roof slope on performance for the U.S. Air Force provided the following important economic conclusions (Sharp 1988):

- Providing positive drainage by increasing roof slope on new buildings to the range of 1 : 48 to 1 : 24 (0.25 to 0.5 in. per ft) has little impact on initial cost and is usually effective on a life-cycle cost basis. (This is consistent with recommended slopes in the United States, at least 1 : 48, and in Scandinavia, from 1 : 40 to 1 : 20).
- Increasing the slope of entire BURs during replacement is more costly than replacement to the original slope and may not be cost effective on a life-cycle cost basis. However, most roof leak problems involve flashings, and provision for good drainage around flashings is beneficial.
- Conversion of smaller buildings from BUR to a watershed system (metal or shingle) can be competitive on an initial cost basis with BUR replacement when reroofing involves an upgrade in thermal performance. Low-density fibrous blanket underdeck insulation, which is suitable for watershed roofs, is much less expensive than the rigid board above-deck insulation that is required with BUR. This insulation cost advantage plus the savings from omitting old roof tear-off cost can offset the cost of adding a watershed roof structure and deck. Such conversion can be very attractive on a life-cycle cost basis, because watershed roofs have very low maintenance costs and long service life.

Good drainage can be achieved in several ways on both new and old roofs. The structural deck can be tapered when a roof is being built either by varying column height or, in the case of poured concrete, by varying the thickness of the pour. Alternate methods of positive drainage include the use of fill material, tapered insulation, or extra drains. Fill materials such as insulation boards, spray foam, or asphalt, can be used to elevate depressed areas on existing roofs so that positive drainage occurs. Regarding taper, the designer has the option of specifying full taper over the entire roof or taper only in limited critical areas. Full taper is a more positive solution to drainage problems, but it may require a significant increase in the height of roof perimeters and curbs and relocation of drains. Proper choice of drain size is also important. All these measures add to roof costs.

Ponding on existing roofs indicates the need to look for more serious building problems such as foundation settlement or permanent structural deflections. If the building structure is sound, adding more drains on existing roofs in areas that pond water may be the most economical way to overcome ponding. Most roof leaks occur at roof details and flashings. Therefore, at the minimum, a designer must prevent ponding in these critical areas. All roofs should have saddles for slope between valley drains, tapers into drain sumps, added roof thickness (crickets) in flat corners and along the high side of long curbs, and perimeter edge tapers for roofs with interior drains.

On large roofs, area dividers are sometimes used to divide the roof into smaller sections. This limits the spread of water damage in the event of leaks.

3.2.5 Fire Resistance

Roof insulation significantly increases the complexity of design to comply with building code and insurance requirements related to both exterior and interior fire sources. In the United States, for example, concern about added heat retention due to extra insulation causes major insurance companies to allow no more than 25 mm (1 in.) of new insulation during recovering. Insulation combustibility can also be an issue, but not all countries have uniform fire resistance requirements. Thermally efficient organic foam insulations became popular during the energy crisis of the mid-1970s but have flammability and membrane compatibility problems. Thus, other insulation types need to be placed under polystyrene and PIR foam insulations for bottom-side fire protection over steel decks as well as combustible decks. Top-side fire protection barriers (perlite, mineral wool, or wood fiberboard) are normally required over polystyrene and PUR foam insulations when they are used with unballasted elastoplastic single-ply membranes.

Top-side barriers are also needed to protect thermoplastic foam insulation (either extruded or expanded polystyrene) from melting when asphalt membranes are installed at temperatures above 230°C (450°F). These barriers also prevent dimensional distortion when sun-induced roof surface temperatures are as high as 65°C (150°F). Top-side barrier protection is commonly recommended over thermosetting foams (PUR, PIR, and phenolic) to prevent BUR blistering or fire hazards from torch-applied asphalt membranes.

3.2.6 Wind Resistance

Observations following recent hurricanes in the United States suggest that many roof systems may not fare well at wind speeds near design limits. Insulation is a factor in the high-wind performance of roofs because it is largely responsible for many of the attributes of modern roofs that make them more vulnerable to damage in high wind (Cook 1990). These include complex edge detailing and attachment issues. These issues are not easy to resolve because, although air flow around buildings is a fairly mature field of study, roof performance in high-wind conditions is not well understood and is hard to replicate in the laboratory (Peterka 1989; McDonald 1991).

Wind directed against roof elements exerts a force in the direction of the wind. This can launch loose roof elements or cause them to rotate about a fixed point. In high winds, loose gravel is an example of the former and bent-back fascia an example of the latter. In addition, wind blowing across a roof reduces the air pressure over the roof, and the resulting difference in pressure across the roof results in a second potentially damaging force that tends to lift the roof. Uplift effects are even more severe when wind breeches the building envelope and the interior air pressure increases, adding to the uplift force on the roof. This uplift force merits special attention because such failures are frequently catastrophic, although it is likely that wind forces on roof edges damage a greater number of roofs (Smith 1990a; O'Dea 1990).

Wind damage draws considerable attention, not because it is so common, but because it is usually so sudden and dramatic when it does occur (Smith 1990b; Massaut 1991). Also, high winds fre-

quently are accompanied by rain. When wind takes off even a small part of a roof, water enters the interior of the building and causes damage that can far exceed the cost of simply repairing the roof. The need to understand these complex effects is critical. Mathematical analysis of building performance in high winds is not readily tractable. Field experience is typically limited to after-storm observations because the relatively small spatial extent of storms and their unpredictability usually precludes placing instruments in their path. Extensive data obtained in boundary layer wind tunnels are available for some types of roof systems (Kind 1989; Peterka 1985), and work is under way to improve correlations to performance (Nimtz 1992; Levitan 1989). Given the lack of performance data and reliable modeling, it is not yet possible to devise general test procedures that are good predictors of roof performance in real storms (Alumbaugh 1989; McDonald 1991).

Fully adhered or monolithic roof systems tend to offer the most wind protection. However, some insulations—such as fibrous insulations with low perpendicular tensile strength when wet or insulation with factory-applied facers that are inadequately bonded—may delaminate when subjected to uplift, even when they are components of fully adhered systems. The use of air barriers, mechanical fasteners, and ballast provides protection for insulated roofs against wind uplift because they divert the upward forces from weak components with high uplift resistance during periods of high wind. Mechanical fasteners have become a common method of attachment for insulated roof systems over “nailable” decks (wood, steel, and lightweight concrete). They provide a positive and economical method of attachment and good wind protection. Mechanical fas-

teners are usually not used with structural concrete because hot asphalt performs very well and masonry fasteners are expensive and sometimes unreliable. For insulations with low compressibility, it is common to use two layers of insulation with the first mechanically anchored to the deck and the second affixed to the first with an adhesive. This keeps fasteners short and reduces the likelihood of lateral motion and fastener fatigue. In addition, it reduces the possibility of membrane puncture if foot traffic is a factor over the life of the roof. Moreover, short fasteners eliminate a significant source of thermal bridging.

Air barriers offer protection for membrane systems against uplift forces due to building interior air buildup. An air barrier diverts upward forces to structural elements. It need not be an added roof system component. A poured concrete deck is an excellent air barrier. Rock or paver ballast is used over loose-laid membrane roof systems. The weight of the ballast is determined by the design uplift pressure protection needed. Rock size is also important because of roof wind scour (Smith 1991). Industry publications and roofing texts provide detailed design information for ballastial and mechanically attached roofs (RMA 1988; Griffin 1982; Baker 1980).

3.3 APPLICATION ISSUES

Proper application of each component of the roof system is important for good thermal performance of the insulation and durability of the insulated roof system. Before the application of the roof system, the roofing contractor must inspect the deck to ensure that it is an acceptable substrate for the roofing. It must be structurally capable of supporting all expected live and dead loads during roof application and roof service. It must accommodate expected

movement of roof systems components. The deck surface should be clean, firm, smooth, visibly dry, and properly secured against movement.

Roof insulation and membrane materials used on a job should comply with design specifications, and all materials should be clean, visibly dry, and undamaged. Insulation types and application techniques must be compatible with the deck and membrane system employed so as to comply with building codes, fire and wind requirements, and performance limitations of the insulation or membrane. All materials must be stored on platforms raised off the ground or roof deck and covered with suitable waterproof covering to keep them dry and undamaged before application.

Experienced roof application crews are essential to achieve a high-thermal-performance roof with a long life. Good roofing practices should be followed, especially avoiding construction traffic over newly laid insulation. Roofing materials should not be installed if moisture, snow, or ice is present on the roof or if precipitation of any kind is expected before complete watertight application can be achieved. Water cutoffs should be applied at the end of each day's work to protect against moisture entry. Special precautions recommended by insulation and membrane manufacturers for cold weather application must be followed when ambient temperatures are below 4°C (40°F).

The heart of a high-thermal-performance roof is the insulation itself. Wet or warped insulation should be avoided. The joints of insulation boards should butt together, preferably with notched (rebated) edges to allow overlap. Gaps between insulation boards and broken corners that can cause thermal loss and increase the risk

of membrane puncture by roof traffic should be avoided. If possible, rigid board insulation should be installed in two layers, with all joints between the upper and lower layers offset. When two layers are installed, on nailable roof decks and steel roof decks, the first layer of insulation should be mechanically fastened to the deck. The upper layer should be attached to the first layer with hot asphalt or adhesive. If roof decks do not provide adequate slope for positive drainage, tapered insulation should be used to give adequate drainage.

For insulation to perform to its design specifications, it must remain in place without gaps appearing between individual pieces. Uniform mechanical or adhesive attachment of insulation to both the decking and the roof membrane is critical to prevent wind blow-off and to resist destructive pull at flashings due to cumulative thermal or moisture contraction. Adequate ballast or insulation attachment is needed with loose-laid roof systems to prevent insulation from shifting and stacking under a membrane because of wind uplift forces. Proper fastener spacing and flush application are important to avoid wind damage or membrane puncture by fasteners.

Recover reroofing without tear-off of the old roof requires individual assessment at the job site. A thin layer of new insulation provides stress divorcement for the reroofing membrane. If allowed by local insurance and other regulations, thicker insulation can be employed to improve the thermal performance of the roof. It is best to attach the new insulation mechanically through the old roofing into the decking to ensure adequate wind resistance.

Proper application of the membrane and flashings is essential for long-term per-

formance of the insulation. Membrane and flashing application should be completed on a daily basis to prevent water from entering the new insulation. Rooftop traffic by other construction crews after the roof is installed should be avoided; it is a major cause of roof punctures that lead to premature failure of the insulated roof system.

3.4 MAINTENANCE ISSUES

All roofs require periodic maintenance for long life. Roof maintenance is the responsibility of each building owner. Unfortunately, it is often overlooked or simply neglected. If problems are allowed to accumulate until they are intolerable, the consequence is very costly roof repair or total replacement well before the life expectancy of the roof.

Roof traffic is a maintenance issue. The most effective measure that prudent building owners can take to protect against damage from roof traffic is to provide defined and protected pathways for access. An alternative is to limit foot traffic on the roof by padlocking the roof hatch or allowing only authorized personnel on the roof. This alternative is often difficult to enforce.

A regular inspection and maintenance program carried out by the proper personnel is highly cost effective, especially on expensive, insulated roofs. The objective is to protect the investment and avoid interruption of internal functions in a building. A well executed maintenance program not only will add years to the life of a roof, but also will detect minor problems before damage is widespread and expensive to correct. Most roof leak sources involve flashing deterioration, puncture damage, or membrane lap defects and are initially limited to a small percentage of the total roof area. Thus, they are relatively inexpensive to repair if detected early.

A good roof maintenance program involves inspections twice yearly, preferably in the spring and fall when the roof is driest and most accessible. More frequent inspection may be cost effective if roof exhaust fans or rooftop equipment discharge debris or oil or other chemicals onto the roof. Special inspections are also needed when there has been construction activity on the roof and after severe hailstorms or windstorms. Regular roof inspections can be done by building maintenance personnel. Some roofing contractors offer the service under a long-term maintenance contract. Any inspection program should include a thorough historical file with detailed roof layout drawings; photographs; and records of inspections, leaks, repairs, and rooftop construction alterations.

Trained roof inspectors can spot most problems visually. Particular attention should be given to flashings around the roof edge and to penetrations, where the most roof leaks occur. On a regular basis, and especially before a roof survey, maintenance personnel should clean all roof drains and remove all debris from a roof. Roof debris often contributes to roof punctures and can be swept into drains by heavy rains and cause serious ponding problems. All roof defects should be marked with bright crayon or spray paint for easy location by repair personnel. Systematic roof survey procedures have been published by the U.S. Army Corps of Engineers and by the Roofing Industry Educational Institute.

When all trouble spots have been located, corrective repairs should be made promptly, using repair materials that are compatible with the particular roof membrane. Some problems present an immediate threat to roof integrity and necessitate emergency measures. Emergency patches can be used to stop further water entry to

avoid prolonged roof leakage that can result in expensive roof system and structural damage. Temporary patches are not sufficient, however. It is necessary to determine the cause of the emergency and the extent of the damage. After doing so, a building owner may call in a consultant or skilled roofing contractor, who may use nondestructive roof survey techniques to determine what permanent repairs are required. All wet insulation should be removed and replaced when permanent repairs are made so that the quality of the repaired roof area will be the same as that of the rest of the roof. Major progressive damage to roofs can occur when significant amounts of wet insulation are not replaced.

Sources of information on good roof inspection and maintenance procedures are listed in Table 3.6.

3.5 REFERENCES

Alumbaugh 1989

Alumbaugh, R. L., "Research Needs: Wind Resistance Testing of Roofing Systems," pp. 121-29 in *Proceedings of the Roof Wind Uplift Testing Workshop*, ORNL CONF-891173, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

ASHRAE 1989

1989 *ASHRAE Handbook: Fundamentals*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, USA.

Baker 1980

Baker, M. C., *Roofs*, Multiscience Publications Limited, Montreal, Canada, pp. 68-78.

Table 3.6. Sources of information on good practices for roof inspection and maintenance procedures (references in Table 3.1 also contain inspection and maintenance practices)

<i>Roof Maintenance Manual</i> published in 1988 by the Roofing Industry Educational Institute
U.S. Army Corps of Engineers CERL Technical Report M-87/13, Vol. II, for built-up roofs published in September 1987.
<i>Manual of Roof Maintenance and Repair for Built-up Roofs</i> published by NRCA ^a and ARMA ^b and revised in 1988.
NRCA/SPRI ^c <i>Manual of Roof Inspection, Maintenance, and Emergency Repair for Existing Single-Ply Roof Systems</i> , published in September 1992.
NRCA/SPRI manual for single-ply elastoplastic membrane repairs, generic repair procedures, written for needs of contractors making major repairs. Due in late 1993.
Tagdaekning, <i>Renovering og vedligeholdelse</i> , (Roofing, Renovation and Maintenance), TOR Anvisning 16, Tagpapbranchens Oplysningsrad, 1990 (in Danish).
<i>Moisture and Fungus, An Advice Collection for Roof Renovation and Maintenance</i> , SABO, Swedish Council of Building Research, and Swedish Building Center, Stockholm (in Swedish).

^aNRCA = National Roofing Contractors Association

^bARMA =

^cSPRI = Society for the Polyisocyanurate Roofing Institute.

- Cook 1990
Cook, R. L., "Hugo Lessons Learned: Roofing Systems and the Navy," Federal Construction Council Report 108, National Research Council, Washington, D.C., USA, pp. 40-52.
- DOE 1989
DOE-2 Reference Manual Version 2.1H and DOE-2 Supplement Version 2.1D, LBL-8706, rev. 2, and LBL-8706 Supp. 5, rev. 5, Lawrence Berkeley Laboratory, Berkeley, Calif., USA.
- Griffin 1982
Griffin, C. W., *Manual of Built-Up Roof Systems*, McGraw-Hill, New York, USA., pp. 353-80.
- Griggs 1989
Griggs, E. I., Sharp, T. R., and MacDonald, J. M., *Guide for Estimating Differences in Building Heating and Cooling Energy Due to Changes in Solar Reflectance of a Low Slope Roof*, ORNL-6527, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
- Kind 1989
Kind, R. J., Wardlaw, R. L., and Savage, M. C., "Wind Effects on Cladding Systems," in *Proc. of the ASCE 1989 Structure Congress*, American Society of Civil Engineers, New York, USA, September 1989.
- Korsgaard 1985
Korsgaard, V., "HygroDiode Membrane: A New Vapor Retarder," pp. 985-91, in *Proceedings, Thermal Performance of the Exterior Envelope of Buildings, III*, December 2-5, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.
- Korsgaard 1992
Korsgaard, V. and Pedersen, C. Rode, "Laboratory and Practical Experience with a Novel Water-Permeable Vapor Retarder," in *Proceedings, Thermal Performance of the Exterior Envelope of Buildings, V*.
- Levitan 1989
Levitan, M. L., Holmes, J. D., Mehta, K. C., and Vann, W. P., "Field Measured Pressures on the Texas Tech Building," in *Proceedings of the 8th Colloquium on Industrial Aerodynamics*, Aachen, West Germany, September 4-7, 1989.
- Massaut 1991
Massaut, B., "European Roofers' Experience After the 100mph Winds of January and February 1990," pp. 476-79 in *Proceedings of the Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.
- McDonald 1991
McDonald, J. R., "Full-Scale Testing of Roofing Performance," *Int'l J. of Roofing Technology*, 3, 299-302.
- Nimtzt 1992
Nimtzt, P. D., "Wind Loads," pp. 86-92 in *The Construction Specifier*, November 1992.
- NSB (National Swedish Board) 1989
Thermal Insulation, Report 1:1, The National Swedish Board of Physical Planning and Building, Stockholm (in Swedish).
- O'Dea 1990
O'Dea, T., "Contractors Speak Out on Wind Uplift," *RSI Magazine*, October 1990, pp. 34-40.
- Pedersen 1990
Pedersen, C. Rode, *Combined Heat and Moisture Transfer in Building Constructions*, Thermal Insulation Laboratory Report 214 (Ph.D. thesis), Technical University of Denmark, Lyngby, Denmark.
- Pedersen 1991
Pedersen, C. Rode, and Courville, G. E. "A Computer Analysis of the

- Annual Thermal Performance of a Roof System With Slightly Wet Fibrous Glass Insulation Under Transient Conditions," *Journal of Thermal Insulation* 15, 110-36 (October 1991).
- Peterka 1985
Peterka, J. A., Meroney, R. N., and Kothari, K. M., "Wind Flow Patterns About Buildings," *J. Wind Engineering and Industrial Aerodynamics* 21, 162-71.
- Peterka 1989
Peterka, J., "Roof Uplift Mechanisms," pp. 61-6 in *Proceedings of the Roof Wind Uplift Testing Workshop*, ORNL CONF-891173, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
- Petersson 1981
Petersson, B.-Å., 1981, "Moisture Mechanics and Thermal Insulation Properties of Expanded Plastics Used as Thermal Insulation in Upside-Down Roofs," *Proceedings of Plastics in Material and Structural Engineering*, ICP/RILEM/IBK International Symposium, 23-24 June 1981, Prague, Czechoslovakia.
- Petersson 1990
Petersson, B.-Å., *Thermal Insulation of the Upside-Down Roofs Corresponding to the New Swedish Code PBL and NR*, Bygg & Teknik Report 2, Stockholm, Sweden (in Swedish).
- Petersson 1992
Petersson, B.-Å., "Protected Membrane Roof and Duo-Roof and their Thermal Insulation Systems," *Journal of Thermal Insulation* (to be published).
- RMA 1988
"Wind Design Guide for Ballasted Single-Ply Roofing Systems," Rubber Manufacturers Association, Washington, D.C., USA.
- Sharp 1988
Sharp, T. R., Wendt, R. L. and McCorkle, J. E., *Decision Guide for Roof Slope Selection*, ORNL-6520, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
- Sheahan 1989
Sheahan, J. P., "Method for Determining Suitability of Roofing over Roof Assemblies in Need of Repair," pp. 172-83 in *Proceedings of Thermal Performance of the Exterior of Buildings IV*, December 4-7, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.
- Smith 1990a
Smith, T. L., "Hurricane Hugo's Effects on Metal Edge Flashings," *Int'l J. of Roofing Technology* 2, 65-70.
- Smith 1990b
Smith, T. L. and McDonald, J. R., "Roof Wind Damage Mitigation: Lessons from Hugo," *Professional Roofer* 20, 30 (November 1990).
- Smith 1991
Smith, T. L., "Wind Design for Ballasted Systems," *Professional Roofer*, 70 (October 1991).
- Tobiasson 1983
Tobiasson, W., Korhonen, C., Coutermarsh, B. and Greatorex, A., "Can Wet Roof Insulation Be Dried Out?," pp. 626-39 in *Thermal Insulation, Materials and Systems for Energy Conservation in the 80s*, American Society for Testing and Materials STP 789, Philadelphia, Pa., USA.
- Tobiasson 1984
Tobiasson, W., "Condensation Control in Low-Slope Roofs," pp. 47-59 in *Proceedings of the Moisture Control in Buildings Workshop*, 1984, Building Thermal Envelope Coordinating

Council, Washington, D.C., USA, September 25-26.

Tobiasson 1986

Tobiasson, W., "Vents and Vapor Retarding for Roofs," in *Proceedings, Symposium on Air Infiltration, Ventilation, and Moisture Transfer*, Building Thermal Envelope Coordinating Council, Washington, D.C., USA, December 2-4.

Walukas 1985

Walukas, D. J. and Courville, G. E., *Decision Guide for Roof Insulation R-*

Value, ORNL-6172, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Wilkes 1992

Wilkes, K. E., "Thermal Performance of Fiberglass and Cellulose Attic Insulations," pp. 357-67 in *Proceedings of Thermal Performance of Exterior Envelopes of Building V*, December 7-10, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

4

INSULATION-RELATED ROOF PROBLEMS

4.1 INTRODUCTION

The data base on insulations, coverings, and roof systems in Sect. 2, as well as the good practices for insulated roofs in Sect. 3, have touched on various problems associated with high-thermal-performance roofs. The purpose of Sect. 4 is to deal with each problem in detail before discussing examples of each roof system in Sect. 5. Section 4 states each problem, descriptions of evidence for its existence, and models that address it. Then the problem is analyzed to put its significance into perspective and to describe remedies that are available for it and secondary effects of those remedies. The analysis includes a list of research needs to address unsolved aspects of each problem.

The problems are presented in four areas: mechanical problems, physical and chemical degradation, shortfalls from design thermal performance, and moisture intrusion and effects of retention. There is considerable overlap among the problem areas. For example, membrane splitting, a mechanical failure, leads to moisture intrusion, which in turn can cause corrosion of

metals and deterioration of insulation in the roof system. Problems are assigned to a specific area primarily because they have similar research needs.

4.2 MECHANICAL PROBLEMS

4.2.1 Membrane Splitting Over Insulation

4.2.1.1 Statement of the problem

Membrane splitting is a localized, often sudden, rupture of a roofing membrane that develops when induced stress causes the differential strain to exceed the limits of the membrane material in place on its substrate. Insulation contributes to membrane splitting because it isolates the membrane both thermally and mechanically from the structural substrate (Gumpertz 1979). Thermal isolation exposes membranes to greater temperature fluctuations that increase induced stresses from thermal contraction and expansion (Rossiter 1967). Mechanical isolation increases the risk of localized stress concentrations in the membrane due to

nonuniform attachment of insulation to either the membrane or structural substrate or due to discontinuities at insulation board joints.

4.2.1.2 Evidence

General descriptive material. Membrane splitting near details of BUR has been a recognized problem for years (Baker 1980; Griffin 1982). It is caused by differential membrane-substrate movement. For example, sheet metal gravel stops have high thermal expansion coefficients and are not always adequately nailed. These characteristics cause splitting throughout the built-up stripping plies that are attached to the stops, which sometimes propagates out onto the field of the membrane.

BUR has very little capability to tolerate elongation. Any significant substrate movement must be accommodated to avoid splitting. If the BUR is solidly mopped to wood decking, it is prone to split as the wood deck dries and shrinks. A nailed base sheet is required to avoid absorption of this deck movement in the narrow band of membrane directly over the wood joint. It is surprising, indeed, that it took several decades of laboratory and field experience to learn that, to minimize splitting, BUR must be installed with a mechanically attached base sheet over any nailable deck, which includes wood, metal, and lightweight concrete.

BUR-membrane splitting in the field of a roof was not a common problem until metal decking gained widespread use after World War II. A thin layer of insulation was required on the steel deck as a leveling course before application of the membrane, and it had to be attached securely to the deck. Splitting problems increased in the United States when Factory Mutual Research Corporation (FM), acting for U.S.

fire insurance corporations, limited the amount of asphalt that could be used to attach insulation to steel decks. The reduced amount of asphalt caused insulation to be inadequately attached to the deck, especially during cold weather roof applications. The accumulated effect of thermal contraction over a relatively large area of unrestrained BUR could not be accommodated without splitting. Wind blow-off problems also increased markedly when the amount of asphalt that could be used to attach roof insulation to steel decking was restricted.

Extensive research, including work by Cullen (1965) and Jones (1967), began in the mid-1960s to solve the splitting problem. At that time, BUR was essentially the only system in use. The principal insulations used then were wood fiberboard, perlite and mineral wool. Perlite and mineral wool were more fire resistant than fiberboard, but their inferior interlaminar strength and the greater compressibility of mineral wool insulation may have increased splitting problems. In the late 1960s and early 1970s, many BURs in Europe used polystyrene foam insulation and also had splitting problems (Carver 1977).

Elastoplastic membrane splitting problems have occurred primarily with unreinforced PVC manufactured during the 1970s. Reinforced PVCs have not experienced those problems. The problems with the early unreinforced PVCs were associated primarily with aging and plasticizer loss (Dupuis 1986). Insulation contributed to the problem because it increased roof temperatures and caused more rapid plasticizer loss. Attachment quality within the roof system was not a factor, because most of these roofs were installed using the loose-laid, ballasted method.

Membrane splitting has also been encountered with spray-on plastic foam insulation that has spray-on polymeric membrane coatings (Jenkins 1985). This occurrence is sometimes called "coating cracking." The qualities of both the insulation and the membrane contribute to this splitting problem. Jenkins noted that membrane coatings with less than a 100% elongation capability cannot accommodate the thermal expansion and contraction of the insulation substrate. It is also recognized that moisture entry through pinholes or punctures in the coating membrane can cause excessive swelling of the insulation that results in major loss of membrane integrity and extensive roof failure.

Field evidence. Field studies of insulated BUR systems applied over steel decks during cold weather showed that the rapid cooling of hot asphalt on cold steel decking made it impractical to consistently obtain adequate adhesion of the roof insulation (Dupuis 1977a; Dupuis 1977b). Analysis of Project Pinpoint, a data base of contractors' experience maintained by the U.S. (NRCA undated), showed that membrane strength and insulation anchorage techniques greatly affect the incidence of BUR-membrane splitting (McCorkle 1981). The Project Pinpoint data, which include roofs installed in all weather conditions and geographical regions, show that the frequency of membrane splits was 2.8 times greater with 3-ply BURs than with 4-ply BURs. Adequate insulation attachment was shown to be at least as important as membrane strength. Membrane splitting occurred 3.3 times more frequently when insulation was attached with hot asphalt rather than mechanical fasteners. From its tracking of insurance losses due to high wind blow-off, FM recognized the value of mechanically fastening the insulation to steel decking. To mitigate wind loss

damage, FM initially required that mechanical fasteners be used for insulation attachment around roof perimeters. With steel decking, FM ultimately required mechanical fastening of insulation over the entire roof area.

The Project Pinpoint analysis also showed that BUR-membrane splitting depends greatly on deck type, length of span between steel deck bar joist supports, and the grade (ductility) of the asphalt in the roofing membrane. Splitting occurred 3 to 3.5 times more often over metal decks than over wood decks, which have always relied on mechanical attachment. The frequency of splits over steel decks increased almost four-fold when the span between deck supports exceeded 1.8 m (6 ft).

Field studies of PVC roofing by Rosenfield (1981) confirmed the existence of splitting problems with unreinforced PVC membranes. He concluded that the two most serious PVC membrane problems are excessive shrinkage and embrittlement. The latter occurs because of loss of plasticizer or exposure of the membrane to ultraviolet rays. These problems have been resolved by using reinforced PVC membranes and by using more stable plasticizers. Insulation compatibility is a related problem that requires the use of approved separator sheets between PVC membranes and polystyrene foam insulations or between PVC and any bituminous surface.

Laboratory evidence. Laboratory work at the U.S. National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), during the past 25 years was undertaken to establish minimum performance criteria for bituminous membranes (Cullen 1967; Mathey 1974). The goal was to identify a property that correlates with adequate resistance to splitting. Early work by Cullen characterized this prop-

erty as "thermal shock resistance." In 1974, a criterion requiring a minimum tensile strength of 1380 kPa (200 lb/in.²) at -18°C (0°F) was recommended and widely accepted in the roofing industry. About this time, restrictions on organic discharges from paper mills and health concerns about asbestos caused fiberglass reinforcements to largely replace organic materials and asbestos in BUR. When glass-reinforced BUR was designed to comply with the new -18°C (0°F) tensile strength criterion, it provided excellent roof performance.

Subsequently, some polyester fiber-reinforced membranes and polymer-modified asphaltic membranes performed well both in Europe and the United States even though they did not meet the 1974 tensile strength criterion. Their good performance was related to superior elongation properties. Alternate criteria based on strain energy and watertightness were recommended in 1986 by NIST (Rossiter 1986; Rossiter 1987).

The effect of increased amounts of insulation on surface roof temperatures was investigated and found to be minimal (Richards 1977). Therefore, the thermal isolation of membranes by insulation is not regarded as a significant contributor to membrane splitting. Field studies showed, however, as documented above, that mechanical isolation effects caused by insulation are a major contributor to membrane splitting.

Modeling. Bonafont (1985) and Chaize (1988) modeled bituminous membranes. Mathematical modeling of roof systems is very complex because roofing components have widely varying viscoelastic properties.

4.2.1.3 Analysis

Significance of problem. The stress-strain mechanisms that cause membrane splitting are well understood for conventional insulated roof systems. Criteria for satisfactory membrane quality and worker-friendly component attachment or application procedures have been established to prevent most splitting problems with conventional roof systems. The severity of splitting problems with BUR in the 1960s and 1970s led to many lawsuits against roofing manufacturers and roofing contractors. The current fiberglass-reinforced BUR and modified asphalt roofing products have encountered relatively few splitting problems when they are installed in accordance with NRCA recommendations. In contrast to the 1960s and 1970s, technical papers on splitting presented in the trade literature and roofing symposiums are now relatively few.

Available remedies. Splitting problems with bituminous roof systems have been substantially eliminated by compliance with the minimum performance criteria in the following documents:

Roofing material performance criteria

- NBS Building Science Series 55 membrane tensile strength recommendation (1974) and
- NBS NBSIR 86-3418 strain energy and waterproofness recommendations (1986).

Roof component attachment criteria

- FM loss prevention data sheet I-28 (requiring mechanical attachment of roof systems over steel decks) and
- FM loss prevention data sheet I-52 (prescribing a field test procedure for

wind uplift useful with both new roof construction and reroofing).

Successful field experience is the ultimate proof that corrective remedies are adequate. All segments of the roofing industry now regard splitting problems with fiberglass-reinforced BUR as minimal. The strong reinforcements and good strain energy properties of modified asphalt membranes have also provided excellent field performance in high-thermal-performance roofs. In fact, modified asphalt products are regarded as superior flashing and repair materials even on older BUR.

Splitting of unreinforced PVC membranes has largely been overcome by using more durable plasticizers and by adding membrane reinforcement. Splitting of spray-applied polymeric membrane coatings can be significantly reduced by using formulations that are more durable and that allow higher elongation.

Secondary impacts of remedies. Compliance with recommended performance criteria has not caused any new roofing problems or economic handicaps for insulated bituminous membrane roofing. Fiberglass BUR is maintaining its share of the roofing market. The field-proven performance of modified asphalt membranes for both new roofs and recover reroofing in Europe and the United States has caused them to capture a sizeable and rapidly growing share of the roofing market.

4.2.2 Flashing Pull-Away and Membrane Splitting Around Fasteners

4.2.2.1 Statement of the problem

Problems with flashing pull-away and membrane splitting around fasteners are encountered in areas of highly localized stressing of the roof membrane. The stress

may be caused either by lack of dimensional stability in the membrane or the roofing felt or by insufficient compression strength in the insulation material. The importance of the latter has increased with the increase in the thickness of insulation and the resulting use of long mechanical fasteners.

4.2.2.2 Evidence

General descriptive material. Problems due to lack of dimensional stability are caused by the same mechanisms as membrane splitting over insulation; therefore, refer to Sect. 4.2.1 for discussion of these problems. Compression of insulation materials did not cause serious problems when insulation thicknesses were rather modest. However, the concern for energy conservation has led to use of far thicker insulation layers. A thickness of 20 cm (8 in.) for low-slope roof insulation is not uncommon in Denmark, for example.

Some serious problems have been observed in cases where the insulation is compressible (e.g., mineral wool) and where the thickness is such that deformation from foot traffic exceeds 15 to 20 mm (0.6 to 0.8 in.). The need for long fasteners for thicker insulation increases the risk of localized stressing and splitting. Roof traffic causes insulation compression that presses fastener heads against the membrane and leads to underside membrane puncture. Traffic loads also can bend fastener plates and cause membrane tearing. Long fasteners are subjected to more rotational movement, which can strip the small length of thread that engages the metal deck. The resulting loose fastener can contribute to wind damage or increased localized lateral thermal movement that produces membrane splitting. However, it has not been possible to find any references

in the literature dealing with the investigation of such problems.

Field evidence. Field studies of roofs with insulation as the substrate for the membrane are reported in only a few cases. These studies reported failures due to shrinkage or thermal movement of the substrate. A study performed by the Norwegian Building Research Institute is the only one to mention a problem with compressibility in connection with the use of mechanical fasteners. Although no failures were observed, stressing of the roofing membrane around the fasteners was reported when people were walking on the roof.

Laboratory evidence. Compressibility of insulation materials has been a subject for investigation (and approval) of the European Union of Agrément (UEAtc) for at least a decade. Testing is done under the combined exposure to a distributed static load and to increased temperature. The product is classified according to the test results. Different classifications allow the insulation to be recommended for different areas of use. In addition, UEAtc offers another compression test that classifies insulation according to relative deformation. The results of this test are given as the residual deformation of the insulation material, but no requirements have been formulated. The Danish Roofing Felt Manufacturers Association also has been using this test and has suggested that the compression should exceed neither 4% nor 12 mm (0.47 in.).

Modeling. No modeling efforts have been reported.

4.2.2.3 Analysis

Significance of problem. In Europe, the problem of membrane splitting around fasteners does not appear to be severe. Most manufacturers are aware of it and

have modified their products so that they function properly with increased thicknesses of insulations. Also, the widespread use of telescopic fasteners for soft mineral wool has eliminated some of the problems. In the United States, locking plate fasteners have been introduced to reduce the problem with thick, soft insulation.

Available remedies. Guidance concerning dimensional stability of insulation materials and roofing membranes is available from the UEAtc guidelines mentioned earlier and from other guidelines for roofing materials. Use of information from the test methods and classification criteria is expected to virtually eliminate compression problems. In practice, problems may be avoided to a large extent by designing around them. For example, triangular clips or telescopic fasteners used around perimeters allow free movement of the roofing membrane.

4.2.3 Research Needs

Design and construction of a durable, high-thermal-performance roof is an art. Much research remains to be done before the appropriate mechanical properties of the component materials can be identified, measured and used in a model of the roof system that yields a predictable design life before failure due to leaks or deterioration. The complexity of the stress field near flashings, fasteners, and other attachments to the roof support structure makes modeling very difficult, although finite element methods combined with large-storage-capacity, high-speed computers have made it possible to attack the problem. Validation of the models is difficult, too, because field measurement of mechanical properties suffers from lack of instrumentation to record the in-situ behavior of mechanical properties of roof systems.

In terms of overall performance of roof systems, research on mechanical properties is very important. Mechanical failure is less forgiving than, for example, a drop-off in thermal performance due to thermal bridges. One leak is enough to compromise the performance of a large area of the roof. A single thermal bridge is not likely to make a significant difference in total insulation value. In designing to avoid even one leak, overuse of material in noncritical areas is inefficient but unavoidable until the system and its properties are understood well enough to relate failure to material properties. Empirical relationships between roof characteristics and life before failure are a start toward optimum use of materials.

4.2.4 References

Baker 1980

Baker, M., *Roofs: Design, Application and Maintenance*, Multi-Science Publication, Ltd., Montreal, Quebec, Canada, 1980, p. 51.

Bonafont 1985

Bonafont, R. L., "Review of Advances in Mathematical Models for Structural Behavior of Bituminous and Similar Membrane Systems," pp. 49-53 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, Ill., USA.

Carver 1977

Carver, J. R., "Some Observations on the Behavior of Built-up Roofing Membranes over Expanded Polystyrene in the U.K.," pp. 179-86 in *Proceedings, Symposium on Roofing Technology*, National Roofing Contractors Association, September 21-23, 1977, Oak Park, Ill., USA.

Chaize 1988

Chaize, A. and Fabvier, B., "Mechanical Behavior of a Roofing Membrane on an Insulation Substrate," pp. 29-40 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, ORNL CONF-890976, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Cullen 1965

Cullen, W. C., *Effects of Thermal Shrinkage on Built-up Roofing*, National Bureau of Standards Monograph 89, Washington, D.C., USA.

Cullen 1967

Cullen, W. C. and Boone, R. B., "Thermal-Shock Resistance for Built-up Membrane," *National Bureau of Standards Science Series 9*, Washington, D.C., USA.

Dupuis 1977a

Dupuis, R. M., Lee, J. W., and Johnson, J. E., "Field Measurement of Asphalt Temperature During Cold Weather Construction of BUR Systems," pp. 272-82 in *Proceedings, Symposium on Roofing Technology*, National Roofing Contractors Association, September 21-23, 1977, Rosemont, Ill., USA.

Dupuis 1977b

Dupuis, R. M., et al., "Experimental Determination of Temperature Induced Loads in BUR Systems," pp. 52-9 in *Proceedings, Symposium on Roofing Technology*, National Roofing Contractors Association, September 21-23, 1977, Rosemont, Ill., USA.

Dupuis 1986

Dupuis, R. M., "The Outlook for Polyvinyl Chloride Membranes," pp. 16-20 in *1986 Handbook of Commercial Roof Systems*, National Roofing Contractors Association, Chicago, Ill., USA.

Griffin 1982

Griffin, C. W., *Manual of Built-Up Roof Systems*, 2nd Ed., McGraw-Hill, New York, USA.

Gumpertz 1979

Gumpertz, W. H., "Performance Considerations for Thermally Efficient Roof Systems," pp. 47-51 in *Proceedings, Fifth Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, Ill., USA.

Jenkins 1985

Jenkins, A. L., "A Study of Some Structural Interrelationships Between Polyurethane Foam and Protective Coatings," pp. 98-105 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, USA.

Jones 1967

Jones, W., "Load-Strain Properties and Splitting of Roof Membranes," in *Engineering Properties of Roof Systems*, American Society for Testing and Materials STP 409, Philadelphia, USA.

Mathey 1974

Mathey, R. G. and Cullen, W. C., "Preliminary Performance Criteria for Bituminous Membrane Roofing," in *National Bureau of Standards Building Science Series 55*, Washington, D.C., USA.

McCorkle 1981

McCorkle, J. E., Dupuis, R. M., and LaCosse, R. A., "Membrane Integrity Depends on Characteristics of Entire Roof Assembly," pp. 34-41, *Proceedings, Sixth Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, Ill., USA.

NRCA undated

NRCA Project Pinpoint, a continuing field survey by the National Roofing Contractors Association, Rosemont, Ill., USA.

Richards 1977

Richards, D. E. and Mirra, E. J., "Does More Roof Insulation Cause Premature Roofing Membrane Failure or Are Roofing Membranes Adequate?" pp. 193-199 in *Proceedings, Symposium on Roofing Technology*, National Roofing Contractors Association, September 21-23, 1977, Oak Park, Ill., USA.

Rosenfield 1981

Rosenfield, M., *An Evaluation of Polyvinyl Chloride (PVC) Single-Ply Membrane Roof Systems*, U.S. Army Corps of Engineers Construction Engineering Research Laboratory Technical Report M-284, Champaign, Ill., USA.

Rossiter 1967

Rossiter, W. J., Jr., and Mathey, R., *Effect of Insulation on the Surface Temperature of Roof Membranes*, National Bureau of Standards NBS TR 76-987, Washington, D.C., USA.

Rossiter 1986

Rossiter, W. J., Jr., and Bentz, D. P., *Strain Energy of Bituminous Built-up Membranes: An Alternative to the Tensile Strength Criterion*, National Bureau of Standards NBSIR 86-3418, Washington, D.C., USA.

Rossiter 1987

Rossiter, W. J., Jr., and Bentz, D. P., "Strain Energy of Bituminous Built-up Membranes: A New Concept in Load-Elongation Testing," pp. 40-49 in *Proceedings, 8th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.

4.3 PHYSICAL AND CHEMICAL DEGRADATION

4.3.1 Corrosion of Metal in Roofing Systems

4.3.1.1 Statement of the Problem

Corrosion of metal in roof systems refers mostly to the deterioration of metal decks or fastener systems. Corrosion weakens the roof structure, increasing the risk of structural failure and making it easier for wind damage to occur. Most evidence indicates that the dominant factor in corrosion is the long-time presence of water. The increased likelihood of water retention in an insulated roof coupled with the potential presence of corrosive ingredients in the insulations increases the possibility that metal components will corrode in high-thermal-performance roof systems.

4.3.1.2 Evidence

General descriptive material. The most common metals in roofs are coated carbon steel and stainless steel. Coatings range from sacrificial metals (like zinc plating) to barrier coatings (like polymers) to combination coatings (like polymers outside with a ceramic base). In nearly all instances, these surfaces can be in contact with insulation. Insulation may contribute to corrosion by holding water that has leaked or construction water near metal components, by contributing corrosive leachants, and by providing a warm environment for the water-metal system.

Field evidence. Little systematic evidence exists to document field experiences on the characteristics of corrosion and the magnitude of the problems it causes in roofing systems. Many observations of corrosion have been reported, but these

observations generally do not contain enough quantitative evidence to pinpoint the type of corrosion and its cause.

In a recent review of warm deck systems that focused on metallic fasteners, Rossiter (1989) conducted a literature search on corrosion of fasteners. Only one technical report was found on the topic. In it, Paulsen (1987) reports that 48 mechanically attached roofs throughout Norway were opened and fasteners in 25 showed evidence of corrosion. The roofs had either EPS or mineral wool insulation. Paulsen notes that in 15 of the 25 roofs where fastener corrosion was observed, the insulation appeared to be dry. However, the report does not discuss the possibility that the insulation may have contained moisture at other times. The report by Rossiter also summarizes several articles written for trade publications. Although many of them express concern over corrosion, particularly in reroofing situations where new roofs are mechanically fastened to existing roofs, there are few substantive data to support the concerns.

More evidence is available on corrosion of metals in insulated cold deck systems and in attic systems. During the 1970s in Scotland, there was a rash of roof failures due to condensation in flat cold decks under pitched roofs. These systems had significant amounts of insulation but little ventilation. Heavy corrosion of metal fixings was noted in several instances. Subsequent attempts to ensure adequate ventilation for insulated cold deck flat roofs proved so difficult that these systems are no longer recommended in Scotland (Beech 1987).

An insulation-related corrosion problem arises in upgraded historic buildings with lead-clad warm deck roofing systems (Falconer 1987). Moisture is drawn through the laps between the cladding into

the small voids between the cladding and the insulation. It condenses as distilled water on the underside of the lead. The driving forces for this pumping action are the diurnal changes in the weather. The lead sheeting is aggressively attacked by the distilled water and roof failure occurs within a few years. By contrast, lead roofs on unimproved buildings survive indefinitely.

Field and laboratory studies of corrosion under insulation are more frequently done in industrial applications. For example, Richardson (1983) presented abstracts from a Conference on Corrosion Under Lagging held in Newcastle-on-Tyne, England, in November 1980. Several case histories showed data on the corrosivity of wet insulation and described corrosion prevention techniques, such as the addition of inhibitors to insulations and the coating of metals. Pollock (1983) collected papers, including Richardson's, dealing with issues such as corrosion mechanisms, field experience, control measures and test methods. Generally, these industrial applications involve loss of production. Thus, analysis and trouble shooting is much more cost effective for corrosion under insulation in industrial situations than it is for corrosion in roofing systems. Lazar (1983) defines three factors that influence the amount of corrosion in metal systems: the duration and frequency of wet periods, the corrosivity of the aqueous solution created from wet insulations, and the failure of protective barriers on metal components. These same factors presumably apply to metal corrosion in roofing systems, also.

Laboratory evidence. Limited laboratory data are available on the corrosiveness of building insulations. Sheppard (1983) visually monitored corrosion of steel and copper tabs placed in loose-fill fiberglass,

rockwool, and cellulosic insulations. Delahunt has measured the pH and corrosiveness of aqueous extracts from various insulations (Richardson 1983). More recently, Subcommittee C-16.31 of the ASTM, in an effort to demonstrate the corrosiveness of insulations, is sponsoring a round robin to determine the feasibility and consistency of electrochemical measurements on slurries made from cellulosic insulations. If the conclusion from the work is that it is feasible to characterize the corrosiveness of cellulose in this way, then it is likely that the technique will be extended to other building insulations.

There is also a risk that certain timber-preserving chemicals or flame-retardant treatments will cause increased corrosion of metal fixings in wood assemblies. Research in the United Kingdom has indicated that this risk increases if the timbers are damp for long periods. The threshold value for moisture content of the timber is about 20%; below this level, no appreciable amount of corrosion occurs. That is about the same as the limit for the growth of wood-rotting fungi in untreated wood (Cox 1983; Cox 1984; Cross 1988).

Modeling. No mathematical modeling work related to corrosion of metals in roofing systems has been reported.

4.3.1.3 Analysis

Significance of the problem. The evidence available qualitatively supports the hypothesis that corrosion of metal in roofing systems is aggravated by the presence of insulation. However, the evidence is inadequate to characterize the severity of the problem. The cost of all types of metal corrosion in 1986 for the United States alone was estimated to be close to \$180 billion (Szeliga 1988). Corrosion in roofing systems probably accounts for only a small fraction of this total. Some experts are pre-

dicting catastrophic increases in its contribution, however. Three facts about modern roofing systems enhance chances for corrosion: the rapidly expanding use of metals, particularly metal fasteners to secure insulated systems from wind uplift; the nearly universal use of significant amounts of insulations in roofing systems; and the very common presence of water (Bradford 1986).

Metals appear in roofing systems as metal decks, comprising about 65% of all new roofing decks, as fasteners, as metal membrane systems, and as stress plates. The latter are the most popular attachment system for insulated roofs in the United States since its insurance industry began requiring full mechanical fastening in 1984 as the only recommended manner of securing insulation to steel decks. There are frequent discussions in the roofing industry's trade literature about corrosion of metal in roofing systems, including instances of wind damage that it allowed (Rossiter 1989). However, these discussions do not describe quantitatively the relationship between the causes and effects of corrosion. Nevertheless, these concerns about the magnitude of the problem have motivated the insurance industry to develop requirements intended to enhance the corrosion resistance of fasteners (Rossiter 1989).

Corrosion of metal fixings in cold deck roofing systems is potentially a more serious problem because it is so difficult to prevent moisture from moving into the roof cavity. This problem may be exacerbated by the presence of corrodants in the preservatives and fire retardants used in wood components. There is also growing evidence that certain metal claddings and aluminum fixings may be particularly vulnerable to corrosive attack by the distilled water that results from diurnal condensation (Falconer 1987).

Available remedies. The three principal factors that induce corrosion in roofing systems are the presence of water, the presence of corrodants from the environment around metal components, and the corrosion potential of the metals. Remedies will be actions that reduce the likelihood of any of these factors. Current practices include the following:

- keeping water out of roofs by good routine maintenance practices, by reducing membrane leaks, by requiring positive drainage, by reducing diffusion and convection of water from moist interiors, and by reducing the chances that construction water is sealed into the roofing system;
- improving the corrosion resistance of metals used in roofing systems by using sacrificial coatings, barrier coatings, or more corrosion-resistant metals;
- taking special precautions in roof design and in selecting materials where local codes or standards require the use of fire retardants and wood preservatives; and
- using nonmetal components (e.g., plastics such as polypropylene).

Additional practices with conceptual usefulness, but which are not now being used, include the following:

- reducing the likelihood of corrosive environments;
- providing ways to remove water from wetted roofs;
- identifying moisture accumulations early enough to correct the situation before corrosion starts; and

- reducing the use of metals in roofing systems.

Secondary effects of remedies. In most instances, available remedies to minimize corrosion problems do not cause any secondary effects except slightly greater roofing costs. One exception would be the decrease in fire resistance and wind uplift protection if metal fasteners were replaced by nonmetal ones.

4.3.2 Physical Deterioration of Insulations

4.3.2.1 Statement of the problem

Physical deterioration of insulation includes moisture degradation, delamination, and inadequate dimensional stability of roof insulation products and their facers. It can cause destructive membrane splitting, lead to lap separation, and allow wind damage to adhered membrane roof systems. Roof systems insulated with high R-value plastic foam often need bottom and/or top barrier boards made of fibrous insulation to protect the plastic foam insulation during membrane application or to achieve acceptable fire resistance. Water entering insulating systems from either roof leaks or condensation can cause severe dimensional change, delamination, and decay in the more moisture-sensitive fibrous insulations, especially fiberboard and perlite. Plastic foam insulations are less affected by moisture, but facer delamination is an issue because it can reduce wind uplift resistance. Also, warm, humid conditions can cause destructive swelling and warpage of PUR and PIR insulations.

4.3.2.2 Evidence

General descriptive material. An insulation product, including any facer component, must have adequate internal

strength to resist wind damage, and sufficient strength and dimensional stability to prevent membrane damage when mechanical and thermal stress transfers occur within the roof system. Manufacturers have had to design and formulate each generic type of insulation to address these needs.

Water attack on insulations containing cellulosic fibers can have serious consequences. Griffin (1982) reports that cellulosic fibers swell because of moisture absorption and contract on drying as much as 0.2 to 0.5% as relative humidity changes from 50 to 90%. This reaction can produce 6-mm (0.25-in.) gaps in joints of 1.2-m (4-ft-) long fiberboard insulation boards. Baker (1980) reports that rotting occurs when wood fiber has a moisture content greater than 20% by weight, especially at elevated temperatures. He noted that these conditions are usually present in a roof system for part of its service life and that they can damage the cellulosic fibers in fiberboard and perlite insulations. Fungicides can be incorporated into the insulation formulations to prevent rotting, but they are often avoided because of concerns about health hazards and possible legal problems they might cause the manufacturers.

Baker (1980) states that glass wool and rock wool inorganic fiber insulations are more resistant to water attack than cellulosic materials. However, water can damage the physical properties of these inorganic fibrous insulations and degrade the binders in them. An asphalt kraft-paper, wrap-around facer is used on low-density mineral wool insulation to improve compressive strength, interlaminar wind resistance, and surface absorption for the bitumens used to attach BUR. In fact, the high asphalt content of this facer limits this insulation product to use with

bituminous-type membranes. The high surface absorption of bitumens that characterizes unfaced high-density mineral wool insulations prevents their use in adhered roof systems having bituminous membranes. Current practice is to use only faced mineral wool. In contrast, unfaced fiberboard and perlite insulations are used for both bituminous and elastoplastic adhered roofs. But these insulations may have marginal interlaminar strength and wind resistance, especially if they are weakened by water attack.

The energy crisis in the mid-1970s prompted the initial use of high-thermal-efficiency organic foam roof insulations with R_{SI} values of 0.3 to 0.6 per cm (R_{US} of 4 to 9 per in.). In general, the organic foam insulations are more water-resistant than the fibrous, low-thermal-resistance insulations. However, the dimensional stability of PUR and PIR insulations can be seriously damaged by high humidity and elevated temperature. Industry specifications have had to include ASTM D2126 dimensional stability testing at 70°C (158°F)/95% relative humidity with rigid quality control on insulation production. Otherwise, moisture swelling and warpage can produce membrane failure and allow wind damage.

Before the use of organic foam insulations, it was extremely rare to intermix different insulation types within a given roof system. However, the fire resistance and membrane compatibility deficiencies of organic foam insulations made it necessary to utilize fibrous types of insulation as bottom and/or top barrier protection for the organic foam insulations. As a result, the water deficiencies of the fibrous insulations are present in high-thermal-performance roofs using organic foams. Bottom-side barrier protection with perlite or mineral wool insulation is needed with

the less fire-retardant organic foams to comply with building code and insurance requirements for interior fire resistance. Top fire barrier protection is also necessary when less fire-resistant membranes are employed. However, fiberboard, perlite, and mineral wool top barriers are more commonly needed for membrane compatibility (e.g., to protect thermoplastic polystyrene foam insulations against hot asphalt or solvents and to prevent blister formation in BUR membranes applied over thermosetting foam insulations).

Facers on insulations are another potential source of delamination problems and cause for wind damage. Thermosetting PUR, PIR, and phenolic foam insulations are produced with facers on both sides to accommodate the manufacturing process. Facer selection has been an evolutionary process. The early facers were either organic felts or asphalt-saturated asbestos felts. These facers had a relatively high equilibrium moisture content that contributed to blistering of BURs. For use with BUR, manufacturers subsequently adopted coated fiberglass facers with much lower equilibrium moisture content. Fiberglass facers are also used with modified asphalt and elastoplastic membranes.

These facers account for a significant portion of the total cost of insulation products. The impact on cost has motivated manufacturers to develop proprietary facers. As a result, roof designers must rely on individual manufacturer guidance rather than generic choice when making decisions about membrane compatibility.

Field evidence. LaCrosse (1988a) cites the following three insulation problems reported to the NRCA in 1987 by U.S. roofing contractors: deterioration of fiberboard, separation of PIR foam facers, and, crushing of phenolic foam. All of these field problems with insulation decay and de-

lamination are isolated occurrences and not well documented in the technical literature. Individual problems seem to have been handled quietly by material manufacturers or contractors without publicity. In many cases, these problems arose from cost-cutting measures wherein marginal or inappropriate use was made of particular insulation systems.

Fiberboard insulation was largely displaced by more fire-resistant mineral wool and perlite for installations during the 1960s and 1970s. During the 1980s, fiberboard gained new use as a protective cover over organic foam insulations either to resist BUR blistering or to prevent damage by the solvent glues and adhesives used with elastoplastic membranes. LaCosse (1988b) reports that the increased use of fiberboard has been accompanied by more numerous reports of moisture-induced fiberboard decay in the roof system. In some cases the problem was caused by using a grade of fiberboard not intended for roof application. LaCosse notes, however, that some of the problem is due to FM's limiting asphalt content in fiberboard roof insulation to 4% to reduce the fire hazard when the fiberboard is placed next to steel decking. This restriction increases the tendency of fiberboard to absorb moisture and deteriorate. It is not a useful restriction when fiberboard is used as a top barrier over organic foam insulation. Low asphalt content also increases the risk of delamination and subsequent wind damage. Haas (1983) described wind damage on a roof covered by a fully adhered, elastoplastic membrane where half of the fiberboard thickness remained attached to the deck and the rest peeled back, still adhered to the membrane.

Perlitic insulation inherently has marginally poor interlaminar strength. Bonafont (1989) reports wind damage on BURs

installed over perlite. Both fiberboard and perlite have to be factory laminated to achieve thicknesses greater than 3.8 cm (1.5 in.). The glue used for lamination has marginal water resistance. Wind blow-off and splitting of BUR membranes have been observed in the field on leaky roofs that allowed water to enter the insulation. The cause was delamination at the factory glue line.

Wind problems involving facer delamination with PIR foam insulation have been limited to adhered elastoplastic membrane systems. The solvent in the membrane glue has been identified as the culprit. Disbondment occurred within the organic foam slightly below the interface with the insulation facer. Manufacturers have corrected this problem by product modification. Some have a special product for adhered elastoplastic membrane use, and some now have an improved universal product for all membrane applications.

Failure of membranes due to warping and swelling of PUR and PIR foam insulations was more common in the 1970s and early 1980s than it is today. This problem was overcome after manufacturers adopted ASTM D2126 dimensional stability quality control testing: 7 days exposure at 70°C (158°F)/95% relative humidity. Problems still occur occasionally because insulation is shipped and used before this 7-day quality control test is completed. If the insulation fails the test, water causes it to swell permanently. Water-induced swelling is a problem with spray-applied foam also, unless the spray-applied membrane remains intact. Alumbaugh (1983) reported that spray-applied foam roof failures have occurred with the use of spray coatings that are too thin or not reapplied periodically. They also occur because of stress-induced delamination when indi-

vidual layers within the foam insulation are sprayed too thinly.

Closed-cell phenolic foam insulation is relatively new in the marketplace. It has rigidity and brittleness similar to the original PIR foam roof insulations, which were subsequently plasticized by polyol modification. Baxter (1984) reported field observations on a BUR insulated with nominal 40 kg/m^3 (2.5 lb/ft^3) density phenolic foam. He observed serious fracture of insulation near mechanical fasteners, insulation shrinkage and delamination, and crushing by normal rooftop application and service traffic.

Laboratory evidence. Most laboratory work related to dimensional stability, delamination, and decay of roof insulations has been empirical and patterned to fit years of actual field experience. The end result is that there are ASTM standards for each type of insulation. Products manufactured in accordance with the ASTM standards have a history of relatively good field performance.

The effect of moisture migration into various types of insulation has been evaluated in several different laboratories. Baker (1980) observed that moisture in liquid or vapor form migrated rapidly into open fibrous insulations (fiberboard, perlite, and mineral wool). In contrast, he reported that water weight gain would not occur in closed-cell plastic foam insulations unless a temperature differential existed across the insulation.

Tobiasson (1979) conducted moisture gain tests on various types of insulation with a temperature differential and vapor pressure differential across the samples. He observed that all insulations remained relatively dry even when significant amounts of water vapor passed through them unless the dew point occurred within the insulation. Then only cellular glass and

XPS had low water gain. Even XPS had a large water gain under this condition if the factory-formed integral skin was removed. Similar results were obtained in tests at the NBS with BUR samples insulated with fiberboard, perlite, mineral wool, EPS, and PUR foam (Knab 1980). The samples were subjected to a temperature differential across the samples, and the fiberboard delaminated after absorbing 18% moisture during 17 days of exposure.

Walters (1988) reports moisture migration over a 4-year period on an actual roof on a South Carolina school with an air-conditioned interior. The instrumented roof on this school had been reroofed with an EPDM membrane over 5.1 cm (2 in.) of EPS foam insulation sandwiched between two layers of 1.3-cm (0.5-in.) fiberboard. The old BUR was not removed. The moisture content of the EPS foam and top layer of fiberboard stayed low and relatively constant (0.07 to 0.22% and 3.66 to 4.86% by weight, respectively), but the moisture content of the bottom layer of fiberboard increased progressively from 5.90 to 10.39%.

Modeling. Dimensional stability, delamination, and decay of roof insulations have not been subjected to mathematical modeling. Modeling of wind damage and moisture migration are only indirectly related to this insulation problem.

4.3.2.3 Analysis

Significance of the problem. Field experience, although not too well documented in the technical literature, has established that serious membrane leaks and wind damage can be caused by moisture degradation, delamination, and inadequate dimensional stability of roof insulation products and their facers. In general, these types of problems have occurred on isolated roof situations and were

solved by material manufacturers or contractors without publicity. The continued use of all types of roof insulation in the marketplace for many years with only minor product modification confirms that these problems are isolated quality control, roof design, or application problems relatively independent of the type of insulation employed.

Available remedies. It is essential that roof insulation manufacturers consistently comply with requirements of appropriate ASTM specifications. Good design and installation of roof drainage are needed to minimize the amount of water entry into roof insulation from membrane and flashing defects. High-quality vapor retarders must be installed when interior and exterior temperature and humidity conditions are expected to create conditions that allow condensation within the roof insulation. The selection of membrane and insulation product combinations in any roof system must be based on proven compatibility.

4.3.3 Research Needs

Because of the increasing importance of fasteners in new roofs and reroofing, they are the dominant subject of research needs in the area of degradation of roofing materials. Rossiter et al. (1989) sought to identify research needs through an assessment of fasteners. They concluded that the basic mechanisms for corrosion are well understood and that the current need is to devise comprehensive test procedures for roof systems and obtain field performance data. The latter is especially important to establish priorities for research. Field data are sparse because of a lack of nonintrusive instruments to monitor the condition of metal components and insulation in-situ.

If instrumentation becomes available, a data base on field performance of fastener systems needs to be developed.

Along with instrumentation to monitor field performance, diagnostic procedures for in-place assessment of fastener corrosion are lacking. More comprehensive laboratory methods for assessing corrosion mechanisms should then build on the field data.

The ideal solution to the problem of metal corrosion is to eliminate the potential for it in roof systems. Standard tests need to be developed that subject roofing material, particularly insulations, to corrosiveness testing, and that establish limits for corrosiveness. Ways should be provided to move water from wet roof insulation to the surface and to enhance diffusion to interior spaces. Moisture sponges in the roof system and power venting to the exterior have been mentioned but may not be practical solutions. Moisture accumulations should be identified before corrosion sets in, and moisture alert systems need to be developed. Finally, a reduction in the use of metals in roof systems needs to be explored (e.g., by overcoming economic and technical concerns about the use of concrete and wooden decks, of fully adhered systems, and of ballasted loose-laid systems).

The key to avoiding most physical deterioration of insulation is the same as for metal corrosion: stop moisture intrusion. The research opportunities for reducing metal corrosion will be equally effective for avoiding insulation deterioration. In addition, there is a special need to improve facer bonding, particularly for foam insulations.

4.3.4 References

Alumbaugh 1983

Alumbaugh, R. L. and Conklin, S. R., "The Pros and Cons of Sprayed-in-Place Polyurethane Foam Roof Systems," *Roofing Spec Magazine* (June 1983), 32-37.

Baker 1980

Baker, M., *Roofs: Design, Application and Maintenance*, Multi-Science Publication, Ltd., Montreal, Quebec, Canada.

Baxter 1984

Baxter, R., "Phenolic Foam: Problem-Solver or Problem?" *Roofing Spec Magazine* (November 1984), 27-31.

Beech 1987

Beech, J. C. and Uberoi, S., *Ventilating Cold Deck Flat Roofs*, Building Research Establishment BRE IP13/87, Harwell, U.K.

Bonafont 1989

Bonafont, R. L., Private Communication to G. E. Courville, June 1988.

Bradford 1986

Bradford, J., "Corrosion is Major Danger for Fasteners," *Roofing, Siding and Insulation* (January 1986), 42-44.

Cox 1983

Cox, R. N. and Laidlaw, R. A., "The Effect of Preservatives on the Corrosion of Galvanized Metal Plate Fasteners in Timber. Part 1: Effect of Joint Strength and the Significance for Trussed Rafter Roofs," *Int. J. of Wood Preservatives* 3(2), 148-52.

Cox 1984

Cox, R. N. and Laidlaw, R. A., "The Effect of Preservatives on the Corrosion of Galvanized Metal Plate Fasteners in Timber. Part 2: The Relative Corrosivity of 'Salt' and 'Oxide' Formulations of Copper-Chrome-Arsenic (CCA)," *J. Inst. of Wood Science* 10(2), 84-88.

Cross 1988

Cross, J. N., "Final Report to the Steering Committee on Corrosion of Metal Fasteners in CCA Treated Timber," UMIST-42, University of Manchester, U.K.

Falconer 1987

Falconer, P., "Metal Industrial Roof Moisture Problems," *The Architects Journal* (May 1987), 62-67.

Griffin 1982

Griffin, C. W., *Manual of Built-Up Roof Systems*, 2nd ed., McGraw-Hill, New York, USA, p. 69.

Haas 1983

Haas, A., "Designing to Prevent Single-ply Blow-offs," *Roof Design* (September 1983), 28-34.

Knab 1980

Knab, L., Jenkins, D., and Mathey, R. G., *The Effect of Moisture on the Thermal Conductance of Roof Systems*, National Bureau of Standards Building Science Series 123, Washington, D.C., USA.

LaCosse 1988a

LaCosse, R. A., "Insulation Necessary But Not Without Problems," *Professional Roofing* (January 1988), 38.

LaCosse 1988b

LaCosse, R. A., "Production, Handling Traits of Fiberboard Insulations," *RSI Magazine* (February 1988), 118-26.

Lazar 1983

Lazar, P., "Factors Affecting Corrosion of Carbon Steel under Thermal Insulation," pp. 11-26 in *Corrosion of Metals under Thermal Insulation*, American Society for Testing and Materials ASTM STP 880, Philadelphia, USA.

Paulsen 1987

Paulsen, E. M., *Roofing Fasteners*, Norwegian Building Research Institute Project Report 21, Trondheim, Norway (in Norwegian).

Pollock 1983

Pollock, M. I., Barnhart, J. M., Eds., *Corrosion of Metals under Thermal Insulation*, American Society for Testing

and Materials ASTM STP 880, Philadelphia, USA.

Richardson 1983

Richardson, J. A., "A Review of the European Meeting on Corrosion under Lagging Held in England, November 1980," pp. 42-62 in *Corrosion of Metals under Thermal Insulation*, American Society for Testing and Materials ASTM STP 880, Philadelphia, USA.

Rossiter 1989

Rossiter, W. J., Jr., Streicher, M. A., and Roberts, W. E., *Corrosion of Metallic Fasteners in Low-Sloped Roofs: A Review of Available Information and Identification of Research Needs*, National Institute of Standards and Technology NISTIR 88-4008, Gaithersburg, Md., USA.

Sheppard 1983

Sheppard, K. and Weil, R., *Corrosiveness Testing of Thermal Insulating Materials*, ORNL/SUB/78-7556/3, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Szeliga 1988

Szeliga, M. J., "Understanding Corrosion," *Maintenance Technology* (October 1988), 32-34.

Tobiasson 1979

Tobiasson, W. and Ricard, J., "Moisture Gain and Its Thermal Consequence for Common Roof Insulations," pp. 4-16 in *Proceedings, Fifth Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, Ill., USA.

Walters 1988

Walters, R. B. and Dupuis, R. M., "A Status Report on the Moisture Gain Behavior of Single-Ply EPDM Roof Systems," pp. 75-84 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, CONF-

8809314, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

4.4 SHORTFALLS FROM DESIGN THERMAL PERFORMANCE

4.4.1 Thermal Bridging

4.4.1.1 Statement of the Problem

A thermal bridge is a material or configuration in a roof that produces localized excessive heat flow from (or to) the roof and a cold (or hot) area on the interior surface. Thermal bridging is the juxtaposition of materials of different thermal conductivities and/or thicknesses. The formation of thermal bridges, whether by compromises in design or bad workmanship, will degrade the thermal performance of a roof and may lead to various kinds of failures of low-slope roof systems. The modes of failure depend upon the form of construction, and they vary in severity. A disastrous failure could be one in which thermal stressing of the membrane at junctions and abutments results in a significant leak. A less catastrophic failure might be one in which a thermal bridge allows surface or interstitial condensation to occur, yielding an unacceptable pattern of water staining or mold growth on an interior ceiling.

4.4.1.2 Evidence

General descriptive material. The potential bad effects of thermal bridges on the performance of the building envelope have been acknowledged for many years (Tye 1985). It is generally true that the visibility of thermal bridges increases with increasing thicknesses of insulation. Thermal bridging is due to dissimilar thermal conductivities of materials in the main body of the roof system or at the junction

of the roof with walls and other support structures, to the penetration of services, to missing or badly placed insulation, or to infiltration of air at junctions.

Many countries, especially in Europe, have included measures in their building regulations, standards, or codes to combat the effects of increased heat loss and the risk of condensation and mold growth due to thermal bridges. As a consequence, a large amount of guidance is available on construction methods to eliminate bridges and methods of assessing and calculating the thermal performance of bridged elements (Mainka 1986; Melton 1988; and Synder 1986).

In Sweden, building codes have recommended since 1975 that infrared thermography be used to check both the air tightness and the continuity of insulation in new buildings (Swedish Building Code 1975; Paljak 1972; and Petersson 1980). The Swedish Building Council offers detailed guidance and standards on the use of thermography.

French regulations require that the effects of all bridged elements, junctions, corners, etc., be determined in assessing the thermal performance of a building (CSTB 1987). Lineal U-values are used to account for edge effects. Detailed guidance is available on the performance of commonly used forms of construction and methods of calculation.

In the United Kingdom, the building regulations for England and Wales were amended and took effect in April 1990 to limit the heat loss through bridged elements (Building Regulations 1985). The Building Research Establishment (BRE) has issued an accompanying document giving guidance on appropriate methods of construction and assessment to meet these amended requirements. Equivalent mandatory requirements have been in

force in Scotland and Northern Ireland for several years (CIBSE 1986).

These examples illustrate that the effects of bridging on the thermal and moisture performance of the building envelope are severe enough to require regulations. The regulations aim at eliminating the effects of heat loss and/or surface condensation due to the major bridging elements. Their methods of assessment rarely take into account, or correct for, the risk of interstitial condensation or the local effects created by fixings and other small objects that penetrate through the roof. These more localized effects, although they have only a marginal effect on the overall thermal performance of the roof, may contribute to failures due to the local thermal stresses that can occur or may create pockets of localized interstitial condensation leading to corrosion problems.

Field evidence. There has been intensive field monitoring of buildings, particularly in Sweden, to determine the effects of thermal bridges using infrared thermography. Also, many whole-building studies focused on energy conservation or condensation highlight the effects of thermal bridges either as the source of energy losses or as potential loci for condensation. For example, as yet unreported research at BRE using matched pairs of houses has isolated the bridging effects of timber joists in pitched roofs.

Laboratory evidence. There has been intensive laboratory monitoring of large sections of walls and roofs containing thermal bridges in both Europe and the United States (Tye 1985). These studies have been done to check the validity of existing methods, to develop improved methods of calculation, and to provide national standards for "hot box" testing of complex elements. National standards are in place in most countries for "hot box" testing un-

der steady-state conditions. Also, some facilities are available that will simulate dynamic and/or diurnal hygrothermal cycling conditions.

The thermal bridging effect of rainwater on an inverted warm deck roof has been monitored in the United Kingdom. The results have shown that the heat loss through a roof can increase and remain high for several hours after a rain storm. The chilling effect of the rainwater creates a corresponding risk of condensation at the underside of the membrane (Beech 1989).

Modeling. Many models are available to predict the effects of thermal bridging. They range from the steady-state methods included in the ASHRAE Handbook of Fundamentals (ASHRAE 1989) to the more complex, dynamic, computer-based, finite-difference methods in the CIBSE Guide (CIBSE 1986). The steady-state models have been used to provide design solutions that can be used to eliminate the heat loss and surface condensation effects of bridges. More complex models are required to estimate the risks from interstitial condensation at bridging elements, whose effects cannot be eliminated (Standaert 1985; Salgon 1987; and Garrett 1980).

4.4.1.3 Analysis

Significance of problem. The available evidence supports the hypothesis that adding insulation to roof systems will enhance the effects of thermal bridges which, in turn, degrades the desired thermal performance of the roof system. It also confirms that more insulation may lead to failures due to interstitial condensation at the bridges.

Available remedies. The best approach to eliminating the effects of thermal bridges is to provide a continuous layer of insulation in the plane of the roof, and, if possible, a continuous link with the wall

insulation. From this perspective, the most satisfactory solution for roofing, therefore, is to use a warm deck roof. If a sufficient thickness of insulation is used, this approach ensures that the heat loss is uniform across the roof. The supporting members and decking are maintained at a uniform temperature close to the room temperature, eliminating or reducing the risk of interstitial condensation.

With the protected membrane or upside-down form of roof system, there is a risk of localized, intermittent cold bridging when the thermal wave due to rain or melting snow passes through the outer insulation layers and chills the deck. The effects of this bridging on heat loss can be reduced by ensuring that the roof deck is well drained. The risk of condensation due to chilling of the membrane can be reduced by providing an additional thin layer of insulation between the main insulation and the membrane (Beech 1989).

In cold deck systems, a continuous layer of insulation can be placed at the ceiling level. This should reduce the heat loss and surface condensation effects of bridges. However, problems still may arise because of interstitial condensation in the colder upper areas of the roof (Anderson 1981).

The effects of thermal bridges formed by parapets, junctions with walls, roof penetrations, and concealed or valley gutters can be reduced by a variety of methods. These methods include using more insulating material in the construction: adding, overlapping or extending insulation to maintain uniform temperature gradients in the bridged areas. Successful use of these methods requires careful attention to the detailed design and subsequent construction. In many cases, it may be preferable to eliminate features such as parapets from the design (Siviour 1988).

4.4.2 Thermal Drift of Insulation

4.4.2.1 Statement of the problem

Closed-cell foam insulations commonly used in roof systems include PIR, PUR, phenolic, and XPS. These insulations are produced by combining a high-pressure gas (a blowing agent) with warm, fluid polyol blends. The blowing agent, trapped in the cooling mixture, expands and causes a rigid cellular polyol structure to form. CFCs are good blowing agents because their pressure/temperature characteristics are a good match to those of the polyols, they have low thermal conductivities, and they are relatively inexpensive. Freshly produced foam insulation is a mostly hollow, closed-cell structure filled with a mixture of air and blowing agent. The total gas pressure is near atmospheric pressure. The low thermal conductivity of the CFC blowing agent causes the overall thermal conductivity for the freshly produced insulation to be about half that for a foam filled only with air. Unfortunately, the foam cell walls are permeable both to air and to CFCs. Thus air tends to diffuse inward until the partial pressure of air inside reaches the pressure of ambient air, and the CFC diffuses outward and leaves the insulation. Diffusion rates are higher for the constituents of air—oxygen and nitrogen—than for the heavier CFC molecules and, to a lesser extent, diffusion rates are different for each of the different polyol structures.

Thus immediately after the insulation is produced, air begins to diffuse in and CFC diffuses out. Both processes cause the thermal conductivity to rise. This increase in thermal conductivity for closed-cell insulation is called thermal drift. For all foams, the loss of CFCs is very slow and difficult to measure. Changes because of

inward diffusion of air, however, are more rapid. Equilibrium between inside and outside air is reached in about 100 days for XPS (Sheffield 1988) and in about 2 years for PIR and PUR (McElroy 1991; Christian 1992). There is less evidence in the literature for phenolic foam, but manufacturers claim that the time to equilibrium is much longer than for other foam insulations (Reeves 1992; Dvorchak 1985).

Newly produced gas-filled foam insulations have a thermal conductivity of less than $0.017 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.12 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. Unfaced foams with high diffusion rates have aged values of about $0.025 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.17 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. Foams with impermeable facers and impermeable foams experience much less thermal drift. Thus, the maximum change in thermal conductivity is nearly 50%. While this is significant, keep in mind that even for foams with *maximum* thermal drift, the final conductivity {about $.034 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.23 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]} is still lower than that for other roofing insulations, for example, mineral wool [$\lambda \approx 0.036 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.25 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]].

Until recently, thermal drift has been an issue to the roofing industry mainly because of conflicting research claims that cloud the design values of drift assigned to insulations and because material specification sheets have not adequately accounted for drift. However, these issues are now overshadowed by the linkage established between CFCs and upper atmosphere ozone depletion, as well as by their impact on global warming. These linkages have led developed nations to adopt schedules to eliminate usage of CFCs in insulation production before the year 2000. While some manufacturers have already acted, others are in the concluding stages of research programs to find acceptable alter-

natives. For the most commonly used foam for roof systems, PIR, the most promising replacement candidate for CFC-11 as a blowing agent is HCFC-141b.

An industry/government consortium in the United States has conducted an extensive test program to compare the performance of PIR foams blown with HCFC-123, HCFC-141b, and blends of the two compounds, with conventional PIR blown with CFC-11 (Baumann 1990). Figure 4.1 shows the long-time change on thermal conductivity (the thermal drift) for

roof insulation specimens, all produced with the same polyol formulation but with different blowing agents (Christian 1992). All specimens were field tested under black EPDM single-ply membranes. The data represent performance at about 24°C. The figure clearly illustrates thermal drift in foam insulations. In addition, it is apparent that the thermal conductivity of PIR blown with CFC-11 is consistently lower than that for the other blowing agents and that, within experimental error, all the foams exhibit similar aging characteristics.

Fig. 4.1. Thermal drift of isocyanurate foam insulation blown with CFC-11 and with environmentally acceptable alternatives. The results show that drift is strong for about 2 years and continues at a slow pace for a longer time (see Christian 1992 for more details).

This test program also produced information on other properties of PIR with alternative blowing agents (Blanpied 1990) and is providing a test protocol for accelerated testing for thermal drift in PIR (McElroy 1990). This procedure is currently under review by ASTM in the United States.

4.4.2.2 Evidence

General descriptive material. The thermal drift problem with CFC-blown foam insulations was recognized before CFC-blown foam was introduced into the roof insulation market. The most comprehensive early research work on thermal drift was done by Norton (1967) at General Electric. Norton showed that thermal drift was caused solely by changes in the composition of the gaseous mixture in the cells and could be predicted by fundamental laws of gas diffusion related to the permeability and solubility of the gas in the polymer cell walls. He developed methods to calculate the thermal life of insulations based on diffusion constants. This early work of Norton was augmented later in England by Ball (1970) and has been confirmed more recently by Glicksman (1988).

When CFC-blown foam insulation initially was introduced into the U.S. roofing market, thermal drift was not adequately represented. Manufacturers initially rated the thermal performance of foam insulations based on thermal resistance at the time of manufacture. This reporting procedure changed in October 1983 when member companies of the Roof Insulation Committee of the Thermal Insulation Manufacturers Association (Schwingen 1984) agreed to promote and advertise only "aged" thermal values. These values are obtained from measurements after 180 days of exposure at 23°C (73.4°F) and 50% relative humidity. Although that procedure was an improvement, it did not ade-

quately represent a true aged value of thermal performance because thermal drift of foams continues to be significant for years after installation into roof systems, as suggested by Fig. 4.1.

Research on gas-blown foam insulations used for building envelopes is summarized in two publications by Brandreth (1986, 1991). Brandreth's books are compilations of key technical articles in the literature and good bibliographies on aging of foam insulations. In the 1986 book, Brandreth appraises various technical considerations that impact the rate of thermal drift. A 1966 DuPont publication is cited to indicate that urethane foams with densities lower than 32 kg/m³ (2 lb/ft³) age rapidly because they have too many open cells. Brandreth states that "the easiest practical solution for the near term is to improve the insulation facer system," but he notes that a good facer might be punctured during the installation of the insulation. In the 1991 book, Brandreth has collected papers that update experimental and analytical work on foam systems. The range of topics is expanded to include a discussion of global CFC effects, the economics of CFC substitutes, and application discussions.

The new complexity in the thermal drift problem is a consequence of measures initially adopted in 1988 to cut back and ultimately to eliminate CFC production. Khalil (1986) describes the effect of CFCs on stratospheric ozone and notes that foam insulations in 1988 constituted the largest and fastest growing use of CFCs. Hoover (1989) discusses the many unknown formulation, processing, and performance changes that will accompany the introduction of CFC substitutes into foam insulations.

Field evidence. Early testing for the aged thermal performance of spray-ap-

plied PUR roof insulation installed in several U.S. and South Pacific locations was reported by Zarate and Alumbaugh (1982). Average exposure was 7 years, and average aged λ -values were $0.023 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.16 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] with impermeable spray-applied coatings and $0.025 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.17 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] with permeable coatings on the foams. However, the observed variability in aged thermal performance was from 0.020 to $0.027 \text{ W(m} \cdot \text{K)}^{-1}$ [0.14 to $0.19 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. This variation presents a potentially serious commercial concern.

Muhlenkamp (1983) reports similar variability with commercial board stock roof insulation. After 3 years of roof service, λ -values for PIR produced by four manufacturers ranged from $0.0238 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.165 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] to $0.0267 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.185 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. He observed good correlation between thermal drift and open cell content of foam insulations. All samples having 10% or more open cell content had λ -values exceeding $0.026 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.18 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] after only a year of exposure. A direct comparison was made between good- and bad-quality insulations purposely made by one manufacturer from different formulations. After 2 years of exposure, the λ -values had drifted to $0.0232 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.161 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] for the good foam (4% open cells) and to $0.0297 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.206 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] for the bad foam (15% open cells). The projected λ -value after 10 years of exposure for the good foam (4% open cells), which was the best product in Muhlenkamp's study, was $0.0254 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.176 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. Comparable measurements have also been made in Sweden (Larsson 1987; Isberg 1988).

The variability in thermal drift of some commercial board stock roof insulation has also been observed by the Midwest Roofing Contractors Association in the United States (Kugler 1986), after warehouse storage and after roof service averaging 3 years. The warehouse study showed that commercial PIR roof insulations sampled from the marketplace had λ -values ranging from 0.0208 to $0.0274 \text{ W(m} \cdot \text{K)}^{-1}$ [0.144 to $0.190 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] after 6 to 12 months of storage and from 0.0237 to $0.0313 \text{ W(m} \cdot \text{K)}^{-1}$ [0.164 to $0.217 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] after 3 additional years of storage. The samples of commercial insulations from in-service roofs had λ -values from 0.0234 to $0.0286 \text{ W(m} \cdot \text{K)}^{-1}$ [0.162 to $0.198 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] after 15 to 51 months of roof exposure. Three-quarters of the roof samples had λ -values higher than $0.026 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.18 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$].

Measurements are also available for XPS. Epstein (1977) studied insulation from 5- to 8-year-old protected membrane systems in Europe, Canada, and the United States. He reports λ -values of 0.029 to $0.032 \text{ W(m} \cdot \text{K)}^{-1}$ [0.20 to $0.22 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$] after exposure. This small range of values is consistent with expectations that XPS shows negligible thermal drift in the field. It is also consistent with the single (aged) value of λ in handbooks (ASHRAE 1989) of $0.029 \text{ W(m} \cdot \text{K)}^{-1}$ [$0.20 \text{ Btu} \cdot \text{in. (h} \cdot \text{ft}^2 \cdot ^\circ\text{F)}^{-1}$]. Some manufacturers (e.g., Dow Chemical USA) have recently replaced CFC-12 with HCFC-142b as the CFC blowing agent. Because the molecules are approximately the same size, this change should not affect conclusions concerning thermal drift.

Few field performance data are available on CFC-blown phenolic foam. Desjarlais (1987) reported that boards stored at

room temperature showed no drift over a 2-year period. Boards from the same lot were installed outdoors on the Roof Thermal Research Apparatus at ORNL. A significant drift was observed, but this test was discontinued after approximately 2 years because the phenolic insulation was not considered representative of then current commercial production (Courville 1989).

Laboratory evidence. Diffusion coefficients for CFCs, nitrogen, and oxygen were reported in PUR by Norton (1967). Bomberg (1980) has discussed the influence of water vapor infusion and temperature and humidity gradients across the insulation. Tobiasson (1979) and Hedlin (1977) evaluated the effect of water vapor infusion on the thermal conductivity of different types of insulations, including XPS foam.

Cell wall permeability and cell wall thickness are influenced by foam formulation, mixing and processing conditions, foam density, and the size and orientation of the cells (Sheffield 1988; SPI 1988). The SPI report states that optimum insulating efficiency is obtained with 29 to 37 kg/m³ (1.8 to 2.3 lb/ft³) density and adds that thin cell walls at lower densities promote diffusion and thermal drift. Some commercial PIR foam roof insulations are manufactured at densities below 29 kg/m³ (1.8 lb/ft³). The effect of open cell content in foams on the rate of thermal drift was cited by Muhlenkamp (1983).

The influence of facer permeability on thermal drift is emphasized by SPI (1979). A DuPont study cited by SPI (1988) describes the importance of low-permeability coatings on aluminum foil facers. These coatings not only protected against pinholing in the foil, but also improved adhesion between the foil facer and foam core. This reduced the potential for air infiltration along the foil interface. Currently, most

commercial PIR roof insulations are manufactured with highly permeable fibrous mat facers.

The long-term thermal stability of closed-cell, CFC-blown phenolic foam is not established. Dvorchak (1985) reports that closed-cell phenolic foams have little or no loss in thermal efficiency after aging for 360 days at 60°C (140°F). However, an important unknown is the ability of phenolic resin cell walls to resist cracking after long-time shrinkage and hardening with age. Cell wall fracture with prolonged aging could cause a relatively sudden loss of thermal efficiency.

Modeling. The thermal performance of cellular plastic foam insulations and thermal drift have been extensively modeled (Sheffield 1988; Valenzuela 1981). Dixon (1970) showed that modeling could reproduce experiments quite accurately. Sheffield (1988) reviewed the extensive modeling efforts by Dow Chemical USA. Investigators at the Massachusetts Institute of Technology in the United States have published extensively on models that predict thermal performance and aging of cellular plastic insulations (Valenzuela 1981; Glicksman 1988). The primary shortcomings of existing modeling efforts are the need for better data on heat and mass transfer in cell walls and the need for a better formulation of radiation heat transfer in the insulation (Glicksman 1988).

4.4.2.3 Analysis

Significance of the problem. Thermal drift reduces the thermal efficiency of roof systems over time. The effect is different in various foam products. Reductions in thermal efficiency increase building operating costs. Extensive laboratory and field research evidence has provided a good understanding of thermal drift and its causes for PUR, PIR, and XPS insulations pro-

duced with CFCs. Mathematical models are fairly good at forecasting the rate of thermal drift for specific foam compositions, provided accurate material property data are available. This data base should also provide a relatively sound basis for predicting the thermal drift behavior of potential CFC substitutes. More technical information is needed on the aging mechanism of various phenolic formulations.

Historically, the thermal drift problem has not received wide attention, because building owners generally have not recognized the economic impact. However, any shortfall of thermal performance compared with design value causes a building owner to pay higher than expected operating costs for heating and cooling energy. When the building eventually is reroofed and the effect of thermal drift must be offset to bring the thermal performance back to the original level of the design, additional capital costs are incurred.

Available remedies. Thermal drift would be of less concern if design values of thermal conductivities for foam insulations were more representative of aged foams.

Secondary effects of remedies. Measures to reduce drift and switch to alternate foaming agents may increase costs for these insulations.

4.4.3 Research Needs

The concept of thermal bridging in roofs is well understood, although there is a need for easy-to-use techniques for estimating their impact. For information on increased risk of interstitial condensation due to thermal bridges, see the research needs for moisture effects in Sect. 4.5.3. Thermal drift is well understood, although there is a need to develop more accurate material properties that will improve predictions of the effect.

Thermal drift is being researched to increase understanding of the performance of the second-generation HCFC blowing agents that have less ODP than CFCs. Work is needed to develop accelerated laboratory procedures for thermal drift testing of closed-cell, high-thermal-performance foam insulations. A more serious long-range research issue is replacement of the second-generation HCFCs with blowing agents having no ODP, and the need to identify and characterize these agents.

4.4.4 References

Anderson 1981

Anderson, B. R., "The Thermal Resistance of Air Spaces in Building Constructions," *Building and Environment* 16, 35-39.

ASHRAE 1989

"Thermal and Water Vapor Transmission Data," 1989 *ASHRAE Handbook of Fundamentals*, ASHRAE, Atlanta, USA.

Ball 1970

Ball, G. W., Hurd, R. and Walker, M. G., "The Thermal Conductivity of Rigid Urethane Foams," *Journal of Cellular Plastics* 6, 66-78.

Baumann 1990

Baumann, G. F., "Are Alternative Blowing Agents Technically Viable for Polyisocyanurate Roof Insulation?" pp. 232-33 in *Proceedings of the 33rd Annual Polyurethane Technical Marketing Conference*, Sept. 3-7, 1990.

Beech 1989

Beech, J. C. and Saunders, G. K., "Thermal Performance of Lightweight Inverted Warm Deck Flat Roofs," *BRE IP 2/89*, The Building Research Establishment, Garston, United Kingdom.

Blanpied 1990

Blanpied, R. H. and Knis, S. A., "The Technical Viability of Alternative Blowing Agents in Polyisocyanurate Roof Insulation, Part 1: Processing and Physical Properties," pp. 234-38 in *Urethanes 90*, Society of the Plastics Industry, New York, USA.

Bomberg 1980

Bomberg, M., "Problems in Predicting the Thermal Properties of Faced Polyurethane Foams," pp. 412-30 in *American Society for Testing and Materials Thermal Insulation Performance Series STP-718 (ASTM)*, Philadelphia, USA.

Brandreth 1986

Brandreth, D. A., *Advances in Foam Aging, Vol. 1*, Caissa Editions, Yorklyn, Del., USA.

Brandreth 1991

Brandreth, D. A., Ed., *Improved Thermal Performance*, Technomic Publishing Co., Lancaster, Pa., USA.

The Building Regulations 1985

1990 Edition, Approved Document, Conservation of Fuel and Power, Part L," HMSO, London, U.K.

Christian 1992

Christian, J. E., Courville, G. E., and Graves, R. S., "Thermal Conductivity of Polyisocyanurate Foam Board Insulation Blown with CFC-11 Substitutes: Laboratory and Long-Term Field Measurements," pp. 57-68 in *Proceedings of the VIII International Waterproofing Congress*, May 20-22, 1992, Bruxelles, Belgium.

CIBSE 1986

"Thermal Properties of Materials," Book A, Sect. A3 of *CIBSE Guide*, The Chartered Institution of Building Services Engineers, London, United Kingdom.

Courville 1989

Courville, G. E. and Childs, P. W., *Measurement of Thermal Drift in Foam Insulation*, ORNL/TM-11290, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

CSTB 1987

"Rules for Calculating Practical Thermal Properties of Structural Components, Rules Th-K77," Unified Code of Practice, Centre Scientifique et Technique du Batiment, Paris, France.

Desjarlais 1987

Desjarlais, A. O. and Tye, R. P., "Experimental Methods for Determining the Thermal Performance of Cellular Plastic Insulation Materials Used in Roofs," pp. 12-22 in *Proceedings, 8th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.

Dixon 1970

Dixon, R. R., Edelman, L. E., and McLain, D. K., "Effect of Aging on Thermal Conductivity of Cellular Materials," *Journal of Cellular Plastics* 6, 44-47.

Dvorchak 1985

Dvorchak, M. J., "Use of Phenolic Foam in Low-Slope Roofing," pp. 360-67 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.

Epstein 1977

Epstein, K. A. and Putnam, L. E., "Performance Criteria for the Protected Membrane Roof System," pp. 27-34 in *Proceedings, Symposium on Roofing Technology, September 21-23, 1977*, National Roofing Contractors Association, Rosemont, Ill., USA.

Garrett 1980

Garrett, K. W., "An Assessment of the Calculation Methods to Deter-

- mine the Thermal Performance of Slotted Building Blocks," *BSER&T* 1, 24-30.
- Glicksman 1988
Glicksman, L. R., "Models to Predict Aging and R Values of Foam Insulation," pp. 99-112 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, CONF-8809314, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
- Hedlin 1977
Hedlin, C. P., "Moisture Gains by Foam Plastic Roof Insulations under Controlled Temperature Gradients," *Journal of Cellular Plastics* 13, 313-19.
- Hoover 1989
Hoover, T., "CFC/Ozone Jigsaw Leaves RSI Industries Puzzled," *RSI Magazine* 66 (January 1989), 46-49.
- Isberg 1988
Isberg, J., "The Thermal Conductivity of Polyurethane Foam," Publ. 88.1, Chalmers University of Technology, Division of Building Technology, Göteborg, Sweden (in Swedish).
- Khalil 1986
Khalil, M. A. K. and Rasmussen, R. A., "The Release of Trichlorofluoromethane from Rigid Polyurethane Foams," *Journal of the Air Pollution Control Association* 36, 159-63.
- Kugler 1986
Kugler, N., Morris, L. B., and McCorkle, J. E., "Are 'Aged' Values Adequate for Rating Roof Insulations?" *RSI Magazine* 63 (July 1986), 38-42.
- Larsson 1987
Larsson, L. E., "Determination in Long-term Tests of the Thermal Conductivity of Foamed Urethane Used as a Thermal Insulation in Sandwich Panels," Publ. 87.3, Chalmers University of Technology, Division of Building Technology, Göteborg, Sweden (in Swedish).
- Mainka 1986
Mainka, G. W. and Pachen, H., "Thermal Bridges Catalogue. Tables with Temperature Charts, Isotherms, and Data on Additional Heat Losses," Stuttgart, B.G., Teuber.
- McElroy 1990
McElroy, D. E., "The Technical Viability of Alternative Blowing Agents in Polyisocyanurate Roof Insulation, Part 2: Acceleration of Thermal Resistance Aging Using Thin Boards," pp. 239-46 in *Urethane 90*, Society of the Plastics Industry, New York, USA.
- McElroy 1991
McElroy, D. E., "Thermal Properties of Polyisocyanurate Foam Board Roof Insulation Blown with CFC-11 Substitutes," pp. 133-42 in *Proceedings 1991 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.
- Melton 1988
Melton, B. S., Scott, T., and Childs, K. W., "Thermal Bridge Report: Building Envelope Thermal Anomaly Analysis," U.S. National Technical Information Service, DE99-006056, Washington, D.C., USA.
- Muhlenkamp 1983
Muhlenkamp, S. P. and Johnson, S. E., "In-Place Thermal Aging of Polyurethane Foam Roof Insulations," pp. 49-55 in *Proceedings, 7th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.
- Norton 1967
Norton, F. J., "Thermal Conductivity and Life of Polymer Foams," *Journal of Cellular Plastics* 3, 23-37.

Paljak 1972

Paljak, I. and Petersson, B., "Thermography of Buildings," The National Swedish Institute for Building Research, Stockholm, Sweden (in Swedish).

Petersson 1980

Petersson, B. and Axen, B., "Thermography. Testing of the Thermal Insulation and Air-tightness of Buildings," Swedish Council for Building Research.

Reeves 1992

Reeves, E., "Phenolic Insulation: One Material Standard, with Vast Differences," *Professional Roofing* 22, 26-28.

Salgon 1987

Salgon, J. J. and Neveu, A., "Application of Model Analysis to Modeling of Thermal Bridges in Buildings," *Energy and Buildings* 10, 109-20.

Schwingen 1984

Schwingen, W., "RIC/TIMA: R-Values of Insulations," *RSI Magazine* 61, 62-64.

Sheffield 1988

Sheffield, C. F., "Description and Application of a Diffusion Model for Rigid Closed-Cell Foams," pp. 113-30 in *Proceedings, International Symposium on Mathematical Modeling of Roof Systems*, CONF-8809314, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Siviour 1988

Siviour, J. B. and Mould, A. E., "Thermal Bridging: Significance in U-Value Calculations," *BSER&T* 9, 133-35.

Snyder 1986

Snyder, M. K., "Heat Transmission Coefficients for Metal Building Systems," *ASHRAE Transactions* 92, Part 2B, 577-83.

SPI 1979

An Assessment of the Thermal Performance of Rigid Polyurethane and Polyisocyanurate Foam Insulations for Use in Building Construction, Urethane Division Bulletin, Society of the Plastics Industry (August 1979), New York, USA.

SPI 1988

Society of the Plastics Industry, Polyurethane Division Special Task Force, "Rigid Polyurethane and Polyisocyanurate Foams: An Assessment of Their Insulating Properties," pp. 29-41 in *Proceedings of the SPI 31st Annual Technical/Marketing Conference*, Philadelphia, USA., October 1988.

Standaert 1985

Standaert, P., "Thermal Bridges: A Two-Dimensional and Three-Dimensional Transient Thermal Analysis," pp. 315-28 in *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE/DOE/BTECC Conference, held at Clearwater Beach, Fla., USA, December 1985.

Swedish Building Code 1975

Swedish Building Code 1975 (3rd ed. 1978), The Swedish National Board of Physical Planning and Building, Stockholm, Sweden (in Swedish).

Tobiasson 1979

Tobiasson, W., Ricard, J., "Moisture Gain and Its Thermal Consequence for Common Roof Insulations," pp. 4-16 in *Proceedings, Fifth Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.

Tye 1985

Tye, R. P., Silvers, J. P., Brownell, D. L., and Smith, S. E., "New Materials and Concepts to Reduce Energy Losses Through Structural Thermal Bridges," pp. 739-50 in *proceedings*

of *Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE/DOE/BTECC Conference, held at Clearwater Beach, Fla., USA, December 1985.

Valenzuela 1981

Valenzuela, J. A. and Glicksman, L. R., "Thermal Resistance and Aging of Rigid Urethane Foam Insulation," pp. 259-79 in *Proceedings DOE/ORNL Workshop on Mathematical Modeling of Roofs*, CONF-811179, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Zarate 1982

Zarate, J. L. and Alumbaugh, R. L., *Thermal Conductivity of Weathered Polyurethane Foam Roofing*, Naval Civil Engineering Laboratory Report N-1643, Port Hueneme, Calif., USA.

4.5 MOISTURE INTRUSION AND EFFECTS OF RETENTION

4.5.1 Membrane Blistering

4.5.1.1 Statement of the problem

Blistering is the presence of separations or voids within a membrane or between a membrane and substrate that cause premature roof failure. Blistering is not always insulation related, but the incidence of blistering is substantially increased when BUR is installed over insulations with entrapped moisture or directly over closed-cell, thermosetting foam insulations (PUR, PIR, or phenolic). Blistering occurs when water or water vapor migrates into voids in the interply mopping asphalt. Vapor pressure increases, caused by solar roof heat, cause void growth and subsequent interply separation.

4.5.1.2 Evidence

General descriptive material. The mechanism that forms blisters in BUR is described by Griffin (1982). He notes that roofing experts generally agree that a void in either the interply mopping or at the insulation-membrane interface is essential for the development of a blister. This void is generally, but not necessarily, initiated when the BUR is applied. Griffin reports that moisture from wet insulation will enter a membrane void and cause blister growth, particularly if underside venting is inhibited by the presence of a vapor retarder. Both Baker (1980) and Griffin reported that BUR blistering had become a widespread roofing problem in the late 1970s when BUR was installed directly on top of closed-cell PUR insulation.

Field evidence. A field testing program was initiated in 1978 by the Western States Roofing Contractors Association in the United States to establish that BUR blistering over PUR insulation was not related to the quality of application workmanship (Porcher 1981). The test roofs were installed with high quality workmanship directly over closed-cell foam insulations in three cities with a range of climates: Tucson, Arizona; Salt Lake City, Utah; and, Seattle, Washington. Blistering developed in all the roofs.

Laboratory evidence. In 1979, laboratory testing sponsored by the NRCA was conducted by Southwest Research Institute (Porcher 1981). To compare blistering tendencies, various types of roof insulation were mopped with hot asphalt under typical roof conditions. Over the closed-cell foam insulations, a large portion of the mopping asphalt contained voids. Over porous wood fiber, perlite, and mineral wool insulations, almost no voids occurred. The identity of the gases that

evolved during hot asphalt application was determined by gas chromatography. The conclusion was that the most probable mechanism for blister formation involved evaporation of surface moisture from the insulation by the hot mopping asphalt, coupled with trapping of the evaporated moisture if the insulation was an impermeable, closed-cell foam.

Similar laboratory tests were conducted in 1978 by Structural Research, Inc., with NRCA sponsorship (Porcher 1981). The tests used PUR, PIR, and phenolic insulation boards made with fiberglass facers that had been adopted in hopes that their relatively low equilibrium moisture content would prevent blistering. Insulation samples were preconditioned at both 50% and 75% relative humidity. Even with the newer fiberglass facers, enough asphalt voids formed and grew to cause Structural Research, Inc. to recommend that a porous insulation board be employed between closed-cell foam insulations and BUR. It was also noted that ventilating base sheets may not provide sufficient protection against roof blister formation under severe application conditions.

Modeling. Blister modeling by Lindholm at Southwest Research Institute in 1980 gave further support to the belief that the mechanism for blister formation involves surface moisture and low insulation permeability (Porcher 1981). Lindholm concluded that diffusion of the CFC blowing agent within the closed-cell insulations would not be toward the hot mopping asphalt. Evaporated moisture from the insulation surface caused voids to form and grow in the mopping asphalt.

4.5.1.3 Analysis

Significance of the problem. Field experience coupled with laboratory and field testing has established that the installation

of BUR directly over closed-cell foam insulation increases the risk of membrane blistering. The extent of this problem was great enough to cause both insulation manufacturers and roofing contractors to undertake extensive research. A virtually complete industry change to low equilibrium moisture content fiberglass facers demonstrates the need for product improvements. NRCA issued Technical Bulletins 4 (1979), 7 (1981), and 9 (1988) recommending that BURs not be installed directly over closed-cell foam insulations.

Available remedies. NRCA Bulletins 4 and 7 recommended the use of either a ventilating base sheet or porous insulation (wood fiber, perlite, or mineral wool) between closed-cell foam insulations and BUR. However, Bulletin 9 subsequently eliminated the ventilating base sheet as a recommendation.

Kindermann reported in a technical paper presented to the Congress of Cellular and Non-Cellular Polyurethane in 1980 that BUR had been used successfully in Germany over rigid PUR insulation for 15 years through the installation of a "vapor pressure compensation layer" between the foam insulation and the BUR membrane (Porcher 1981). Perforated base sheets have been used in Europe for many years to attach the membrane by flow of hot asphalt through the perforations only. This spot-bonding to the insulation may provide more blister venting relief than the unperforated venting base sheets commonly used in the United States. If blistering occurs in an existing BUR system, techniques are available to relieve the pressure in the membrane. One example is the pressure relief valve developed at the U.S. Army Corps of Engineers Cold Regions Laboratory (Korhonen and Greatorex 1983).

Secondary effects of remedies. The only deleterious effect of installing porous fibrous insulation between closed-cell foam insulation and BUR is increased roof costs, which can be justified by the longer life of blister-resistant roofing.

4.5.2 Localized Ponding and Freezing of Pools of Water

4.5.2.1 Statement of the problem.

Insulation increases the severity of problems associated with ponding and poor drainage of water. Insulated membranes are colder for longer periods in winter. This circumstance increases the depth, area, and duration of ponding from snow and frozen melt water on roof areas with deficient slope and/or poor drain design and location. The consequence is increased risk that the membrane will split from freeze bonding of water pools and that water will enter the roof system over the tops of flashings or through defects in the membrane.

4.5.2.2 Evidence

General descriptive material. Griffin (1983) notes that a sloped, water-shedding roof can tolerate minor imperfections in both design and construction and still perform its primary waterproofing function. In stark contrast, a roof that chronically ponds water requires perfection—or near perfection—in design details and application quality. The amount of water that leaks into a roof system, or into the building beneath it, is directly related to the volume of water feeding the leak. If the leak is through a flashing in a water run (valley), the area of the roof that drains into the run affects the amount of the leak. Baker (1980) notes that the amount of leak water penetration through a membrane

defect depends directly on the amount of time that water lies on it. Griffin (1983) noted that ponding supplies a volume of leak water proportional to the ponding area and exponentially related to its depth.

Accumulated snow provides a continuing source of melt water when it is heated by solar radiation, warm air temperatures, or heat loss through the roof (Baker 1980). Roof insulation reduces heat loss through a roof and thereby significantly increases the reservoir of snow for conversion to melt water during warm weather. Ice formation at colder areas of a roof may produce a dam that prevents melt water from flowing to roof drains. The dam increases water accumulation in roof depressions and greatly increases the amount of water available to enter any membrane leak source. The redistribution of melt water back-up during warm weather can produce structural deflection of decking and thick ice formation during subsequent freezing weather. Baker (1980) states that water penetration will cause progressive deterioration of membranes and insulations and is a principal hazard to the integrity of the system.

Prolonged exposure to ice, slush, and back-up melt water makes roof repairs almost impossible. Even after warm weather eventually evaporates all rooftop water, deposited sediment makes it much more difficult and costly to make proper roof repairs (Griffin 1983). Firman (1989) notes that weak points of any roof system must be readily accessible for inspection and maintenance. He states that protected membrane systems using elastoplastic single-ply membranes are not considered maintainable systems, because the logistics of moving and storing the ballast make it virtually impossible to achieve the necessary inspection and maintenance of the membrane seams. Firman also noted that

about one-third of U.S. manufacturers' roof warranties exclude damage resulting from lack of adequate drainage.

Field evidence. The hypothesis that ice played a definite role in membrane splitting was prevalent enough in the 1960s that members of ASTM Committee D8 were charged with finding evidence for a relationship between ice formation and splitting. Most committee members agreed that ice was an important factor, but they could not come forward with any convincing evidence (Riedel 1985).

Riedel investigated the cause of catastrophic splitting of spray-applied PUR roofing installed over old, insulated, flat, gravel-surfaced roofs in Indiana and Canada. He concluded that ice was the cause because the roof splits ran in all directions randomly without any relation to layout of components in the roof system. Roof splits caused by freezing of ponded water have also been reported in Sweden (Fahlstrom 1980).

Baker (1980) reports that membrane splitting has been directly related to ice splitting on many roofs with thick layers of ice. The membrane splits followed exactly the haphazard pattern of the ice splits that occurred with sudden impact and loud noise as a result of thermal movement in the ice. Baker does not believe that thin ice from shallow ponding can cause roof splits. He notes that many roofs in Canada have thin layers of ponded ice, but only a few have encountered splitting. The splitting in those cases was generally traced to other causes. Membranes with low inherent strength or ones weakened by wetting or freeze-thaw cycles may be more prone to splitting. Moreover, stress transfer from ice plates is unlikely to occur on roofs with gravel or similar surface roughness. Therefore, Baker infers that membrane splitting associated with thin layers of ice would

probably be limited to weak, smooth-surfaced BURs.

Laboratory evidence. The amount of slope needed to drain melt water is not well defined. Schaefer showed that the good insulating characteristics of snow cover can keep much of the region between the roof membrane and the snow surface at a temperature above freezing (Riedel 1985). For example, with roof insulation having a thermal resistance of $1.75 \text{ (K} \cdot \text{m}^2\text{)W}^{-1}$ [$(10^\circ\text{F} \cdot \text{ft}^2 \cdot \text{h})\text{Btu}^{-1}$] and 7.6 cm (3 in.) of snow, the interface melts at an outside temperature of about -21°C (-5°F) for an inside temperature of 21°C (70°F). If a roof does not have a uniform snow cover, the snow can melt in one place and refreeze at another. Actual conditions found in Wisconsin verified this. A school roof with $R_{SI} = 1.75$ ($R_{US} = 10$) insulation and 1:12 (1 in. per ft) roof slope was found to have ankle-deep slush under a foot of snow on a cold day without sunshine. During subsequent nighttime cold, the heavy layer of slush can become a thick layer of ice (Riedel 1985).

Both ponding and freezing can have very detrimental effects on the strength that some membranes need to resist splitting. Laboratory tests by Laaly (1977) on a BUR membrane showed an 81% loss of strength after 110 days of water immersion and an 89% loss of strength after ten freeze-thaw cycles.

Modeling. Most ponding problems can be understood without the use of mathematical modeling. But ice melting and refreezing under various weather and snow loading conditions, as well as the stress transfer effects of ice bonding to membranes, can be mathematically modeled. For example, the influence of frozen ponded water on membrane splitting has been modeled in Sweden (Cederwall 1983).

4.5.2.3 Analysis

Significance of the problem. The major deleterious effects of ponded water on a roof are widely recognized. Handegord (1966) provides a concise statement about them: "Control of water penetration through flat or low-slope roofs can only be accomplished by the use of a continuous, watertight membrane. Perfect watertightness is not only difficult to achieve, it is even more difficult to maintain. If a roof is designed to be level, ponding of water is inevitable. Not only will this lead to accelerated deterioration of the roof membrane, but the water retained on the surface will act as a reservoir to supply any leak that develops and thus increase the quantity that enters the roof system."

Empirical evidence has shown that the snow depth and the resulting melt water reservoir on a roof increase as insulation is added. Both field observations and mathematical calculations show that heat loss through a roof and solar radiation produce slush and melt water. Localized refreezing from temperature variations across a roof causes melt water back-up even when some roof slope is present. Ponding depth increases, leading to thick ice formation at night. These consequences of more roof insulation increase the severity of potential ponding and ice splitting problems. The increased amount and duration of snow, slush, and melt water also make roof maintenance much more difficult.

Available remedies. Remedies for ponding and ice splitting are good roof drainage design and the use of the most puncture-resistant and split-resistant roof membranes available. Good drainage design is more than just an increase in roof slope. Equally important are the location, frequency, and types of scuppers/drains that are used. Drains must be located at the

points of lowest elevation on a roof. Consequently, they usually will be located at mid-span rather than next to a roof deck column or beam support. Enough drains must be used to carry off heavy rain water and minimize melt water back-up. Interior drains are usually preferred in cold climates so that heat loss from the building interior will prevent ice damming.

Exterior scuppers or drains can freeze easily and prevent drainage, especially if they are located in shaded areas of a roof. It is usually better to locate scupper leader runs down the inside of an exterior wall or to provide large overflow openings in scuppers to prevent freeze blockage. Large rooftop equipment should be avoided, because it often serves as a water dam. At the very least, added roof thickness (crickets) must be installed on the high side of roof penetrations to prevent ponding.

Gravel surfacing is often used, at least in ponded areas and valley water runs, to minimize the risk of ice splitting. The presence of the rough surface may help to prevent ice splitting, but gravel can also interfere with roof repairs. It may be preferable to use highly puncture-resistant and split-resistant membranes that are easy to repair.

Secondary effects of remedies. If drainage must be installed to correct ponding after the roof is constructed, more than considerable cost is involved. It may be necessary to cut through the deck or other structural supports in ways that compromise the load-bearing capacity of these structures.

4.5.3 Roof Leak Detection and Correction

4.5.3.1 Statement of the problem

Roof insulation complicates leak detection and makes repair more difficult. Insu-

lation can hide the source of a leak because moisture travels laterally within the insulation. Leak or condensate moisture storage within insulation can produce a long time lag between leak occurrence and leak detection. The result may be damage to roof system components over a large area of a roof before repairs are made. Insulation makes roof leak repairs more expensive because, in addition to membrane patching, replacement of all wet insulation is often needed to preserve the investment in the total roof system.

4.5.3.2 Evidence

General descriptive material. A basic function of a modern roof is to prevent water leakage and subsequent damage to interior space. Energy conservation and control of the interior building environment for its desired occupancy and use are important, but secondary, concerns.

Damage to a roof system itself from moisture intrusion can progress rapidly, and repair can be costly or impossible. The damage can often happen before leakage into the building is significant enough to warn of problems with the roof. Even if water does not enter the building to damage the interior, it attacks the insulation (Baker 1980). Most insulations used in compact low-slope roof systems, including cellular foam insulations, must be kept dry to retain their insulating ability and other desirable features (Tobiasson 1982).

Insulation materials can absorb significant amounts of moisture. In fact, the moisture content for some insulations can exceed several times their dry weight. Table 4.1 provides laboratory and field data on the moisture pickup for various roofing materials. The agreement between laboratory and field data is reasonably good. Differences in the low values are expected because temperature and humidity condi-

tions cannot be controlled for field samples. The discrepancy between the full immersion value and the highest field measurement suggests that EPS retains more water the longer it stays wet.

This ability to store water causes insulation to act as a water reservoir within a roof system (Schwartz 1977). As a result, interior building leaks are sometimes encountered many hours after all water on top of the roofing membrane has drained away or evaporated. No other component of the entire roof system, including the deck and membrane, has a similar capacity for water entrapment. Every roofing crew that has torn off old roofs knows that waterlogged insulation is extremely heavy compared with dry insulation.

Wet insulation damage observed during a roof tear-off typically does not extend to more than 15% of the total roof area (Tobiasson 1982). The large investment in high-thermal-performance roof insulation makes it critically important to locate and preserve the large amount of good, dry insulation on an old roof when reroofing is done. The safest practice, total tear-off during reroofing, will eventually become economically prohibitive to building owners as energy efficiency requirements demand larger amounts of insulation. Better record keeping on the history of locations of roof leaks and areas of roof ponding will be essential to identify localized areas where damaged, wet insulation is most apt to occur. This information, together with improved moisture surveys, should locate most wet insulation that must be replaced.

Laboratory and field evidence. Link (1977) and Tobiasson (1985) have demonstrated that wet areas of insulated roofs can be located by nondestructive infrared, nuclear, and capacitance measurements that differentiate between the properties of wet and dry insulation. Link described the use

Table 4.1. Laboratory and field measurements of moisture content in roof materials

Type material	Laboratory		Field samples	
	Equilibrium 95%RH, 24.4C	Maximum (by immersion)	Lowest (from core)	Highest (from core)
Organic builtup membrane (field sample size: 607)	1	20	0.15	28
Fiberboard (field sample size: 1984)	12	430	3.8	480
Perlite (field sample size: 249)	4	580	0.39	533
Glass fiber (field sample size: 166)	2	610	0.64	580
Urethane (field sample size: 160)	6	520	1.3	552
Expanded polystyrene (field sample size: 73)	3	540	5.29	2,446
Light weight concrete (field sample size: 74)	6	110	2.95	114
Cellular glass	0.01	30	NS ^a	NS ^a
Extruded polystyrene	0.5	10	NS ^a	NS ^a

^aNS = no samples available

Source: Anderson, R. G. 1985. "Dry Range and Wet Range Moisture Content of Roofing Materials as Found in Existing Roofs," pp. 409-15 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, USA.

of airborne infrared and nuclear measurements for rapid, multi-roof moisture surveys. Tobiasson showed that smaller wet roof areas are missed by airborne surveys and can be detected only by measurements directly on the roof. In all cases, indicated areas of wet insulation must subsequently be confirmed by roof cut gravimetric analysis, because none of the instrumented techniques directly measures the amount of water.

Extensive use of infrared surveys on roofs of military installations has located some roof areas with very wet insulation and resulting energy loss, where no roof leaks had been reported and the roof appeared visually to be good (Link 1977). It is significant that most wet insulated roof areas found in these infrared surveys were relatively small and associated with a drain, vent, or other penetration, or with flashings and roof terminations.

A moisture meter using a nuclear measurement technique was used to locate the source of hard-to-find roof leaks that had short-circuited an electrical busway (Griffin 1982). Remedial repairs based on visual leak source investigation had been ineffective, but the meter was able to trace the long lateral travel of water in insulation to its entry point at a gap in counterflashing between the roof and a penthouse. A computer-analyzed survey with this same type of meter on a blistered BUR with many leaks avoided a complete reroof that would have cost \$210,000 (U.S.). The actual repair cost was only \$62,000 (U.S.) for the 13% of the roof area that was found to contain wet insulation.

NIST investigated the reliability and accuracy of the infrared, nuclear, and capacitance techniques to determine quantitatively the moisture content of BUR samples insulated with mineral wool, perlite, fiberboard, EPS foam and PUR foam,

over concrete and steel roof decks (Knab 1981). All techniques were found to be useful for actual field surveys, but quantitative results varied with the composition of the insulated roofing, the moisture content and its distribution, the temperature, and the type of instrumentation used. The report recommended that nondestructive moisture evaluation of a roof always be accompanied by visual inspection and gravimetric analysis of the moisture in roof core samples.

Laboratory and field measurements described in Table 4.1 show that the equilibrium moisture content and maximum moisture content vary widely according to the type of roof insulation. More detailed results of a large sample of roofs in the source report further suggest that the moisture content of leaky roofs varies almost uniformly from equilibrium values to maximum values depending upon the nature of the roof, the leak, and environmental conditions (Anderson 1985). This finding further complicates attempts to quantify survey results.

In situ drying of wet insulation after leak repair is an attractive but elusive goal. Many "breather vent" products have been introduced to the market. Their purpose is to use the vapor pressure difference between the interior of the wet roof and the ambient to drive moisture from the roof. Testing has consistently shown that these devices are ineffective for drying large areas, mainly because of high air-flow resistance within the insulation (Tobiasson 1983). While their effectiveness increases as they are moved closer together, their cost and the increased possibility of new leaks because of the many membrane penetrations generally make this drying scheme less attractive. Power venting, that is, forcing dry air to move through the wet roof system to vents, can reduce drying

times. However, high costs and mechanical complexities make this an unlikely solution for most wet roof problems. Another suggestion has been to combine a venting system with a wicking material (Glicksman 1985). The wicking material is laid out as a horizontal sheet in a new roof and extends up the throat of each vent. Outside air evaporates water from the exposed wick and capillary action quickly replaces it. Laboratory tests have shown the feasibility of the technique; it has not yet been field tested.

A more natural drying technique is drying to the building interior (Sheahan 1989). This process can be very effective under appropriate conditions. In fact it is likely, but undocumented, that drying to the interior is widely responsible for removal of roof water in most patched roofs. The simple mechanism involved is transport of water from the wet system to the upper side of the deck, passage through the deck, and evaporation to the interior. This mechanism is being studied aggressively because of the critical importance of removing water from old roofs scheduled for recover without tear off (Pedersen 1991; Pedersen 1992).

Modeling. Early work on water vapor migration and condensation in roof systems was reviewed by Busching, et al. (1978). More recently, a comprehensive model for combined heat and moisture transfer has been developed by Pedersen (1990) and used to investigate the drying rates of wet, in situ roof insulation and to predict the reduction in the R-value of mineral wool insulation due to evaporation/transport/condensation cycling under diurnal weather conditions. Burch (1991) has also developed a model for describing moisture movement in building construction. Sheahan (1989) has developed a technique that employs steady-

state moisture diffusion for solving roof drying problems under special conditions. Childs (1985) has developed a numerical surface model for roofs that predicts surface temperature for a range of roof systems, for environmental and solar conditions, and for wet insulation. Empirical relations are developed from the data base to predict the success of infrared surveys for various conditions.

4.5.3.3 Analysis

Significance of the problem. The potential for damage by water penetration into a roof is exacerbated by insulation. Insulation allows water to migrate rapidly from a leak source, making it difficult to identify sources. Insulation also has a high capacity for water absorption. This absorption delays the time between water entering the roof and appearing as a leak. In addition, the water can remain in the system for long times, which increases the likelihood that wood and organic material will rot, metal will corrode, and dimensional changes will occur in system components. Retained water also reduces the thermal resistance, thereby increasing building energy costs.

Available remedies. Good roof drainage is critical. Baker (1980) states that the severity of moisture damage to insulation is influenced by the quality of roof drainage even on protected membrane roofs. Roof details and flashings must have the highest practical quality. Nondestructive moisture surveys on many roofs have shown that most leaks occur at the roof perimeters, penetration flashings, and drains. From a roofing survey of U.S. Air Force buildings, Tobiasson (1982) concluded that 80% of all roof leaks occur at flashings and embedded sheet metal details.

Semiannual roof inspection and maintenance are needed to correct small problems before they become major failures. Fortunately, lateral movement of water is usually slow within the insulation on low-slope roofs with good rooftop drainage. Usually, only a small percentage of total roof area is affected by water attack. This fact decreases the cost of roof maintenance provided wet and dry areas can be differentiated. Weak points in any roof, such as flashings and membrane laps, must be readily accessible for inspection and maintenance actions. For this reason, Tobiasson (1982) claims that ballasted or protected-membrane, elastoplastic single-ply roofs cannot be adequately maintained.

Secondary effects of remedies. As with ponding, installing extra drainage to correct the causes for leaks can cause weakening of the roof support system.

4.5.4 Condensation Effects From Trapped Water

4.5.4.1 Statement of the problem

Water from construction or other sources can be trapped inside a roof system. If it is trapped locally, with no means for lateral dispersion, alternate cycles of evaporation and condensation can lead to local blistering. If the moisture can move, temperature fluctuations and some combination of capillary flow and diffusion induced by a vapor pressure differential will keep it constantly in motion. Condensation will occur when the local temperature falls below the dew point. But, especially for small amounts of water, diurnal and seasonal temperature fluctuations will soon cause evaporation and subsequent drying.

If portions of a roof do remain wet for extended periods, problems can occur. Liquid condensate in a roof can degrade nonmetal materials, cause metals to cor-

rode, and encourage rot and mold of organic materials. It also affects the thermal performance of the system. Not only does it increase the effective thermal conductivity of the insulation, but also it allows heat transfer through moisture movement in the roof (Pedersen 1991). Insulation also thermally isolates the components above it from the moderate temperature of the building interior. If the ambient temperature is sufficiently low, any condensate that has formed might freeze into ice underneath the membrane. When the ice melts, a relatively large amount of water could be released suddenly to run down through the roof.

4.5.4.2 Evidence

General descriptive material. Moisture trapped inside a new roof system most likely will be from one of two sources: It was trapped during construction or it entered from the interior of the building. So-called construction water is due to the failure to protect the roof system against precipitation during the construction period or due to the use of wet materials to construct the system. Some materials must be kept dry. For example, most thermal insulations must be well protected against wetting during the entire process from manufacture to installation. Other materials necessarily contain large amounts of water right after construction. For example, a concrete deck has on the order of 100 kg/m^3 (6 lb/ft^3) of water when cast. Most of it must leave the construction before stable thermal performance can be expected.

Small amounts of water are not usually a problem. Dispersal throughout the roof or evaporation usually will neutralize their effect before any damage occurs. If wet insulation is installed, or if rain or snow directly wets the roof interior during the

construction period, the drying period is much longer. The risk of moisture damage increases, especially if the thermal insulation and other moisture-sensitive materials are placed between two layers that are both water impermeable. Drying is effectively prevented, and some moisture damage is likely.

Moisture from room air enters a roof space through diffusion or convection. Diffusion of moisture results from differences in the partial pressure of water vapor between room air and the roof interior. This difference in vapor pressure is usually small. When it is not, for example, because of the high room-air moisture content above interior swimming pools or in wet kitchens, a vapor retarder is advisable. Mechanical humidification and reduced interior ventilation resulting from energy conservation measures can also be sources of enhanced room-air moisture content.

If parts of a roof are vented, for example, in cold deck roof systems, air convection can move moisture from the room into the roof. This movement will usually occur even when a moisture retarder is used because it is so hard to seal leakage paths around penetrations. Moisture will be driven into the roof system by the air overpressure between room air and the roof cavity, especially in tall buildings and when the outside air is cold. Wind and mechanical ventilation systems can also contribute to this effect.

Convective moisture transfer may also occur from outdoor air via leakage paths in the roof construction. Roofs with profiled sheeting as the roof covering are a special case. In addition to moisture movement from the indoor air, the moisture in the outdoor air condenses on the inside of the sheeting in the ventilation channels formed between the sheeting and the insulation. This condensation occurs when the

temperature of the external sheeting is lower than the dew point of the outside air, for instance, on cold nights, on warm spring days when snow is on the roof, or during cold summer rains.

Whether the thermal insulation is placed above or below the membrane affects potential moisture problems greatly. When the ambient temperature is cold and most of the total insulation value in the roof is installed above the membrane, then everything below the membrane is warm. The possibility of cold bridges is diminished, and there is less risk of moisture damage. When most of the thermal insulation is below the membrane, the membrane itself is cold. Andersson (1979) deals with this problem for walls and roofs. She showed that, as more insulation is installed below the membrane, the risk of condensation at cold bridges and other cold elements in the construction increases.

Field and laboratory evidence and modeling. Thermal insulation installed outside a membrane, a so-called protected membrane system, mitigates potential moisture problems in a roof. It makes no difference whether the roof is new or recovered. Petersson (1983) reached this conclusion by examining conditions before and after insulation was added to different types of roof constructions. He predicted the results theoretically, and his conclusions were confirmed by results from a number of test roofs.

Particularly, when insulation is added to an existing roof, it is particularly essential that the climate control and ventilation characteristics of the building are understood. Both the performance of the existing roof and the effects of additional insulation should be predictable to ensure that condensation damage does not spoil the effect of the added insulation. Petersson also points out that workmanship must be of

high quality to ensure that the installation of the additional insulation achieves the design goals.

Research on test roofs has shown that adding insulation directly to the top of the outer surface of roofs improves moisture control and thermal performance (Höglund 1988). In sheeting roofs consisting of loadbearing profiled sheeting and thermal insulation covered by a weatherproof membrane, Samuelsson (1976) has demonstrated that moisture moves into the roof space from inside the building and condenses on the underside of the membrane. The moisture moves through overlaps between the sheets or through holes in the sheets. Inside the roof, transfer of vapor occurs by diffusion, upward through the thermal insulation during wetting or downward during drying. Vapor also moves through the gaps between layers of thermal insulation by diffusion or convection. Liquid water moves under the action of gravity.

4.5.4.3 Analysis

Significance of the problem. Damage due to condensation can occur in roof constructions. The source of the water can be moisture that moves by convection or diffusion from the building interior or other spaces next to the roof. The damage due to condensation of water from outdoor air is seldom major. Another source is construction water. Normally it is present to some extent in roofs as built and the problems caused by it are, in most cases, confined to the first heating season. Retrofit efforts to increase the airtightness of building envelopes, combined with increased thermal insulation to save energy, can also contribute to an increased moisture load. When thermal insulation is placed between two water-impermeable layers in a roof system, the risk of moisture problems is in-

creased. However, up to now, only isolated instances of such problems have been recorded.

Available remedies. To stop the construction water in a concrete deck from diffusing up through the thermal insulation, a vapor retarder can be laid on top of the deck below the insulation. It should be sealed carefully at joints and around holes for penetrations. The water in the concrete must then escape downward into the interior of the building by diffusion. Either the underside of the deck is left unfinished, or it is painted or coated with materials that offer little resistance to water vapor diffusion.

The following practices should prevent humidity in the indoor air from moving into the roof by convection:

- Make the roof deck airtight.
- Reduce the level of humidity in the interior of the building.
- When reroofing over an existing roof, place enough thermal insulation on the outside of the existing roof covering that no condensation will occur on the underside of the old roof covering.

To prevent abnormal quantities of construction water from being trapped in the roof, observe the following simple rules:

- Do not accept delivery of materials containing abnormally high quantities of moisture.
- Cover stockpiles of materials on the construction site to protect them against rain and snow.
- Carefully cover parts of roof surfaces that have not been completed at the end of each shift.

If there is a risk that moisture will be trapped in the construction and could cause damage, an estimate of the effect of this moisture should be carried out in time to modify design and construction plans. But, if construction water can dry to the ambient air or to the interior, the problem is probably confined to the drying period (normally about a single heating season) and should be of no concern afterward.

The presence of condensation under a membrane entails the risk that water will drip out of the roof. If the water path is through joints between insulation boards, this risk is reduced by laying the insulation in several layers with the joints staggered. Placing a vapor retarder below the thermal insulation prevents moisture in the indoor air from entering the thermal insulation. However, it also prevents construction moisture from escaping into the interior of the building. This prevents drying so that the roof may never achieve its design thermal performance.

4.5.5 Diurnal Hygrothermal Cycling

4.5.5.1 Statement of the problem

Diurnal hygrothermal cycling is the movement of moisture within the roof system and between the roof system and its surroundings due to diurnal variations in conditions imposed on the roof. It occurs in all roof systems permeable to water vapor. Changes in external weather, in environmental conditions in the enclosed space, and in setpoints of the heating and cooling system all have significant seasonal and diurnal effects. With some roof systems, the diurnal variations of the external climate, particularly solar radiation, can create rapid changes in the hygrothermal conditions within the roof system. Insulation plays a central role in these effects.

Diurnal moisture cycling in roofs has not been a particularly well researched topic in the past. This lack of research has been due largely to the absence of transient modeling capability with which to interpret test results and to predict untested behavior. Also, there was the perception that there was little practical value in understanding roof moisture dynamics. Not so now! Transient models are available and important issues are appearing as a direct consequence of moisture dynamics. Diurnal latent heat transport in wet mineral wool insulations measurably affects thermal performance (Hedlin 1988; Pedersen 1991). Materials are now available that offer significant improvements over conventional water vapor retarders (Korsgaard 1985).

4.5.5.2 Evidence

General descriptive material. Failures of roof systems due to water damage can be found in most countries. In almost all cases, although the movement of moisture within the roof system is influential, other factors, such as leaks in the membrane or faults in vapor retarders, are identified as the main cause of failure. Detailed analysis of the diurnal effects is ignored in the failure analysis.

Diurnal processes can lead to effects such as blistering, corrosion, condensation under the membrane, summer condensation, or a one-way heat-pipe effect in mineral wool insulation. They contribute in some part to most of the moisture-related problems of low-slope roofing. The most common failures directly caused by diurnal hygrothermal cycling are failures due to blistering of BUR membranes that are not related to surface moisture on foam insulations during application.

Most methods commonly in use to determine the risk of interstitial condensation

assume steady-state or quasi-steady-state conditions. The main driving forces for moisture movement are postulated to come from within the building during the winter heating season. These methods approximate the actual risk, but occasionally roof systems experience condensation problems from diurnal effects that are not anticipated by the steady-state analysis at winter conditions. The addition of thermal insulation and its position within a roof system will alter the hygrothermal balance and change the risk of failure. The steady-state, interstitial condensation predictions, which do not account for these effects, may suggest inappropriate designs.

As roofing technology changes to meet the need for energy conservation and to cope with the more common forms of failure due to moisture, there is growing evidence in the United Kingdom and elsewhere that failures due to diurnal cycling are on the increase. Therefore, more refined methods are required to predict the likely consequences of the effects of imposed conditions on diurnal moisture movement within roof systems. The strongest evidence for this claim is the increasing number of reports of failures of metal clad roofs in the United Kingdom due to interstitial condensation. These failures have occurred despite the best efforts to build roofs to standards that protect against the risk of interstitial condensation under winter conditions.

The most quoted example is the failure of a lead-clad roof in the United Kingdom that occurred within a few years after completion. The mode of failure in this case was especially unusual. The roof had been designed as a warm deck type. A good quality vapor retarder isolated the insulation hydraulically from the timber decking. The decking supported the sheets of lead cladding in a way that resulted in

numerous, small, unconnected voids under the cladding. The lead cladding bordering these voids corroded within a few years because of the action of thin films of distilled water that condensed on it.

It was conjectured that the source of this distilled water was rainwater being drawn through the laps between the lead cladding on a typical showery day. The suggested process was that a rain shower followed by a period of bright sunshine created sufficient pressure difference between the voids and external air to draw the rainwater through the overlaps in the cladding. The rainwater trapped between the vapor retarder and the cladding then evaporated and condensed out on the underside of the lead. Subsequent laboratory experiments confirmed that this apparently unlikely process could occur. The roof was redesigned and rebuilt to incorporate a continuous void between the cladding and the vapor barrier in an attempt to prevent the pressure built-up. The situation is being monitored and the solution is apparently successful.

The term "thermal pumping" was coined to describe the process that caused the collapse. Since then, similar cases have been identified. The preceding example is quoted in detail to demonstrate the complexity of potential failures due to the diurnal hygrothermal processes that may occur in roofs. They occur despite design and construction to the highest standards to keep the weather out and prevent the migration of moisture into the roof system from the building under winter conditions.

Other examples of the potential problems that can arise in roof systems from the effects of diurnal changes are available because of various studies of what is termed "summer condensation" (Anderson 1987). The term refers to water that drips out of the ceiling or stains it during spring or

early summer on a clear, sunny day. The phenomenon usually occurs only in cold deck systems with mineral wool insulation under plywood or other wooden materials. Studies carried out in Scandinavia, Canada, and the United Kingdom show that, during winter, moisture can be driven inward through an imperfect vapor retarder and condense inside the roof or be adsorbed in the wood. Once moisture in any quantity has gotten into a well-sealed roof system, it can be driven by the heat of the sun to the vapor retarder, condense there, and leak through any flaws in it.

Field and laboratory evidence. Few references are available describing field and laboratory monitoring of low-slope roof systems to detect moisture movement within the roof systems due to diurnal changes. The work of Korsgaard (1989) in Denmark and associated work in the United Kingdom are providing some valuable data. Most other studies have concentrated on the long-term effects of moisture transfer from the inside of the building during the winter heating cycle. With this focus, the diurnal variations have either gone undetected or unreported.

Work at BRE and elsewhere during the 1950s drew attention to the risks of condensation forming on the underside of simple sheeted roofs under clear nighttime sky conditions. At that time in the United Kingdom most roofing material was asbestos, and the cavities were not filled with insulation. Thus the moisture could be absorbed in the roofing material or carried off in the ventilation air without condensing.

It is not surprising that few field and laboratory measurements exist for diurnal hygrothermal effects. It is necessary to gain access to the inside of the roof spaces for field measurements, which is difficult in itself. Moreover, the appropriate types and numbers of sensors must be in place to

detect moisture movement within the roof space with the accuracy and response time necessary to follow diurnal variations.

Modeling. Dynamic models of the thermal and hygrothermal performance of buildings have been available for many years. However, most of these are tailored to analyze a complete building. They are rarely capable of being modified to examine in detail the performance of individual elements of the structure of a building to the required accuracy for diurnal variations.

The dynamic hygrothermal process within even the simplest of building structures is a complex process that requires three-dimensional modeling of the roof space. Knowledge is required of at least the following:

- the pore structure, vapor permeability and thermal properties of the materials in the roof space;
- the equations governing the physical processes of vapor diffusion, heat transfer and liquid water movement;
- the boundary conditions that set the limits on the vapor, heat and liquid water movement across the roof space; and
- independent measurements from field or laboratory studies that validate the model.

There is considerable research activity to obtain much of this knowledge. The work of Korsgaard and others, referred to in the previous subsection, is particularly relevant.

4.5.5.3 Data analysis

Significance of the problem. There is theoretical and physical evidence to support the hypothesis that adding insulation

to roofs changes the diurnal hygrothermal balance. It is harder to get evidence that these modifications change the risk of problems in roof systems due to interstitial condensation. The effects are masked by other moisture-related problems such as rain penetration.

Available remedies. There are no easy ways to prevent diurnal hygrothermal cycling. One limiting solution is a roof system that can dry naturally and reach a stable and safe moisture equilibrium. The other limit is a completely sealed system that remains completely dry during construction and is maintained that way thereafter. Unfortunately, the need to provide a waterproof external membrane to exclude rainwater eliminates drying to the exterior and typical deck designs restrict drying to the interior. Also, roofs that remain completely watertight and completely dry construction materials are elusive concepts.

Cavities that are well ventilated to either the external or internal air allow roofs to dry and prevent the creation of pressure differentials. However, under certain conditions, natural ventilation may draw in moisture to the roof and add to the problem. If necessary, a mechanical venting system can create the overpressure required in the roof void to prevent room air from entering during the winter and to allow drying during the summer. In the United Kingdom, it is recommended that metal clad industrial roofs incorporate an internal lining of metal under the insulation. This added liner acts as a drainage channel for the moisture that accumulates despite the presence of a ventilated cavity.

Besides the use of ventilation, available remedies include the use of new materials such as water-permeable vapor retarders and breathable membranes. They appear to reduce the long-term moisture load in roof voids, but there is still a risk that mois-

ture may accumulate in vulnerable areas during the drying-out process. Conversion of a cold deck system to a protected membrane system by adding insulation on top of the existing membrane not only improves thermal performance, but also should increase the temperature of the wood deck above the dew point of room air during the winter.

4.5.6 Research Needs

Research is needed on all aspects of moisture problems in roofs: how to prevent moisture from entering; how to detect the amount that has entered, including instruments to detect whether moisture is present and to monitor the actual amount; how long it is tolerable to retain moisture; and how to dry the roof out.

To prevent localized ponding and freezing of pools of water, which serve as a reservoir for leaks, modeling is needed to define optimum roof slope and drainage design for various climatic conditions; varying amounts of roof insulation; and different roof coverings, including membrane-type roofing and metal roofing. More technical information is needed on the significance of roof surface color and texture so that solar radiation can be used to minimize snow, ice, and melt water build-up on high-thermal-performance roofs. The interrelated problems of icicle formation and hazardous snow slides also need more study for various insulated roof systems. Research is also needed to find the relationship between building activities and the moisture loads on roofs from convection of room air into the roof. Relatively simple analytical models should be developed so that roof system designers may identify potential condensate problems from sources such as construction water and moist air convected into the roof from spaces adjacent to it.

For moisture trapped in the roof, existing moisture detection techniques are reasonably effective at identifying wet areas. Additional work is needed to improve their reliability. Research is needed to develop nonintrusive methods that provide a quantitative measure of the amount of moisture in a wet roof system. Moisture alert sensors embedded in roofs for leak detection and location are needed for niche markets such as roofs directly over computer rooms.

Related research should address the question of how wet insulation needs to be before removal is recommended. Since some drying always will occur, the issues more precisely are

- What is the drying rate for a specific system in a specific environment?
- What is the effect of waiting for drying to occur?
- How long can a specific system remain wet before some sort of irreversible deterioration starts to occur?

Key factors are the amount of water involved and the timing: whether the insulation is too wet to dry out before the moisture present can damage the new system. The Single-Ply Roofing Institute in the U.S. is developing a procedure to help answer this question in special cases (SPRI 1992). As an example, in Fig. 4.2, the old system is fibrous insulation over a metal deck. The fibrous insulation has known water vapor permeability and known saturation water content, and the deck has a known "effective" water vapor permeability. The new system has sufficient new insulation that the temperature at the old membrane surface is nearly the same as the interior temperature. In this case, the water vapor pressure difference and the rate at which water is transported from the roof to

Fig. 4.2. An example of downward drying of a wet roof. The wet roof is recovered. This makes the temperature in the old insulation not much different from the interior space temperature. In this case, the vapor pressure difference across the deck is due only to the difference in relative humidity (see SPRI 1992).

the room are readily calculated from the saturation vapor pressure over the deck and the room relative humidity, both at room temperature. Finally, knowing the amount of water initially present in the old roof allows calculation of the drying time. One must then independently assess whether this time is short enough to avoid damage to the new system. Tests are needed to determine both the amount of wetness that can be tolerated and the time allowed before it damages roofs irreversibly. For complex roof systems, and when real weather conditions must be accounted for, the situation is beyond the scope of the SPRI technique.

Given some idea of how much moisture is present in a roof and the boundary conditions imposed on the roof, one-dimensional models are available (Pedersen 1991) or under development (Burch 1991) to predict moisture movement, including diffusion out of the system, and the effects on thermal performance. Work remains, though, to

- identify roof systems that are most at risk for moisture problems, especially from diurnal cycling;

- carry out detailed monitoring of the conditions in a sample of these roof systems, including developing appropriate sensors;
- develop appropriate methods to predict performance, especially validated models and the properties to use them; and
- produce guidance for the industry.

It is important to know the ability of a roof to dry downward, not only for correcting problems in an existing roof, but also for reroofing decisions. Tearing off wet insulation may not be necessary if moisture can be vented to the interior in a timely fashion after a new membrane seals the system from the top. This issue is particularly important in nations that saw big increases in the use of roof insulation in the 1970s (Sheahan 1989). Roof coverings for these systems are reaching their useful lifetimes in increasing numbers, and there are strong cost and environmental incentives to keep the original insulation in place. These incentives are balanced by concerns that moisture in the existing insulation may damage the new roof system.

4.5.7 References

- Anderson 1985
Anderson, R. G., "Dry Range and Wet Range Moisture Content of Roofing Materials as Found in Existing Roofs," pp. 409-15 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, Ill., USA.
- Anderson 1987
Anderson, N. E., "Summer Condensation in an Unheated Building," CIB W40 meeting, Boras, Sweden.
- Andersson 1979
Andersson, A-C, *Internal Additional Insulation. Thermal Bridges, Moisture Problems, Movements and Durability*, Lund Institute of Technology, Division of Building Technology, Lund, Sweden (in Swedish).
- Baker 1980
Baker, M., *Roofs: Design, Application and Maintenance*, Multi-Science Publication, Ltd., Montreal, Quebec, Canada.
- Burch 1991
Burch, D. M. and Thomas, W. C., "An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to a Winter Climate," NISTIR-4674, National Institute of Standards and Technology, Gaithersburg, Md., USA.
- Busching 1978
Busching, H. W., Mathey, R. G., Rositer, W. J., Jr., and Cullen, W. C., *Effects of Moisture in Built-Up Roofing—A State-of-the-Art Literature Survey*, National Bureau of Standards Technical Note 965, Washington, D.C., USA.
- Cederwall 1983
Cederwall, C., "The Action of Ice on Flat Roofs of Shallow Slope with a Roofing Felt Covering," Chalmers University of Technology, Div. of Structural Engineering, Göteborg, Sweden (in Swedish).
- Childs 1985
Childs, K. W., *The Use of Roof Temperature Modeling to Predict Necessary Conditions for Locating Wet Insulation with Infrared Thermography*, Oak Ridge Gaseous Diffusion Plant Report K/CSD/TM-58, USA.
- Fahlstrom 1980
Fahlstrom, K-E, "Icing on Roofs in the North of Sweden," Swedish Council of Building Research,

- T9:1980, Stockholm, Sweden (in Swedish).
- Firman 1989
Firman, D., "Maintenance Needs: An Owner's Perspective," pp. 15-19 in *Proceedings, 9th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA.
- Glicksman 1985
Glicksman, L. R. and Hallenbeck, A. J., "Drying of Roof Insulation: The Use of Wicks to Enhance Vent Performance," pp. 428-32 in *Proceedings, 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, USA.
- Griffin 1982
Griffin, C. W., *Manual of Built-Up Roof Systems*, 2nd ed., McGraw-Hill, New York, USA.
- Griffin 1983
Griffin, C. W., "Draining the Roof," *Roof Design* 22(4), 28-32.
- Handegord 1966
Handegord, G., "Moisture Considerations in Roof Design," *Canadian Building Digest* 73(7), 42-46.
- Hedlin 1988
Hedlin, C. P., "Heat Flow Through a Roof Insulation Having Moisture Contents between 0 and 1% by Volume, in Summer," *ASHRAE Transactions* 94, 1579-94.
- Höglund 1988
Höglund, I. and Andersson, P. *Additional Insulation of Flat Roofs with Thin-Walled Metal Structures*. Royal Institute of Technology, Division of Building Technology, Stockholm, Sweden (in Swedish).
- Knab 1981
Knab, L., Jenkins, D., and Mathey, R.G., *Laboratory Evaluation of Nondestructive Methods to Measure Moisture in Built-up Roof Systems*, National Bureau of Standards Building Science Series 131, Washington, D.C., USA.
- Korhonen 1983
Korhonen, C. and Greatedorex, A., "Examination of a Blistered Built-up Roof: O'Neill Building, Hanscom Air Force Base," CRREL Special Report 83-21, p. 12, Hanover, N.H.
- Korsgaard 1985
Korsgaard, V., "HygroDiode Membrane: A New Vapor Retarder," pp. 985-91 in *Proceedings, Thermal Performance of the Exterior Envelope of Buildings III*, American Society of Heating, Refrigerating and Air Conditioning Engineers, December 2-5, Atlanta, Ga. USA.
- Korsgaard 1989
Korsgaard, V. and Pedersen, C. Rode, "Transient Moisture Distribution in Flat Roofs with Hygro Diode Vapor Retarder," pp. 556-65 in *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings IV*, ASHRAE/DOE/BTECC/CIBSE Conference, December 4-7, Atlanta, USA.
- Laaly 1977
Laaly, H. O., "Effects of Moisture and Freeze-Thaw Cycles on the Strength of Bituminous Built-up Roofing Membranes," pp. 244-51 in *Proceedings, Symposium on Roofing Technology, September 21-23, 1977*, National Roofing Contractors Association, Oak Park, Ill., USA.
- Link 1977
Link, R. E., Jr., "Airborne Thermal Infrared and Nuclear Meter Systems for Detecting Roof Moisture," pp. 252-60 in *Proceedings, Symposium on Roofing Technology, September 21-23, 1977*, National Roofing Contractors Association, Oak Park, Ill., USA.

Pedersen 1990

Pedersen, C. Rode, *Combined Heat and Moisture Transfer in Building Constructions*, Thermal Insulation Laboratory Report 214 (Ph.D. thesis), Technical University of Denmark, Lyngby, Denmark.

Pedersen 1991

Pedersen, C. Rode, Courville, G. E., "A Computer Analysis of the Annual Thermal Performance of a Roof System with Slightly Wet Fibrous Glass Insulation under Transient Conditions," *J. of Thermal Insulation* 15, 110-36.

Pedersen 1992

Pedersen, C. Rode, Petrie, T. W., Courville, G. E., Desjarlais, A. O., Childs, P. W. and Wilkes, K. E., *Moisture Effects in Low-Slope Roofs: Drying Rates After Water Addition with Various Vapor Retarders*, Report ORNL/CON-308, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Petersson 1983

Petersson, B.-Å., *Additional Insulation of Roofs. The 9th CIB Congress in Stockholm 1983*. National Swedish Institute for Building Research, Stockholm, Sweden. Also, a summary of the report *Adding Insulation to Roofs: Problems, Experiences and Possibilities*. Swedish Council for Building Research Report R81:1983, Stockholm, Sweden.

Porcher 1981

Porcher, H., "Blistering Over Urethane," pp. 46-9 in *Proceedings, Sixth Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, Ill., USA.

Riedel 1985

Riedel, R. G., "A Theory to Explain Roof Splitting by Ice," pp. 112-14 in *Proceedings, 1985 International Sympos-*

ium on Roofing Technology, National Roofing Contractors Association, Chicago, Ill., USA.

Samuelsson 1976

Samuelsson, I., *Moisture Transfer in Insulated Metal Deck. CIB W40 Meeting in Washington, 1976*. Also, a summary of the report *Moisture Transfer in Steel Decks*, Lund Institute of Technology, Division of Building Technology Report 67, Lund, Sweden (in Swedish).

Schwartz 1977

Schwartz, T. A. and Cash, C. G., "Equilibrium Moisture Content of Roofing and Roof Insulation Materials and the Effect of Moisture on the Tensile Strength of Roofing Felts," pp. 238-43 in *Proceedings, Symposium on Roofing Technology, September 21-23, 1977*, National Roofing Contractors Association, Oak Park, Ill., USA.

Sheahan 1989

Sheahan, J. P., "Method for Determining Suitability of Roofing over Roof Assemblies in Need of Repair," pp. 172-83 *Proceedings, Thermal Performance of the Exterior Envelope of Buildings IV*, American Society of Heating, Refrigerating and Air Conditioning Engineers, December 4-7, Atlanta, USA.

SPRI 1992

Single-Ply Roofing Institute, "A Method to Determine the Suitability of Recovering and Existing Moisture," presented at the 1992 Roofing Consultants Institute Convention, March 16-18, Rosemont, Ill., USA.

Tobiasson 1982

Tobiasson, W., "Roof Moisture Surveys: Current State of the Technology," *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 371, 24-31.

Tobiasson 1983

Tobiasson, W., Korhonen, C., Coutermarsh, B. and Greathouse, A., "Can Wet Roof Insulation Be Dried Out?", pp. 626-39 in *Thermal Insulation, Materials and Systems for Energy Conservation in the '80's*, American Society for Testing and Materials STP 789, Philadelphia, USA.

Tobiasson 1985

Tobiasson, W. and Korhonen, C., "Roof Moisture Surveys: Yesterday, Today and Tomorrow," pp. 438-43 in *Proceedings of the Second International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Ill., USA..

5

DISCUSSION

5.1 INTRODUCTION

This section presents examples of common insulated roof systems that have been built in participating countries. The characteristics of each example are set forth, and potential problems and limitations on their use are presented. These examples serve as case studies of how problems have been overcome to achieve high-thermal-performance roofs.

5.2 WARM DECK SYSTEMS: SINGLE TYPE OF INSULATION

Conventional warm deck systems have insulation installed over a roof deck and under a waterproof membrane. This system, with a single type of insulation, is illustrated in Figs. 5.1–5.3. Cases of reroofing over old roofs are included here because of the increasingly widespread occurrence of reroofing without tear-off.

5.2.1 New Construction

Single insulation roof systems require few components and minimum application labor. Therefore, they are economical. Typical insulation-related issues with

Fig. 5.1. A typical roof system employing a single type of insulation.

these systems are material compatibility and thermal bridging. A common roof system of this type is shown in Fig. 5.1. It has mineral wool insulation adhered to a concrete deck with a two-ply BUR, which serves as a vapor retarder. It is waterproofed with a BUR membrane. The use of a vapor retarder under the insulation is optional but is normal in cold and mild but humid climates. This system has good fire resistance because the deck and the insulation materials are mostly noncombustible inorganics. Wind uplift resistance is high because air leakage through concrete decks is minimal and the bonding between surfaces is good. This system can provide

the thermal performance needed for most climates through proper selection of insulation thickness (see Sect. 3.2.1). The material compatibility and dimensional stability of this system are very good because the deck and insulation are relatively insensitive to temperature, moisture, and aging. In Denmark, the water-permeable vapor retarder (see Sect. 3.2.3) is now commonly used with mechanically attached hybrid low- and high-density mineral wool insulation and single-ply roofing.

An alternate single insulation system over a concrete deck would use perlite or fiberboard insulation. However, these are not generally considered to be high-thermal-performance roof systems. PIR insulation is often used because it has a high thermal resistance per unit thickness compared with other common roof insulations. However, the CFC gases in these foams cause thermal drift and, especially, environmental concerns (see Sect. 4.4.2). In addition, if foam insulation is used, precautions must be taken to prevent membrane blistering. One such precaution is using a vented base sheet or a porous coverboard insulation (see Sect. 4.5.1). Another alternative is loose-laid EPS or PIR insulation with a ballasted elastomeric membrane. In this instance, total roof weight and wind uplift may be issues (see Sect. 3.2.6).

Building economics has caused the widespread adoption of metal decks. One common single insulation system over a metal deck is PIR insulation with an elastomeric membrane either mechanically attached or loose-laid and ballasted. Another is mechanically fastened mineral wool insulation or PIR under a BUR. A fully adhered system over a metal deck is not generally recommended because of fire safety (see Sect. 3.2.5), wind uplift (see Sect. 3.2.6), and splitting (see Sect. 4.2.1).

All single insulation systems installed in a single layer will have increased heat losses at joint gaps. In addition, a mechanically fastened single-layer system will have thermal bridges through the fasteners (see Sect. 4.4.1). The most common corrective action is to use multiple layers of the same type of insulation with joints staggered and with only the lower layer of insulation mechanically fastened to the deck.

5.2.2 Reroofing Over an Old Warm Deck Roof

Reroofing without removing the old roofing system involves applying a new roof membrane on top of the old membrane, usually incorporating a layer of new insulation between the old and new membranes. Mechanical attachment of the new roofing through the old roof system and into the deck is preferred for best wind resistance. If hot asphalt or adhesive attachment of the new roof is used instead of mechanical fasteners, the old roof must be carefully inspected for proper interlaminar strength (ply separation) and repaired as needed to ensure that wind damage will not occur (Petersson 1983; Petersson 1984).

A typical reroofing application over an old warm deck roof is illustrated in Fig. 5.2. Mineral wool insulation is applied on top of the old membrane and mechanically fastened to the steel deck. A BUR or modified asphalt membrane is then installed on top of the new mineral wool insulation.

Mineral wool is an attractive recover insulation because it readily conforms to old roof surface irregularities, such as gravel. Its porous nature provides vapor pressure relief and minimizes the risk of membrane blistering. The new layer of insulation also reduces the negative effects of any thermal bridges in the old roof system. It serves as a divorcement layer between

Fig. 5.2. An example of reroofing over an old warm deck roof.

the old and new roof systems to reduce stress transfer that might cause membrane splits to reoccur. If the added insulation is tapered, it can correct a former ponding problem and provide positive roof drainage.

This reroofing system is not limited to the materials shown in Fig. 5.2. Any type of roof deck, insulation type, or membrane type is suitable. The new roofing system might even be a metal roof with low-density fibrous blanket insulation. In this situation, special venting between the old and new roofs may be required to prevent corrosion from trapped moisture in the old roof insulation.

In most cases, the new insulation added on top of the old roof will reduce moisture condensation concerns within the total roofing system. However, if underdeck insulation is added during reroofing, careful design, including moisture calculations, is needed to avoid condensation problems, especially if the old above deck insulation is wet and thermally ineffective. A very good vapor retarder may be needed on the underside of the added underdeck insulation.

5.2.3 Reroofing Over an Old Cold Deck Roof

Cold deck systems are potentially more susceptible to underdeck condensation problems than warm roof systems. The primary difficulty is to avoid penetration and open lap joints in a vapor retarder on the underside of a roof. If moisture condensation has been a problem with a cold deck system, reroofing with added insulation over the deck not only will improve thermal performance, but also should solve the moisture problem.

A typical cold deck reroofing configuration is shown in Fig. 5.3. The original system has a wooden deck with low-density mineral wool bats placed between

Fig. 5.3. A typical reroof over an old cold deck roof.

joists. A vapor retarder is between the insulation and the ceiling board. Concrete decking with metal purlins is also used. Steel decks are not common for cold deck design. The flutes in steel decking must be covered by at least a leveling layer of top side insulation. This tends to negate the benefits of using low-cost underdeck insulations and causes the system to be more like a warm deck roof.

In Fig. 5.3, high-density mineral wool with a BUR or modified bitumen membrane is used for reroofing. For a wood deck, the new insulation is typically at-

tached with fasteners. If the deck is concrete, hot bitumen attachment is common. In the latter case, it is important to remove or solidly fix loose plies in the old membrane to ensure good wind uplift resistance. A concrete deck system seldom has underdeck insulation. Mineral wool insulation is good for recover over irregular surfaces because it will readily conform to the existing surfaces. An alternate, less costly, system is loose-laid foam insulation and a single-ply ballasted membrane. This system requires a fairly level old roof and a deck that can structurally support the added weight of the ballasted system. It is more frequently used over concrete deck systems where weight is less an issue.

Condensation is an essential design consideration for reroofing over an old cold deck system, particularly one with past moisture problems. Under winter conditions, trapped water vapor moves upward in the roof system and may condense. An adequate amount of insulation is needed in the recover system to prevent condensation.

In climates with long winter seasons, the moisture problem is compounded for buildings with high interior humidity. While condensation may not be an issue, the moisture content at the deck plane can still exceed values at which deterioration begins (about 30% moisture content by weight in wood). Thus, for wood decks, the thickness of new insulation should be sufficient to keep the moisture content at the underside of the deck below 20%.

Good, approximate, steady-state techniques for carrying out these calculations are readily available (ASHRAE 1989; Griffin 1982). More sophisticated, transient moisture transport models for roofs are also available (Pedersen 1990).

The addition of new insulation over a deck also provides an opportunity to cor-

rect ponding problems and avoid ice stress damage to the new membrane by using tapered insulation. Sometimes a screed fill will be useful under the new insulation to avoid ponding below the new insulation if a leak occurs in the new membrane.

5.3 WARM DECK SYSTEMS: MULTIPLE TYPES OF INSULATION

5.3.1 Insulation with Coverboard

Demand for high-thermal-performance roof systems resulted in widespread use of thermally efficient organic foam insulations. This led to the use of different types of insulation together in a roof to overcome certain flammability or membrane compatibility limitations associated with organic foams. The organic foam served as the primary thermal insulation, and the other type of insulation installed over it provided the required fire resistance or membrane compatibility.

A common insulated roof system with coverboard protection is shown in Fig. 5.4. It has PIR foam insulation attached to a steel deck with mechanical fasteners. A thin layer of perlite insulation board is adhered over the PIR foam with hot asphalt, and BUR is applied on top of the perlite layer. This use of coverboard (wood fiberboard or mineral wool can also be

Fig. 5.4. A typical two-insulation roof system. The perlite coverboard provides required fire protection.

used) over foam insulation in the United States is recommended by the NRCA to minimize BUR blistering. In Europe, a perforated, ventilating base sheet is commonly used instead of the coverboard layer to resist BUR blistering over PIR foam insulation.

Coverboard insulation is also used for other reasons. Coverboards, such as high-density mineral fiber, corkboard, wood fiberboard, perlite, or mineral wool, are used over polystyrene foam insulation to resist hot asphalt melting or elastoplastic solvent adhesive attack of the polystyrene. Relatively rigid coverboards are also used over polystyrene foam with mechanically-fastened elastoplastic membrane systems to minimize cold flow compression loss at the fasteners during service. In Europe, rigid fiberboard is used as a coverboard over mineral fiber insulation to provide a suitable support for applying asphalt mastic membranes. Coverboards are also used to satisfy exterior fire resistance requirements for some unballasted elastoplastic membranes installed over organic foam insulations. Coverboards can be incorporated into foam insulation systems either by factory lamination or by field application.

The use of two layers of insulation provides a means to reduce the thermal bridges encountered with a single layer of insulation. Gaps at joints are protected by staggering the joints with the coverboard insulation, and coverboard installed over mechanical fasteners through the lower layer of insulation minimizes thermal bridge losses encountered when fasteners penetrate the entire insulation system.

5.3.2 Three-Layer System

Multiple insulation systems require at least three layers when the primary insulation needs both bottom-side and top-side

protection to comply with interior and exterior fire resistance and/or membrane compatibility requirements. A typical roof system of this type employs perlite bottom board insulation mechanically fastened to a steel deck, EPS primary insulation, and fiberboard coverboard insulation. Both the EPS and the fiberboard are attached with hot asphalt under a BUR membrane. The use of a vapor retarder under the insulation is optional but typically is recommended in cold climates. This system, described in Sect. 2.4.2, can provide the thermal performance needs for most climates through proper selection of insulation thickness. Satisfactory long-term performance has been established. Good workmanship is required during roof application to keep the asphalt from melting the EPS while at the same time keeping it sufficiently molten to provide adequate interlayer attachment and wind uplift resistance.

Interior fire resistance over wood or metal decks is provided by perlite bottom protection. Fiberboard top protection is needed with a BUR to prevent very hot asphalt from attacking the EPS insulation and to provide exterior fire resistance for smooth-surfaced membranes that do not employ mineral surfacing for fire resistance. The added cost of the barrier protection layers must be offset by a price advantage for the EPS primary insulation. Otherwise, more fire- and heat-resistant PIR or phenolic insulation is used.

Alternate three-layer systems may employ PUR insulation in place of EPS. Cork board or high-density mineral wool insulation may be used for either top or bottom fire barrier protection of the EPS. Perlite is sometimes used as top barrier protection in place of fiberboard. Elastoplastic membranes may be used in place of BUR membranes. Then the top barrier protection

provides not only compatibility against attack from solvent glue, but also the exterior fire resistance needed with an unballasted membrane.

Cost considerations sometimes favor mechanical attachment of all three layers of insulation simultaneously. Research is needed to evaluate the difference in thermal performance between fastener penetration through only the bottom layer, and penetration through the entire insulation system. The thermal effect of plastic versus metal screw and plate construction should also be determined for optimum roof design.

5.4 COLD DECK SYSTEMS

5.4.1 Conventional Cold Deck System

In cold deck roof systems, the thermal insulation material is placed below the deck. Waterproofing is attached directly to the deck. This means that the temperature of the deck and the weatherproofing layer will be close to the outside temperature. Cold deck roofs are described in Sect. 2.4.3. The deck is typically wood or wood product (e.g., tongue-in-groove, plywood, or chipboard) over structural members. Construction water should be kept out of cold deck assemblies. For this reason, deck sections sometimes come with a factory-applied base sheet. A BUR membrane can be applied with hot asphalt directly to the deck or the base sheet, lowering the risk of wind uplift, or a single-ply membrane can be mechanically fastened or fully adhered to the deck. For the insulation material, low-density mineral wool is well suited and highly fire resistant. A cold deck roof is not a good system over buildings with known high internal humidities (e.g., swimming pools or drying rooms in a paper mill). Their use is also discouraged in

regions with appreciable cold, damp weather.

5.4.1.1 Ventilated cold deck systems

A conventional cold deck roof system is built up of plywood, chipboard, or tongue-in-groove boards nailed on top of wooden joists. The height of the joists will usually be determined by structural requirements and not by insulation requirements. Typically, the insulation thickness is less than the height of the joists. The insulation is placed in the lower part of the cavity, leaving a void for ventilation between the insulation and the deck.

In cold or temperate climates, the temperature of the deck will often be low enough to cause condensation of interior water vapor that migrates to the underside of the deck. The condensation can cause rot or fungal attack on the wooden materials, particularly if the moisture content of the wood increases to 20% by weight or more in periods when the temperature is above 5°C (about 40°F).

To minimize or prevent moisture migration by diffusion into the roof system, a vapor retarder is installed below the insulation layer. To prevent moisture migration by convection, the vapor retarder should be installed with airtight joints, including overlaps. Very often, an effective air and vapor barrier is difficult to achieve. One alternative that has been proposed is to ventilate the roof void to the outside air by openings in the eaves for small roof areas, by eave-to-eave distances of less than 10 m, or by placing roof vents at certain intervals for large areas. The idea is that cold outside air, which has low absolute humidity, will enter the voids through some vents and will be heated by the heat transmission from below so that it can take

up moisture before leaving the roof through other vents. If the roof is well insulated, the heat loss from this mechanism is small, and hence the capability of the ventilation air to remove moisture is also small. On clear nights, the ventilation air may even deposit moisture by condensation in the void.

For small roof areas, wind-created pressure differences may ensure a sufficient ventilation rate through the eaves to prevent moisture problems if the air-vapor retarder is reasonably tight. For large roof areas, ventilation through the eaves, even when supplemented by roof vents, may not provide sufficient ventilation to prevent moisture problems. The reason is that there may be inadequate pressure difference between the vents. Furthermore, in windy periods, roof vents create an underpressure in the roof cavity relative to the indoor environment and thus promote further intrusion of moist indoor air into the roof through unavoidable leaks in the air-vapor retarder. Therefore, in some countries with a cold or a temperate, humid climate, the ventilated cold deck roof is regarded as a poor option.

5.4.1.2 Unventilated cold deck systems

Until recently, the unventilated cold deck roof system was not considered a viable option because of concern over cold deck moisture problems. Two sources of moisture are of concern: water vapor migrating into the system and liquid water trapped there. Convection of room air is the main source of water vapor migration into cold deck roofs. It can be greatly reduced by adding a vapor retarder to the system and by omitting vent openings in the roofing membrane and in the eaves. Moisture migration due to diffusion, usually a minor source, can be reduced even

more by a vapor retarder with only a moderate diffusion resistance. Even if joints and overlaps are imperfectly sealed, there is little total pressure difference to transport room air into the cavity insulation because outside venting has been eliminated.

The second source of moisture is liquid water from construction, water from leaks, and migrating water that accumulates. It could be trapped in the space between the two impermeable membranes, the roof membrane, and the vapor retarder. This problem can be alleviated by replacing the traditional waterproof vapor retarder with a water-permeable vapor retarder that allows trapped moisture to escape to the building interior while providing an effective vapor retarder against upward diffusion (Korsgaard 1985; Korsgaard 1989) (see Sect. 3.2.3).

Since ventilation is unnecessary, the space between the deck and the ceiling can be totally filled with insulation material. Thus the unventilated cold deck system can have a very high R-value. It also is especially well suited for prefabrication in the form of closed cassettes. Computer programs are available that can verify the indoor and outdoor climatic conditions for which the potential for vapor diffusion into the unventilated cold deck roof during winter is less than the potential for drying during summer (Pedersen 1990).

5.4.2 Raised Cold Deck Roofs

In raised cold deck roofs, the roof deck or outer roof comprises tongue-and-groove boards that are covered with a BUR membrane. The boards are nailed to timbers, which are sloping beams with short vertical wooden supports fixed to a concrete or lightweight concrete underlying structure. The thermal insulation, normally mineral wool, is laid on the underly-

ing structure. The space between the outer roof and the thermal insulation functions as a ventilation space large enough to crawl around in. This space can be inspected, usually through a hatch in the outer roof. Older roofs of this type have proved to be good candidates for extra insulation (Petersson 1983). It is usually installed as an extra layer of loose-fill mineral wool on top of the existing thermal insulation. Both in adding extra insulation and in new construction, ventilation in the roof cavity is important, so there should be ventilation openings at the eaves.

The low slope of the roof means that internal warm drains often are used to achieve runoff, so the roof is usually of the butterfly type (see Fig. 5.5). Wind effects must be taken into account in dimensioning the vertical supports, particularly in the way they are fixed.

Fig. 5.5. A raised cold-deck roof system.
The roof slope is toward internal drains.

The membrane on the roof boarding must also be completely waterproof and able to withstand a certain pressure from water, because water may collect on the roof. A minimum roof gradient of 1 : 100 has been specified in Sweden to reduce water collection. The underlying structure and its thermal insulation should be designed so that a minimum amount of moisture reaches the roof from below. A vapor retarder can be used; it usually is placed

above the underlying concrete structure. As an alternative, moisture transport can be retarded by creating an underpressure indoors under the supporting structure with the help of mechanical fans. Avoiding moisture transport is particularly important for roofs with strong thermal insulation in combination with cold outdoor climates. Otherwise, there is a risk that the indoor moisture can spread convectively to the ventilation space in the roof and cause damage (Petersson 1983). A vapor retarder on the topside of the underlying structure prevents moisture from new concrete from drying upward into the roof space, which also would cause moisture damage.

Ventilation in the roof is also necessary to remove occasional concentrations of moisture in the form of snow blowing in through the ventilation openings, or in the form of moisture in the ventilation air condensing inside the cold outer roof because of heavy heat loss from the roof on clear, cold nights. The cold conditions for the outer roof are accentuated by increased thermal insulation in cold climates. Normally, the wooden boards have sufficient moisture capacity to handle nighttime condensation if given the chance to dry out with daytime ventilation.

The ventilation may be either thermal, wind-dependent, or mechanical, depending on the design. As a result of a high degree of insulation and thus a low temperature in the ventilation space in the winter, the ventilation air has only a limited capacity to take up moisture; the thermal ventilation is also limited. Therefore, it might be a good idea in certain cases to install mechanical fans in the roof to ensure an adequate flow of air through the roof. The fan should blow the air into the ventilation space to create an overpressure in relation to the underside of the underlying

structure and thus eliminate the risk of convection moisture reaching the roof from below.

5.5 METAL ROOF SYSTEMS

5.5.1 New Roof

Insulated metal roofing systems employ exterior metal panels for durable waterproofing, along with insulation installed underneath the metal panels and a variety of system attachments to the structural roof supports. The exterior metal roof panels are most commonly polymer-coated, corrosion-treated steel, but other metals such as uncoated copper, aluminum, and stainless steel are used.

A common roof system of this type is illustrated in Fig. 5.6. It has rigid PIR or PUR insulation sandwiched between structural metal decking and the external metal roof panels. The metal roof panels have long runs to minimize the need for end joints, and the side seams have a standing (raised) seam design to minimize the

opportunity for water intrusion. Attachment clips eliminate any penetration of the roof panels, and they are designed to accommodate movement resulting from thermal expansion and contraction of the metal roofing. The "secret fix" (so named because no attachments are apparent or exposed externally) roof panel designs include standing seam, spring clip joints, and sheets that interlock at the overlaps.

The application of fixings has become more complex as the thickness of insulation materials has increased. Longer fixings (for thicker insulation) require that the effects of lateral forces be assessed. Additionally, the compressibility of insulation materials can produce failures by allowing water ingress as the compression seals leak during flexing of the sheet under roof traffic. One method to overcome this failure is the use of two threads on the fastener screws. The lower thread (toward the point) catches the structural support, and the larger diameter thread at the head of the shank holds the top sheet a fixed distance from the purlin. Z-shaped spacers are also used between the top roof panels and the bottom liner panels to fix the distance between them. This permits the use of less rigid insulation materials, but some type of thermal break protection must be provided for these spacers to avoid thermal bridging and the risk of condensation.

Various types of insulations, including mineral fiber insulation, can be used in place of the rigid PIR/PUR insulation shown in Fig. 5.6. Alternate methods of incorporating and attaching insulation are also employed. When insulation initially was introduced into the metal roof system, it was either hung from the underside of the metal roof panels or adhered to the underside. The bonding of rigid insulation to metal roof panels increased stiffness and allowed longer spans, but overestimation

Fig. 5.6. A representative structural standing seam metal roof system. Detail of standing seam concealed fastener system is shown at the clip. The assembly allows the entire roof to move with expansion and contraction. **Source:** Armco Building Systems.

of long-term rigidity eventually resulted in some unacceptable sagging between supports.

Loose insulation has also been used in metal roof systems by supporting it on liner panels, which may be fixed to the top roof panels to add structural support or allowed to span independently between existing supports. Insulation has also been bonded to unitized liner panels for easy application and attachment to the purlins. Another form of construction in insulated metal roofing is the use of composite insulated sandwich panels, in which the insulation is foamed between two profiled sheets in a factory. This type of product has performed well in service, and similar panels can be used for wall cladding to provide a uniform appearance for the complete building envelope.

Insulated metal roofing is characterized by long-term durability, provided that design and application procedures address potential concerns about (1) the integrity of roof panel joints and metal flashing around roof penetrations associated with the high thermal expansion and contraction of metal roofing, (2) internal condensation risks, and (3) long-term metal corrosion. Metal roofing is relatively susceptible to roof traffic damage, and access to equipment that requires maintenance should be provided by independent walkways.

Good design and application of metal roof seams and metal flashing seals around roof penetrations are critically important on low slope roofs, especially at slopes of 1 : 48 (0.25 in./ft). The use of sealants provides some integrity for joints, but prolonged movement from thermal expansion and contraction will eventually render sealants ineffective. As roof slope increases above 1 : 4 (3 in./ft), joint integrity quality is less important for leak-free performance.

Condensation is a concern. Water vapor can penetrate into the roofing system and can condense on metal panels that are cooled by winter weather and by long-wave clear-sky radiation. Natural or mechanical ventilation will lessen the risk of condensation on uninsulated metal roofing. On insulated metal roofs, water vapor penetration through insulation joints due to inadequate joint seals in the vapor retarder will also cause condensation problems. Even though metal liner panels are excellent vapor barriers, vapor-tight joints are difficult to achieve during application, and joint seals can fail later because of thermal movement and flexing. In some countries, breather membranes are often used. These vapor-permeable membranes collect water that condenses and drips from the underside of metal roofs. If the system has adequate slope, then water will drain to the gutter.

Concerns about corrosion of the metal roof panels themselves are generally addressed adequately by protective zinc or aluminum coatings and polymeric paints. However, cut ends of steel roof panels can corrode without job-site application of protective coating. Bimetallic corrosion is an important concern that must be addressed by good design and application. It is essential to isolate dissimilar metals to prevent electrolytic contact and corrosion in the presence of moisture. Dissimilar metal corrosion can easily occur in metal flashing areas, and electrolytic corrosion potentials need to be evaluated between roof panels and attachments (fixings) or decking.

5.5.2 Reroofing

The use of metal roofing to reroof over an existing roof involves adding a new framing system above the old roof to support the new metal roof. The added fram-

ing system is usually installed 6 to 12 cm (2.5 to 5 in.) above the lowest point of the old roof. The framing is designed to provide at least 1 : 48 (0.25 in. per ft) slope for the new roof. This frame allows space for adding more insulation under the new roof. The new framing system may be attached to the old roof deck or the substructural members, depending on the structural capabilities of the existing building.

A common system of this type has an added metal frame that is attached over the existing BUR and old metal decking. Standing seam metal roofing is installed on the new framing with concealed, sliding fasteners that allow the metal roofing to "float" with thermal expansion and contraction. Flexible mineral wool insulation blankets are located within the added framing between the old and new roofs. This system is described in Sect. 2.4.4.

This reroofing system has the same characteristics as new metal roofing, because it is essentially a new metal roof installed over an existing roof. These roofs are usually designed to accommodate up to 7.9 cm (2 in.) of thermal movement in a metal roofing panel. This limits roof sections to about 61 m (200 ft) in most climates without the use of overlapping panel sections terminated with suitable expansion detail. Provision for roof movement in all directions is critical for leak-free performance of metal roofing. Metal roofing is not well adapted for roofs that have many, large roof penetrations or rooftop traffic in service.

Condensation is a special concern for metal reroofing over old roofs. Typically, many cuts are made in the old roof to attach framework. If the old insulation is wet or if there is a ready path from the building interior to the cold chamber between the old and new roofs, condensation and sub-

sequent corrosion problems can occur (see Sects. 4.3.1 and 4.5.4).

Experienced, competent designers and roofing contractors are critical to successful metal reroofing. The panelized nature of metal reroofing makes the adaptation required for each reroofing geometry unique to the job. Flashings must accommodate much thermally-induced movement and remain watertight. Small plumbing penetrations, such as plumbing vents, must be located in the flat area of metal roofing panels and not in the standing seam. Large openings for mechanical equipment or ductwork require roof curbs and addition of material for extra thickness (crickets) between standing ribs to keep the roof surface higher than the drain openings and avoid ponding. Double curbs may be required for large, heavy rooftop equipment; one curb is fixed to the building structure and the equipment and the other curb is allowed to float with the metal roof.

Metal reroofing can be installed over any type of old roof membrane or roof decking type. The type of fastener used to attach the new framing system must be suitable for anchorage to the existing wood, steel, or concrete decking. Toggle bolt attachment may be required over old lightweight insulating concrete decks.

Research is needed to address corrosion concerns and the life-cycle economics of metal reroofing. The use of aluminum-zinc coated steel (Galvalume) to achieve greater corrosion resistance has increased substantially during the past decade. The initial cost of metal reroofing is high compared with that other types of reroofing. It is selected on the assumption that lower maintenance costs and longer service life will provide life-cycle cost advantages, but evidence to document those advantages is

limited, especially for the newer metal roofing products and systems.

5.6 PROTECTED MEMBRANE SYSTEMS

In protected membrane systems, a thermal insulation layer is installed on top of the waterproofing membrane. This type of roof is also called an upside-down roof. Even if the roof has insulation both above and below the membrane, it is still considered a protected membrane system. In Scandinavia and Germany, this hybrid is known as the "duo-roof."

To withstand exposure to the elements, the insulation material normally is XPS boards. Depending on the desired thickness of the insulation, there are one or two layers on top of the membrane. Materials other than XPS are used (Hens 1986). If mineral wool is used, it typically is one layer with ballasting only on the perimeter and around penetrations. The mineral wool should have a factory-applied vapor retarder on the underside to prevent rainwater that enters at joints and moves into the space between the membrane and the insulation from diffusing into the insulation during cold weather. Moisture that evaporates and diffuses upward through the porous mineral wool carries the heat of vaporization with it. This added heat loss can degrade the insulation by as much as 20%. For duo-roofs, the lower thermal insulation type can be selected in the same way as it is for conventional roofs because it is below the membrane and can thus be of less expensive material.

The exposure of the insulation above the membrane to the climate, precipitation, and wind can degrade its thermal performance. Research projects in Sweden (Petersson 1980), Germany (Künzel 1972), and the United States (Aamot 1976) have shown

that the loss of insulating value is moderate and can be offset by installing a somewhat thicker layer. Data on the thickness required for protected membrane systems are found in Swedish building codes (Petersson 1990, 1992). See the example in Sect. 3.2.1 for the method used to correct the thermal performance to in-service conditions. A performance standard is required because the insulation that protects the membrane is covered by various toppings, depending on the application: a simple layer of gravel for low-slope roofs; a layer of concrete, possibly sealed with asphalt, for parking structures atop buildings; concrete paving stones in gravel or earth over sand for a terrace.

Moisture takeup by the XPS, and consequent degradation of its thermal performance, varies with the topping (Petersson 1986). A single layer of XPS with little gravel cover had low moisture content, varying seasonally. Moisture increased during the winter and decreased during the summer, but remained below 1% by volume. This level of moisture has negligible effect on the thermal conductance of XPS. In a double layer of XPS covered by gravel, the lower layer was more moist than the upper; the upper layer prevents the lower layer from drying. The upper layer dries if the gravel layer is not thick enough to seal off the XPS. XPS boards laid in sand and covered by earth to form a roof terrace showed moisture content as high as 6 to 8% by volume after 10 years. This level of moisture noticeably affects thermal performance. Corresponding moisture measurements for EPS in 3-year-old roofs showed a moisture level of 14 to 15% by volume (Petersson 1981).

Although some degradation in performance is inevitable for insulation installed above the membrane, efforts should be made to minimize it. The objec-

tive is to leave little space for water to collect and to make it difficult for water to penetrate into the exposed insulation and accumulate there. Therefore, the following practices should be followed:

- Insulation boards should have notched (rebated) edges so that they butt together to form a single layer with no openings between boards.
- If the boards are laid in two layers, the joints in one layer should be offset from the joints in the other.
- An air-permeable sheet should be placed between the insulation and the gravel or other topping material to allow air to pass through to the insulation.
- To avoid accumulation of water on the membrane, it should have a minimum slope of 1 : 100 to 1 : 75 (about 0.13 in. per foot).

Special considerations are necessary for a duo-roof. The insulation above the membrane must be thick enough to provide adequate mechanical and thermal protection. Also, there is a risk of condensation in the insulation below the membrane. If the duo-roof is built on a concrete deck, a vapor retarder should be placed atop the concrete.

5.7 SPRAY-APPLIED POLYURETHANE FOAM SYSTEMS

Spray-applied PUR foam roofing is a monolithic, seamless, self-flashing system consisting of foamed-in-place insulation covered with a spray-applied membrane coating. A common system of this type employs PUR foam with a density of 40 to 56 kg/m³ (2.5 to 3.5 lb/ft³) sprayed in successive layers each about 13 to 19 mm (0.5

to 0.75 in.) thick over a primed concrete deck. For weather protection, an elastomeric coating is spray-applied on top of the PUR foam. This system is shown in Fig. 2.11 and is described in Sect. 2.4.6.

When the spray layers are properly formulated and applied, the advantages of this system are that it is easy to apply, it is water-tight, and it can provide any desired amount of thermal resistance. The ease of application has, however, been responsible for hurried or careless application and resulting roof failure. Spraying over a moist surface generally causes failure, and spraying should not be done at temperatures near the dew point.

Poor spray application is characterized by pinholes in the elastomeric coating. To minimize pinhole formation, the spray-applied foam must cure for at least 2 hours before the elastomeric membrane is applied. The elastomeric coating is normally applied in two layers, and it must be sufficiently thick to provide abrasion resistance and pinhole-free weather protection. Its main purpose, though, is to protect the insulation. PUR foam degrades when it is exposed to sunlight and moisture. These coatings are relatively sensitive to damage by bird pecking, hail, and foot traffic during roof service. Recoating every 5 to 10 years is recommended.

Alternate uses of spray PUR foam roofing include both new and recover reroofing on almost any type of deck. Substrates must be moisture-free, and cracks exceeding 6 mm (0.25 in.) need to be filled before foam application. Flutes in metal decking may be covered with polyester tape to provide a uniform spray surface. Lightweight concrete decks are generally not recommended as a base for spray-applied PUR foam systems.

Research is needed to understand climatic and roof slope limitations for suc-

cessful use of this method. The best performance has been achieved in warm, relatively dry climates. Good roof slope and drainage appear to be essential for long life on roofs that are subjected to ice and snow conditions.

5.8 REFERENCES

Aamot 1976

Aamot, H. W. C. and Schaefer, D. *Protected Membrane Roofs in Cold Regions*, Cold Regions Research and Engineering Laboratory Report 76-2, Hanover, N.H., USA.

ASHRAE 1989

ASHRAE *Handbook of Fundamentals*, Chaps. 6 and 20, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

Griffin 1982

Griffin, C. W., *Manual of Built-Up Roof Systems*, 2nd ed., McGraw-Hill, New York, USA.

Hens 1986

Hens, H. L. and Vaes, F. *An Inverted Roof with Mineral Wool*, Building Research and Practice Report No. 14, Belgium.

Korsgaard 1985

Korsgaard, V., "HygroDiode Membrane: A New Vapor Retarder," pp. 985-991 in *Proceedings, Thermal Performance of the Exterior Envelope of Buildings, III*, American Society of Heating, Refrigerating and Air Conditioning Engineers, December 2-5, Atlanta, USA.

Korsgaard 1989

Korsgaard, V. and Pedersen, C. Rode, "Transient Moisture Distribution in Flat Roofs with Hygro Diode Vapor Retarder," pp. 556-65 in *Proceedings, Thermal Performance of the Exterior Envelope of Buildings, IV*, American Soci-

ety of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

Künzel 1972

Künzel, H., "Wärmeschutz und Temperaturverhältnisse beim 'Umgekehrten Dach'" *Kunststoffe im Bau* 27, 84-91 (in German).

Pedersen 1990

Pedersen, C. Rode, *Combined Heat and Moisture Transfer in Building Constructions*, Thermal Insulation Laboratory Report 214 (Ph.D. thesis), Technical University of Denmark, Lyngby, Denmark.

Petersson 1980

Petersson, B.-Å., *The Upside-Down Roof. Field and Laboratory Studies of Thermal Insulation, Moisture Conditions and Performance*, Publ. 80:6, Chalmers University of Technology, Division of Building Technology Publ. 80:6, Göteborg, Sweden (in Swedish).

Petersson 1981

Petersson, B.-Å., "Moisture Mechanics and Thermal Insulation Properties of Expanded Plastics Used as Thermal Insulation in Upside-Down Roofs," in *Proceedings, ICP/RILEM/IBR Symposium on Plastics in Materials and Structural Engineering*, June 23-25, Prague, Czechoslovakia. (Available as Publ. 81:6, Chalmers University of Technology, Division of Building Technology, Göteborg, Sweden).

Petersson 1983

Petersson, B.-Å., "Adding Insulation to Roofs, Problems, Experiences and Possibilities," Swedish Council of Building Research, Publ. R81:1983, Stockholm, Sweden (in Swedish).

Petersson 1984

Petersson, B.-Å., "Adding Insulation to Roofs," *Building Research and Prac-*

tice 13 (3), International Council for Building Research, Studies and Documentation, Rotterdam, Netherlands.

Petersson 1986

Petersson, B-Å, *The Moisture and Thermal Insulation Conditions in the Duo-Roof*, Bygg and Teknik Report No. 4, Stockholm, Sweden (in Swedish).

Petersson 1990

Petersson, B-Å, *Thermal Insulation of the Upside-Down Roofs Corresponding to the New Swedish Code PBL and NR*, Bygg and Teknik Report No. 2, Stockholm, Sweden (in Swedish).

Petersson 1992

Petersson, B-Å, "PMR and Duo-Roofs and Thermal Insulation Systems," *Journal of Thermal Insulation*, to be published.

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