PRACTICAL EXPERIENCES WITH BITUMINOUS LOW-SLOPE ROOFS IN COLD CLIMATES

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A Canadian perspective of the successes and failures of new bituminous low-slope roof designs and new roofing materials that have been introduced since the 1950s is given. What has been learned in the relatively cold climate of Canada is discussed in a qualitative way.

Roof surface temperatures, heat flow, and insulation joint movements that were measured on five well-instrumented test roofs located in Montreal, Canada, are also reported.

Some lessons learned from experiments and field experiences in Canada are discussed in the hope that the roofing industry will not make the same mistakes in the next century. Firm securement of roofs to the structural deck, maximizing adhesion between components in the roof system, and minimizing air and water entrapment during application are keys to constructing good bituminous roofs. Careful attention to the design and construction of continuous air and vapor diffusion barriers is important to prevent condensation in heated buildings in cold climates, and timely maintenance may double the useful life of a well-designed and well-built roof.

KEYWORDS

Bituminous, design, heat flow, insulation joint movement, performance, practical experience, practice, surface temperature.

SUMMARY

This paper looks back at the changes that have occurred in the Canadian roofing industry over the latter half of this century. New materials, products, and roof systems have firmly established themselves in this industry but not without some problems that were unforseen at the time of their introduction. These changes and their associated problems are discussed qualitatively. Quantitative information about temperatures, heat flow, and movement between insulation joints that were measured on well-instrumented roofs in Montreal in the early 1980s also is reported. Until recently, this information was not available to the general public, but it provides an example of research that can be useful in connecting laboratory evaluations with experience from commercial-sized roofs. The last part of this paper illustrates some examples of good roofing practices that have been derived from past experience and the lessons that roofing professionals should heed as they move into the next century.

INTRODUCTION

As the next century and millennium approach, it is useful to look back at the changes that have occurred in roofing technology and roofing in general over the latter half of this century. Roofing technology has advanced from being mainly art to being mainly science; on the other hand, roofs in Canada do not appear to last as long now as they used to.

This paper looks back at the last four decades of bituminous low-slope roofing in Canada with the view of learning from it. Much of what has been experienced in Canada is relevant to other countries, and much is relevant to nonbituminous roofs.

Major changes in roofing materials, roof system designs, and construction practices have occurred in Canada during the past four decades. These changes, almost without exception, caused unforseen roofing problems during the periods of their introduction. The first section of this paper discusses, in a qualitative way, the probable causes of the problems that were created and how these problems have been, or can be, resolved.

The second section of this paper presents a summary of a model test roof program that monitored and evaluated the effects of climate on roof systems in Montreal, Canada. This section provides quantitative data about roof systems. Quantitative data are important in an industry where conventional wisdom is often mistaken for fact.

The third section of this paper discusses good roofing by building on what has been learned from past experiences. Good and poor bituminous roof designs currently in use in Canada are discussed. This section illustrates that roofing professionals know how to design and construct roofs that will outperform latter-day roofs, but that they do not always use this knowledge.

CHANGES IN ROOFING, 1950 TO 1990

Through the first half of this century, low-slope roofing in Canada changed little. Some minor changes in application methods occurred because of the introduction of mechanized equipment, but roof designs and roofing materials did not change much.

Through the latter half of this century, there have been many changes in roofing, through the introduction of new materials and systems. Most, if not all of these changes brought about unforseen problems that resulted in reductions in roof life expectancy. It is widely believed that roofs constructed in the latter part of this century have, on average, lasted less than those constructed in the first half of this century.[1, 2, 3]

This is not only true for roofing. In 1990, Statistics Canada introduced new estimated service lives for 49 categories of industrial and institutional constructions. According to its survey of owners, expected service lives dropped by 20 to 50 percent during the forty years from 1947 to 1987.[1]

The Canadian Standards Association S478-95 "Guideline on Durability in Buildings" lists current design service lives for buildings and building assemblies (foundations, walls, roofs, etc.).[2] The guideline lists the design service life for a single-ply membrane roof over rigid insulation on a reinforced concrete deck as 15 years.

Surveys about roof longevity must be compared carefully because roof life, roof failure, and roofing problems are often defined differently in different studies. Also, roof replacement periods can be misleading when roofs are replaced for reasons other than lack of performance (e.g., prematurely for building expansion or tardily because of lack of funds).

A 1985 study of built-up roofs owned by the Ontario Ministry of Housing showed a roof replacement cycle of 12 years.[3] Facility managers of some large Canadian private and public organizations located in Canada have reported average roofing replacement cycles between 10 and 15 years.

Communications with foreign roofing organizations suggest that U.S. and Canadian roofs have similar life cycles, but European roofs are thought to last longer. Using NRCA Project Pinpoint data, it has been reported that 62 percent of U.S. roofs experienced defects in the first year of life and 99 percent of U.S. roofs experienced some defects in the first 10 years.[4] Statistics from the United Kingdom (UK) indicated that 45 percent of roofs had some defects within the first year and that all roofs experienced leaks after 20 years.[5]

The majority of low-slope roofs constructed in Canada the 1950s were one of two types:

- The first type consisted of:
  - wood deck;
  - two plies of nailed felt;
  - three-ply organic felt and coal tar pitch built-up roof membrane;
  - coal tar pitch and gravel surface.
- The second type consisted of:
  - concrete deck;
  - 25- to 50-mm-(1- to 2-inch-) thick wood fiberboard, bitumen applied;
  - four-ply organic felt and coal tar pitch built-up roof membrane;
  - coal tar pitch and gravel surface.

These two systems performed extremely well; both roofs were over strong substrates, and their attachment was appropriate. Uniform nailing of dry felts over wood deck provided good securement, and it divorced roof membranes from moisture-induced shrinkage forces in wood deck. Fully adhered fiberboard between roof membranes and concrete decks divorced membranes from forces associated with concrete cracking.

These two specific systems accounted for approximately 40 percent and 20 percent, respectively, of low-slope roofs in eastern Canada. Other roof systems were used over wood and concrete decks; wood decks accounted for approximately 57 percent of roofs in eastern Canada, with 32 percent concrete, 3 percent steel, and 8 percent other. Wood decks were even more prevalent in western Canada.

Until 1958, built-up roof membrane manufacturers provided 15- and 20-year roof bonds for three-ply and four-ply built-up roof membranes. Records indicate that 15- and 20-year life expectancies were routinely achieved for built-up roofs constructed in Canada up to 1958.[6]

Statistics on roofs constructed in eastern Canada in 1958 are interesting when compared to those of today's roofs. During the 20-year period from 1958 to 1978, only 17 percent of these roofs had leaked, all within the first 10 years. Leaks were more prevalent on:

- larger area roofs;
- dead level roofs;
- insulated roofs;
- four-ply rather than three-ply (two dry, three mopped) built-up roof membranes;
- new rather than reroof applications;
- over concrete and steel decks (rather than wooden decks).

The average roof size in eastern Canada in 1958 was approximately 7,850 square feet (730 m^2). Steel deck had just been introduced into the market; roofs over steel deck were twice the average size.

Major changes occurred in the second half of the century. Initially, at least, none of these changes appear to have had a positive effect on roof longevity:

- ca. 1955—Profiled steel roof deck was introduced and quickly began to replace wood and concrete. Being lightweight and strong, it could span widely spaced supports and was very economical. (In the next 20 years, roof sizes tripled, and steel accounted for about 70 percent of new nonresidential low-slope roof decks).

  Some disadvantages of steel roof deck are:
  - reduced contact area for roof system securement;
  - reduced airflow resistance;
  - temperature induced expansion and contraction;
  - load-induced flexing;
  - rapid cooling of hot bitumen adhesive in cool weather;
  - corrosion weakening.

  There was poor compatibility between the flexible steel deck and built-up roof membranes, which become rigid and brittle in cold weather.
- 1958—Roof bonding by product manufacturers was terminated in Canada. Regular maintenance was required for roof bonds to remain effective. After the demise of roof bonding, less diligent maintenance procedures resulted.
- 1960s—New single-ply membranes (e.g., butyl and neoprene rubber, chlorosulphonated polyethylene) were introduced. With very few exceptions, these did not perform well, and they were removed from the Canadian market around 1964.

  Glass felt built-up roofing was introduced into Canada. Splitting problems in cold weather occurred because of the low strength and high thermal contraction stresses of the early glass felts.
- 1970s—The energy crisis of 1973 led to increased demand for thermal efficiency. Lightweight plastic insulation foams became more popular. Lightweight foams are typically 3 percent solid and 97 percent gas, so they have low

strength, and all lightweight foams have little air permeability, which makes it easier to entrap moisture and other gases during hot bitumen roof applications. Less robust and more blister-prone roofs resulted. Poor adhesion between some plastic foam insulations and bitumen caused significant problems, as did the dimensional instability of some foam insulations. The use of a fibrous board between foam insulations and roof membranes was introduced to reduce many of these problems.

Increased insulation levels did not make the outside temperature of a roof colder or the inside temperature warmer, but they did reduce the amount of heat flowing through roofs and, therefore, reduced the drying potential. This resulted in higher condensation potentials and the need for more careful attention to continuous air-vapor retarders, particularly over steel roof decks.

Two-ply No. 40 organic coated sheet membranes were introduced. Without the perforations of No. 15 organic felts (or glass felts), these coated sheets were more prone to blisters. Less hot bitumen was used during application of these two-ply (vs. four-ply) membranes, and in winter, the thin layers of hot bitumen were rapidly cooled by the thicker sheets. These thicker sheets had more built-in tension from manufacturing operations, and it was found to be necessary to cut the rolls into 3-m (9.8-foot) lengths and lay them on a roof to relax prior to use. The two-ply No. 40 coated sheet membrane did not perform well and was withdrawn from the market before 1978.

- 1980s—By 1980, a second wave of new membranes had firmly established itself in the Canadian marketplace. Some of these membranes brought about radically different methods of attachment, such as loosely laid roof systems that were divorced from the structural deck. Project Pinpoint data in the United States indicate that new membrane materials have had more than their share of problems, as shown below.[7]

Material	Problem ratio per roof in USA
"Old" built-up roofing	0.89
"New" modified bitumen	1.05
"New" EPDM	1.09
"New" PVC	3.60

Major problems with the new membranes included (Reference 7 and direct observations):

- insufficient seam strength, resulting in roof leaks; poor roof edge details/adhesion, resulting in shrinkage/tenting;
- weak reinforcements of modified bitumen resulting in splitting and shattering of nonreinforced PVC membranes;
- insufficient air and water vapor protection, resulting in wind uplift and condensation problems.

In Canada, as compared to the United States, modified bitumen membranes are almost never used as single-ply membranes, and PVC membranes are almost always reinforced with fabric. Thus, the number of seam/lap problems with modified bitumen membranes and the number of shattering problems with PVC membranes would be expected to be reduced in Canada. On the other hand, splitting and shrinkage problems with modified bitumens and condensation problems are more pronounced in cold climates.

The pace and style of building in North America has led to a higher percentage of large area lightweight roofs here compared to Europe. A UK Building Research Establishment study indicated that lightweight roofs might cost as much as six times more to maintain compared to heavyweight roofs.[8] This might account for some of the difference in roof life expectancies between Europe and North America. Climatic differences and trade apprenticeship programs are also significant differences.

EFFECTS OF COLD CLIMATES ON ROOF SYSTEMS

Until 1980, most roofing research had dealt with the physical properties of waterproofing membranes independently of the roof system. Moreover, most physical properties were evaluated at room temperatures. The usefulness of this work was limited, especially if it was the build-up and transfer of stresses to and from various roof components rather than the room-temperature properties of roof membranes that caused failures.

To address this situation, Domtar, at that time the largest manufacturer of building materials in Canada, constructed five model test buildings at its research center in Montreal. These buildings were covered with five different roof systems.*

These test roofs were instrumented with temperature, heat flow, and insulation joint movement sensors. Thermocouples were placed on the roof surface, between the top coating of asphalt and the uppermost felt, between the membrane and insulation, between the insulation and deck, and underneath the deck. Heat flux transducers monitored heat flow at roof deck level, and linear variable differential transformers monitored joint movement between insulation boards at the roof membrane/insulation interface. The relative humidity inside the buildings was cycled from 30, to 90, to 50 percent (one month per condition) in order to accelerate many of the processes causing roof failure. Data were collected for a four-year period starting in December 1980. Each roof was 7.5 m^2 (81 square feet) in area.

The five roof systems had 0.76-mm- (0.03-inch-) thick, 200-mm (8-inch) module galvanized steel decks with the following insulation and built-up bituminous roof membranes:

- XPS/2C—Extruded polystyrene insulation (0.05 by 0.61 by 2.44 m [0.16 by 2.0 by 8.0 feet]) with a two-ply No. 40 organic felt membrane.
- EPSFBD/3G—Expanded polystyrene/wood fiberboard composite insulation (0.06 by 0.61 by 0.91 m [0.2 by 2.0 by 3.0 feet]) with a three-ply glass felt BUR membrane.
- EPSFBD/4G—Expanded polystyrene/wood fiberboard composite insulation (0.06 by 0.61 by 0.91 m [0.2 by 2.0 by 3.0 feet]) with a four-ply glass felt BUR membrane.
- EPSFBD/4C—Expanded polystyrene/wood fiberboard composite insulation (0.06 by 0.61 by 0.91 m [0.2 by 2.0 by 3.0 feet]) with a four-ply organic No. 15 felt BUR membrane.
- RGF/4C—Rigid glass fiber insulation (0.06 by 0.91 by 1.22 m [0.2 by 3.0 by 4.0 feet]) with a four-ply organic No. 15 felt BUR membrane.

The XPS/2C roof system was chosen because its premature failure was anticipated, and the RGF/4C roof system was cho-

* Domtar has permitted the author to present a summary of its test results in this paper.

sen because it had historically given good service (with a vapor retarder, which was omitted here for experimental reasons).

The EPSFBD composite product contained a 51-mm- (2-inch-) thick layer of expanded polystyrene with a 13-mm- (0.5-inch-) thick upper layer of wood fiberboard.

Type 2 bitumen conforming to Canadian Standards Association CSA A123.4 was used as the adhesive and waterproofing agent. All roof membranes were topped with a 1.5 kg/m² smooth surface of asphalt.

Roof Surface Temperature Extremes and Temperature Changes

Maximum Canadian roof surface temperatures have been reported to be 60°C (140°F) (twice), 73°C (163°F), and 98°C (208°F). [9, 10, 11, 12] The observed maximum roof temperature in Washington, D.C., has been reported as 74°C (165°F), and the predicted maximum has been reported as 80°C (176°F).[13] Minimum roof surface temperatures have been predicted to be anything between the minimum air temperature and 11°C (20°F) below this value, depending upon the information source.

Maximum and minimum roof surface temperatures recorded in this experiment were 79°C (174°F) and -30°C (-22°F). The maximum roof surface temperature was 45°C (81°F) higher than the corresponding air temperature because of solar radiative heating, and the minimum roof surface temperature was 14°C (7°F) below the corresponding air temperature because of nighttime radiative cooling.

Although a roof surface temperature of 79°C (174°F) may be as high as one would normally expect in Canada, the -30°C (-22°F) temperature would be considered to be mild in some areas of Canada (e.g., the January design temperature for Dawson is -50°C [-58°F]).

A detailed formula to predict roof surface temperatures was developed. However, although this formula could be used to calculate maximum and minimum roof surfaces precisely, it was not useful as a predictive tool. Even with the abundance of data generated in this experiment, the author found it impossible to accurately predict the effects of air movement close to the roof surface. Air temperature, wind effects, radiation, and heat capacity of the substrate are major factors influencing roof surface temperature. It was noted that halving or doubling the 1.75 (m².°C)/W (9.94 ft².h.°F/Btu) R-valve on these roofs would have had a minor effect upon roof surface temperature, because heat transfer through the roof system comprised only 1 percent of the total heat transfer at the roof surface.

For most purposes, the simple equations given by Baker[12] were almost as accurate as the more detailed formula. Baker's equations for a roof membrane directly over insulation are:

Maximum roof surface temperature = $(T_a + 55a)$ °C
Minimum roof surface temperature = $(T_a - 10a)$ °C

where

T_a = air temperature
a = solar absorption coefficient of roof surface.

Baker developed other formulae that predicted less extreme temperatures over substrates with high heat capacity (e.g., concrete) and more extreme temperatures in sun traps (e.g., where light-colored walls reflect sunlight onto roofs).

Diurnal Roof Surface Temperature Changes

Most of Canada enjoys clear skies, and Canadian roof surfaces experience large diurnal temperature changes because of radiative heat gain (solar gain) and heat loss (radiation to night skies).

The contrast between roof surface temperatures on clear and overcast days is illustrated by Figures 1 and 2. The responses of heat flow and insulation joint movements to roof surface temperatures are also shown in Figures 1 and 2.

Minimum and maximum diurnal roof temperature changes ranged from 1°C (1.8°F) on a snow-covered roof in January to 65°C (117°F) on a clear July day. Even in cooler months (February and October), daily roof temperature swings of 50°C (90°F) were measured.

Rate of Roof Membrane Temperature Changes

Except for periods of precipitation, the maximum rate of roof membrane change recorded was 15°C (27°F) per hour. It is important to qualify this statement with the fact that the data was only collected hourly, and thus, rapid temperature changes were "smoothed out."

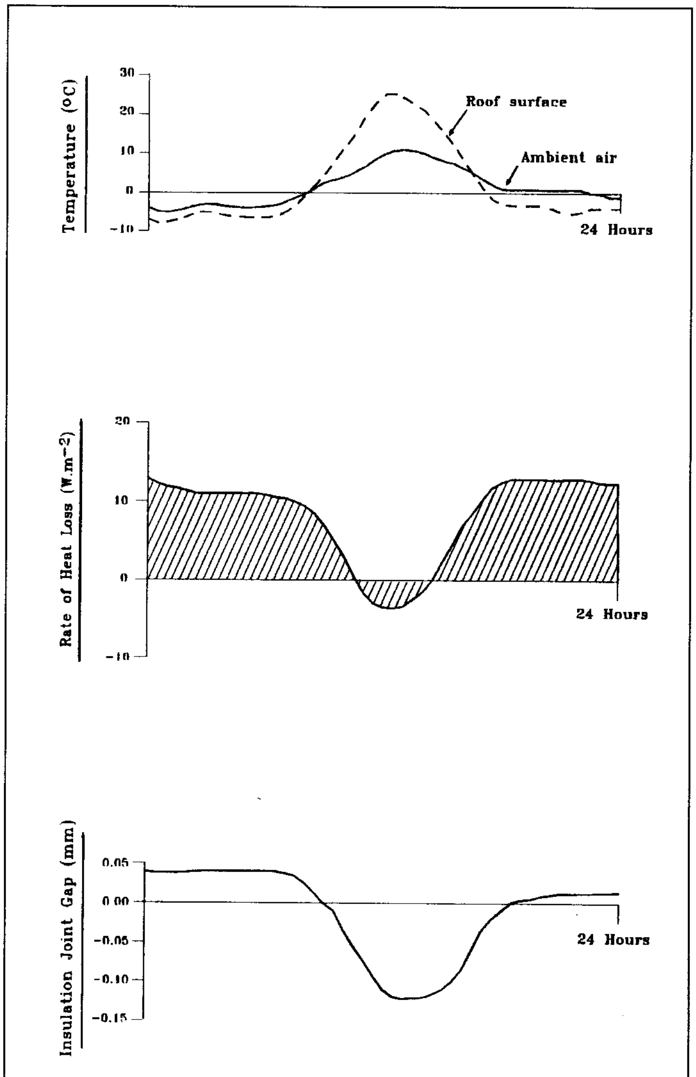


Figure 1. Typical roof surface temperatures, heat flows and insulation board joint movements on a clear, cool day (13 November 1981.)

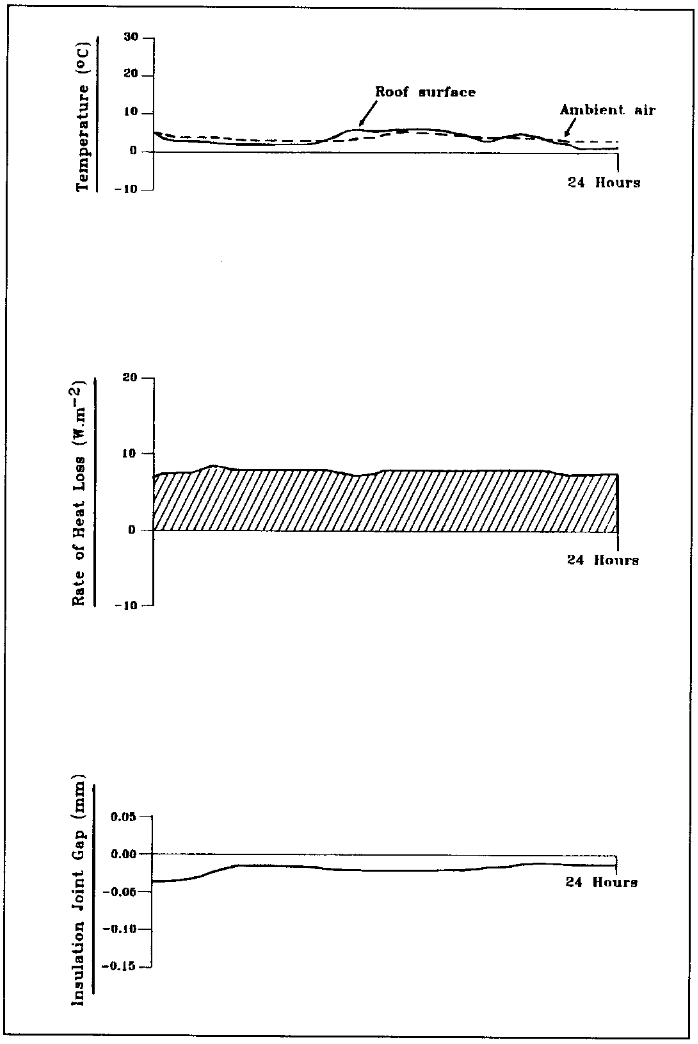


Figure 2. Typical roof surface temperatures, heat flows and insulation board joint movements on a cloudy, cool day (17 November 1981).

Cullen found roof surface temperature fluctuations as large as 25°C (45°F) over a 30-minute period on insulated roofs in Washington.[13] Roof surface temperature fluctuation on membranes covering wood and concrete decks were 17°C (31°F) and 8°C (14°F) during the same 30-minute period.

Effect of Cloud and Rain Upon Roof Surface Temperatures, Heat Flow, and Insulation Joints

On May 19, 1982, roof surface temperatures, heat flow, and rigid thermal insulation joint positions were monitored at one-minute intervals between 9:43 a.m. and 4:00 p.m. From 10 a.m. to 11 a.m., a lawn sprinkler sprayed the equivalent of 18 mm (0.71 inches) of rain over the roof surfaces. Between 11:00 a.m. and 12:30 p.m., the strong sun dried the roofs. The skies clouded over at 12:30 p.m., and from 1:00 p.m. to 2:15 p.m., a light (less than 1 mm [0.04 inches]) natural rainfall occurred. The day remained cloudy thereafter.

Figure 3 illustrates how roof surface temperatures responded to changes in atmospheric conditions. The maximum rates of roof surface temperature changes were:

At the onset of light rain:	-6°C (-11°F) per minute
Drying of a wet roof by strong sun:	2°C (4°F) per minute
Sudden cloud cover:	-10C (-2¯F) per minute

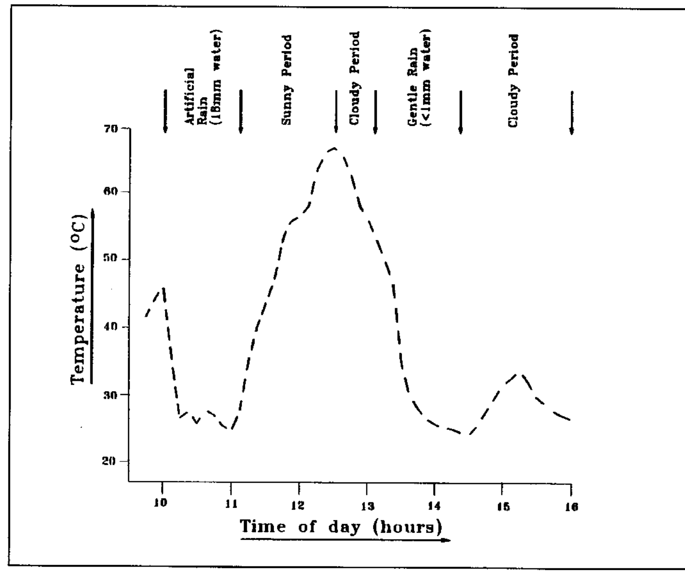


Figure 3. Effect of rain and cloud on roof surface temperature (19 May 1982).

All plies of the roof membrane experienced similar temperatures and rapid temperature changes. The insulation experienced less rapid changes, with heat flow and insulation joint movements lagging behind roof surface temperature changes by up to one hour (Figures 4 and 5).

Maximum rates of joint movement on the five roofs are shown in Table 1.

Roof Label	Maximum Rates of Insulation Board Joint Movement			
	Artificial Raining Period		Drying Period	
	mm/minute (inches/hour)	%* /minute	mm/minute (inches/hour)	%* /minute
XPS/2C	0.033 (0.078)	†	0.013 (0.031)	†
EPSFBD/3G	0.004 (0.009)	0.10	0.003 (0.007)	0.08
EPSFBD/4C	0.002 (0.005)	0.05	0.002 (0.005)	0.05
EPSFBD/4G	0.005 (0.012)	0.13	0.001 (0.002)	0.03
RGF/4C	0.001 (0.002)	0.03	0.001 (0.002)	0.03

*Assuming a 4-mm (0.16-inch) joint gap as being typical.

†It was noted that the XPS/2C roof had untypically wide insulation joints, and therefore, the rate of joint movement expressed as percent/minute would be misleading. However, the actual movement between the extruded polystyrene boards was about four times larger on this roof than on the other roofs.

Table 1. Maximum rates of joint movement.

Except for the large rate of insulation joint movement in the XPS/2C roof,* these data support previous claims that thermally induced movements experienced by roof membranes in end-use are no more rapid than 0.1 percent per minute.[14]

Effect of Wood Nailers on Roof Surface Temperatures

Thermocouples were placed on roof membrane surfaces over wood nailers at roof edges. It was found that with winter

* It was noted that the XPS/2C roof had untypically wide insulation joints, and therefore, the rate of joint movement expressed as percent/minute would be misleading. However, the actual movement between the extruded polystyrene boards was about four times larger on this roof than on the other roofs.

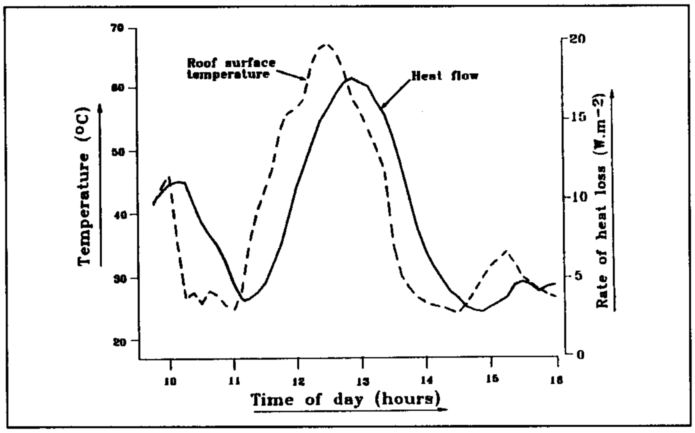


Figure 4. Rate of heat loss vs. roof surface temperature (19 May 1982).

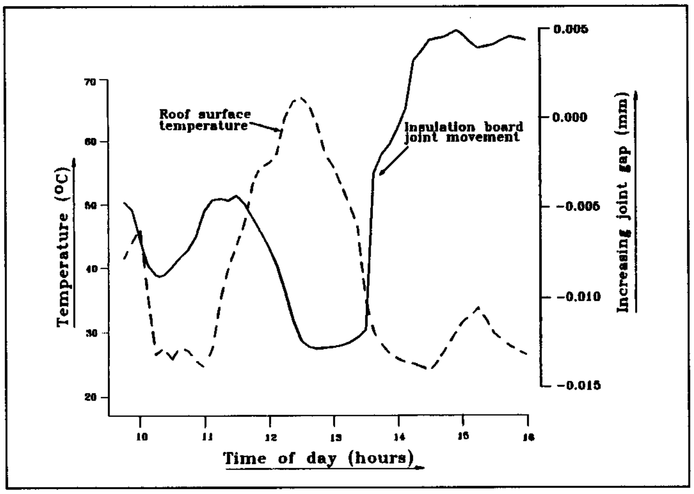


Figure 5. Insulation board gap vs. roof surface temperature (19 May 1982).

air temperatures below -10°C (14°F), there was about a 7°C (13°F) temperature difference between roof membranes located over wood nailers (at the roof edges) and roof membrane located over thermal insulation. This was attributed to the higher rate of heat loss through wood nailers compared to thermal insulation.

Effect of Insulation Joints on Roof Surface Temperatures

Roof membrane surface temperatures were measured over insulation board joints and over the center of insulation boards. Marked differences were only observed on roof XPS/2C. On this roof, surface temperatures were up to 6°C (11°F) warmer in winter and 12°C (22°F) cooler in summer over the joints. Figure 6 shows the difference between roof surface temperatures, measured over insulation board centers and over board joints, on January 10, 1982.

Roof XPS/2C had square-edged extruded polystyrene insulation, and it was known, from observations made when the membrane was cut to install linear variable differential transformers (LVDTs), that the joints between the insulation boards were wide on this roof. Roofs with expanded polystyrene/fiberboard composite insulation had tight shiplapped joints, and the roof with square-edged glass fiber insulation had well-butted joints when LVDTs were installed.

Effect of Partial Snow Cover on Roof Surface Temperatures

On March 22, 1982, the air temperature was 10°C (50°F), snow-covered areas of the roof were 2°C (36°F), and bare

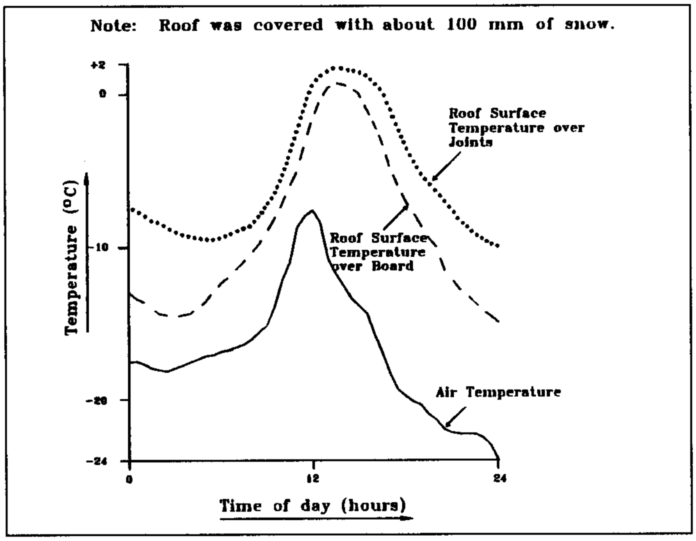


Figure 6. Roof surface temperature over XPS insulation and at insulation board joints (10 January 1981).

areas of roof (warmed by the morning sun) were 30°C (86°F). This 28°C (50°F) temperature differential occurred over a distance of 300 mm (1 foot) in both machine and cross-machine directions of the membrane felts. The temperatures were uniform through the membrane's thickness (i.e., the top and bottom plies of the membrane were the same temperature).

Such temperature differentials could induce stresses up to 1.7 kN/m^{-1} (10 lbf/in^{-1}), which is approximately 10 percent of the cross-machine breaking strength of a new, dry four-ply cellulosic roof membrane at 30°C (86°F).

Heat Flow Through the Roof Systems

The measurement of heat flow through roof systems is complicated by the unsteady state conditions that are reality. At the time these data were collected (1980 to 1984), compensation for unsteady heat flow involved elaborate calculations of linear partial differential equations[15] or reliance upon time averaging methods.[16, 17]

Hedlin found that simple averaging was unreliable and resorted to using the slope of heat flow vs. the temperature difference as the basis for calculating thermal resistance.[16]

Like Hedlin, the author found that simple time-averaging of heat flow divided by the inside-to-outside temperature differential was unreliable. Reasonably consistent measures of thermal resistances were obtained by time-averaging all data except that collected when temperature differences or heat

Roof Label	Measured R-Value °C.m².W-1 (ft².h.°F/Btu)	Design R-Value °C.m².W-1 (ft² .h.°F/Btu)	Difference Measured vs. Design
XPS/2C	1.83 (10.39)	1.97 (11.19)	-8%
EPSFBD/3G	1.64 (9.31)	1.72 (9.77)	-5%
EPSFBD/4C	1.69 (9.60)	1.72 (9.77)	-2%
EPSFBD/4G	1.83 (10.39)	1.72 (9.77)	+6%
RGF/4C	2.02 (11.47)	1.85 (10.50)	+8%

Table 2. The measured vs. design R-values.

flow across the roof was small.

Table 2 shows the measured vs. design R-values on a yearly basis.

The measured thermal resistance values were within 9 percent of the calculated design thermal resistances. This agreement was considered to be good.

Effect of Snow Cover and Solar Radiation on Heat Loss

A formula commonly used in Canada to calculate annual heat losses through a roof is:

$$\text{Annual Heat Loss} = \frac{\text{Roof Area x Heating Degree Days x 24}}{\text{Total R-Value for Roof}}$$

Where:

- The heating-degree-days value is the difference between 18°C (64°F) and the mean daily air temperature, accumulated for all days when the mean daily air temperature is below 18°C (64°F).
- Total R-value is the sum of the R-values for the interior still air film, all roof components, and the exterior air film.

This heating-degree-days calculation is based on daily air temperatures, but on a roof, it should be based on roof surface temperatures. Both solar heating and the insulating effect of snow cover resulted in mean winter roof surface temperatures that were substantially higher than mean winter air temperatures. For example, from August 1991 to July 1992, the heating degree days based on air temperature readings were 3450°C/day (6210°F/day), but the effective heating degree days based on roof surface temperatures were only 1320°C/day (2376°F/day).

Thus, conventional calculations of heat losses through these roofs predicted more than twice the actual heat losses. This has obvious implications on the economics of insulating flat roofs. On the other hand, many roofs in Canada are underinsulated, and the reliance on snow to insulate roofs is a risky business.

Movements at Insulation Board Joints

Joint movements were measured with linear variable differential transformers (LVDTs) attached across insulation joints. Like heat flow, joint movements lagged behind roof surface temperature changes by as much as one hour (Figures 1, 4, and 5).

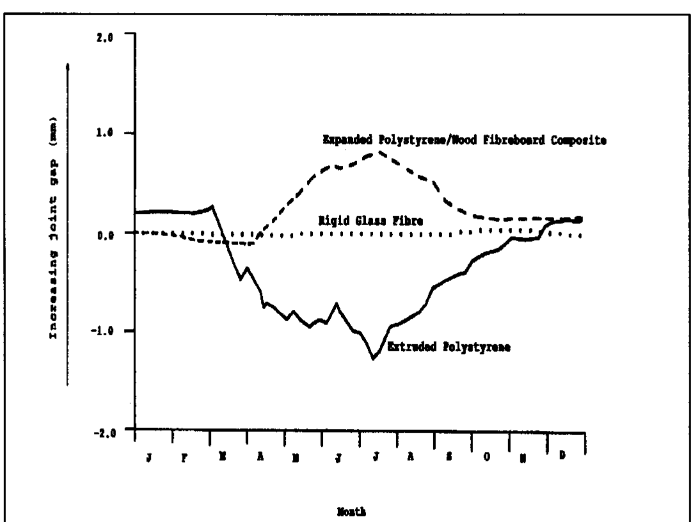


Figure 7. Long-term joint movement between insulation board joints.

Data collected over a one-year period are shown in Figure 7.

Little movement was seen at the joints between insulation boards in winter. The strength of bituminous built-up roof membranes typically doubles in winter, and the adhesive strength of bitumen also improves. The small joint movement between insulation boards in cold weather is likely due to the enhanced holding power of the roof membranes. At warmer temperatures, the joint movements appeared to be governed by the insulation type.

Discounting the effect of live loads, rigid glass fiber insulation was found to be the most dimensionably stable insulation board used. Maximum daily joint movement never exceeded 0.08 mm (0.003 inches) and no long-term joint opening or closing was observed. Also, changes in interior relative humidity had no significant effect on joint movement.

Extruded polystyrene insulation was found to be the least dimensionally stable insulation used, with maximum daily joint movements up to 1.23 mm (0.05 inches) (fifteen times that of glass fiber). From the magnitude of the joint movement, it is obvious that there must have been adhesion problems on the XPS/2C roof, because such a large joint movement would have caused a fully adhered membrane to split.

Beech and Hudson reported that extruded polystyrene insulation on a roof in the UK had joint movements of 0.90 mm (0.036 inches) when the roof surface temperature changed by 50°C (90°F).[18]

The composite insulation (51-mm- [2-inch-] thick expanded polystyrene with a 13-mm- [0.5-inch-] thick wood fiberboard upper layer) was found to be stable on a daily basis.* Daily movements were approximately twice that of rigid glass fiber but about eight times less than extruded polystyrene. On a seasonal basis, the composite insulation behaved more like wood fiberboard than expanded polystyrene, as it expanded in winter (when the relative humidity is higher) and contracted in summer (when the relative humidity is lower). In summer months, the insulation joints opened by an average of 1.1 mm (0.04 inches), but in winter, they closed again. This movement is likely to impose little stress on roof membranes because they want to contract in winter, and closing insulation joints help to relieve contractional stresses in the membrane that bridges the insulation joint.

Insulation Joint Movements Under Live Loads

Joint movement sensors on the five roofs were mounted on ball joints so that they could measure both horizontal and vertical movements and anything in between. Their outputs were monitored continuously while a 82-kg (180-pound) man walked in 600-mm (2-foot) circles around them. Roof surface temperatures were about 40°C (104°F). The maximum measured joint movements are shown in Table 3.

The results support the use of overlay boards, particularly on more compressible rigid glass fiber insulation. It is suspected that such large instantaneous strains can only be accommodated without significant damage when bituminous membranes are warm and viscous.

Unfortunately, a similar experiment was not undertaken in winter.

*LVDT readings from one of the three EPSFBD roofs were ignored because the LVDT became defective.

Roof Label	Maximum Instantaneous Joint Movement	
	inches (mm)	%*
XPS/2C	(0.11)	†
EPSFBD/3G	(0.03)	0.8
EPSFBD/4C	(0.11)	2.8
EPSFBD/4G	(0.04)	1.0
RGF/4C	(0.28)	7.0

* Assuming a 4-mm (0.16-inch) joint gap as being typical.

† It was noted that the XPS/2C roof had untypically wide insulation joints, and therefore, the rate of joint movement expressed as percent/minute would be misleading.

Table 3. Maximum instantaneous joint movement.

Moisture Absorption in Test Roofs

Small square plugs of roof (100 mm by 100 mm [4 inches by 4 inches]) were periodically removed from the roofs and weighed to determine moisture content. The plugs were replaced in the roofs after weighing.

Little moisture absorption occurred within the roofs in summer even at 90 percent relative humidity, but in winter, the upper parts of the rigid glass fibre and the composite boards were saturated with ice and water (see Table 4).

Wintertime absorption of large amounts of water renders thermal insulation inefficient precisely at the time that it is most needed in Canada. Moisture absorption followed by freeze-thaw cycles can destroy the cellular structure of some lightweight plastic foam roof insulations, resulting in permanent R-value loss.

BUILDING ON LESSONS LEARNED

Most problems with roofing have been attributed to poor workmanship (e.g., Reference 19), and yet, most changes in roof design and materials have further complicated roof applicators' lives.

Product changes since 1950 have resulted in:

- reduced stiffness and continuity of roof decks;
- the use of less robust and less dimensionably stable insulation products;
- less drying potential within roof systems;
- reduced redundancy (fewer plies) in air-vapor retarders and roof membranes.

Roof Label	Typical Water Contents Measured After Four Weeks of Exposure to an Interior Relative Humidity of 90 Percent	
	Summer (kg/m^2 [lbm/ft^2])	Winter (kg/m^2 [lbm/ft^2])
XPS/2C	0.10 (0.020)	2.0 (0.410)
EPSFBD/BUR*	0.25 (0.051)	10.0 (2.049)
RGF/4C	0.20 (0.041)	20.0 (4.097)

* The three roof plugs with EPS/wood fiberboard composite insulation were averaged.

Table 4. Typical water contents measured after four weeks of exposure to an interior relative humidity of 90 percent.

On top of this, winter construction and cost cutting to the point of silliness have resulted in some very poor roofs.

It is instructive to consider a roof system layer by layer. This approach focuses attention on two critical aspects of roofing: 1) the attachment between layers and 2) the function and proper location of components within the composite (roof) system.

Almost all buildings in Canada are heated and insulated; therefore, this paper will consider only insulated bituminous roof systems.

Structural Support and Condensation Protection

The roof deck provides structural support and the layer(s) next to the roof deck include materials that prevent condensation through air movement or vapor diffusion. The secure attachment and consistent performance of these lower layers are prerequisites for the construction of durable roofs in cold climates.

Wood deck

Nailing two plies of dry felt and then adhering a two-ply bitumen air-vapor retarder provides excellent condensation protection for insulated roofs over wood deck. The nailed dry layers (with or without a first layer of kraft paper) provides secure attachment and divorces the fully adhered air-vapor retarder from any shrinkage forces in the wood deck.

Concrete deck

The use of primer, a button base sheet, and one or two plies of modified bitumen sheets embedded in bitumen provides excellent condensation protection. For a conventional roof system, one ply of fully mopped modified bitumen over the button base sheet will function as the air-vapor retarder. In a protected membrane roof (PMR) system a two-ply modified bitumen membrane over the button base sheet will function as both the air-vapor retarder and the waterproofing membrane. The button base sheet provides partial adhesion, which reduces the chances for membrane splitting over any concrete cracks, and modified bitumen sheet(s) have better crack bridging performance than oxidized bitumen sheets.

Serious consideration should be given to the installation of a protected membrane roof over well-sloped concrete decks because performance-over-cost considerations usually favor PMR.

Steel deck

Screw attachment of a thin layer of gypsum, cement, or insulation board directly over steel deck provides continuous support for the air-vapor retarder. In addition, this layer increases roof deck stiffness, reduces problems with the cooling of hot bitumen (over steel deck) and provides a better working surface for roof applications. Fully adhering a two-ply bitumen air-vapor retarder over this layer provides good condensation protection.

If gypsum board is used on new roof decks, adequate ventilation of moisture generated from subsequent wet construction activities (e.g., the pouring of concrete floors) should be ensured.

Thermal Insulation

Full adhesion of insulation obviates the problem of penetrating air-vapor retarders with mechanical fasteners (except at roof edges and curbs if wood blocking is used). Compared to mechanical fasteners, full adhesion does not introduce thermal bridges through the insulation and full adhesion provides more secure attachment of insulation in the horizontal plane.[18]

Some design authorities specify the use of mechanical fasteners with insulation. Mechanical fasteners may be prudent if delamination of insulation is considered to be a possibility. However, in such cases, full adhesion of insulation with better laminar strength would likely be the better option.

Insulation Overlay

The application of a layer of wood fiberboard (or similar product) over roof insulation is recommended throughout Canada for the following reasons:

- It provides a robust surface for roof membrane applications.
- It provides good support for roof membranes and protects roof insulation from roof traffic.
- It provides a venting layer to allow the escape of moisture and other gases that could otherwise become entrapped during roof membrane application. Thus, it reduces the potential for blisters.
- It allows insulation to be salvaged when reroofing. Old bituminous roof membranes can be removed (with the thin upper layers of fiberboard) without damaging the primary insulation, and thus, the lower layers of the roof system may be reused by applying new coverboard and membrane.
- Wood fiberboard joints close in winter, working in harmony with the contracting roof membrane.

Full adhesion of fiberboard is preferred over mechanical fastening for the same reasons that full adhesion of insulation is preferred. Also, it is not prudent to lay roof membranes directly over mechanical fasteners in case they should back out.

Membrane

Bituminous membranes must be firmly secured through the roof system in order to transfer thermally induced stresses to the roof deck. Contractional forces as high as $15kN/m^{-1}$ (1030 lbf/ft) have been measured at the edges of unsecured built-up roof membranes.[20] Adequate securement of all roof components, down to the roof deck, is vital for successful roof performance.

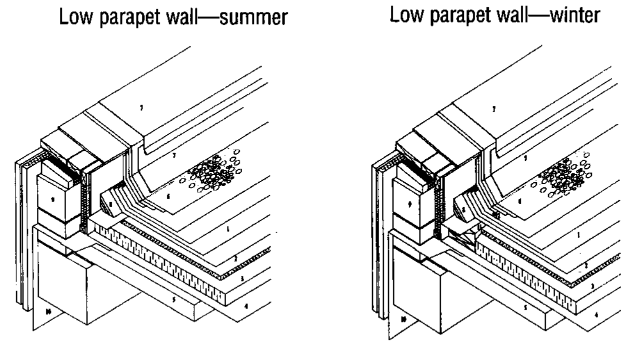
Proper application and adhesion of membrane plies is critical. The majority of built-up roofing reinforcements in Canada are cellulosic felts with manufactured perforations. Adequate brooming of these felts to ensure intimate contact and embedment of membrane plies is critical to minimize building voids into the roof (potential sites for subsequent blisters).

Edge Details

There is considerable discussion in Canada about the need for wood blocking at roof edges and upstands (curbs, parapets).

The two main advantages of using wood blocking are that the roof membrane and flashing membranes can be firmly secured to the roof with nails, and differential roof-wall movement can be accommodated. The three main disadvantages of wood blocking are additional costs, heat loss, and perforation of the air-vapor retarder.

In cold weather applications, the author prefers to use wood blocking, because full adhesion is more difficult to accomplish and flashings are one of the more critical parts of a roof.



1. Roofing membrane and membrane protection.
2. Insulation overlay, usually fiberboard.
3. Primary insulation.
4. Air-vapor retarder.
5. Acceptable structural deck and support for air-vapor retarder, by others.
6. Membrane base flashing.
7. Metal flashing.
8. Fiber cant. Secondary and primary insulation continued under cant.
9. Wall construction by others. Top of parapet wall is minimum 200 mm above membrane.
10. Wall air barrier.
11. Wood blocking firmly secured to structural deck.
12. Roof membrane securely nailed to wood blocking.

(Based on CRCA FL. 1 flashing guideline).

Figure 8.

Figure 8 illustrates a typical flashing. Basic guidelines for flashings include:

- Terminate roof waterproofing at the outside face of exterior walls (extend membrane flashings over parapets, or use thru-wall damp courses).
- Shed water away from flashings and onto the field of the roof.
- Tie the roof air-vapor retarder to both the wall air-vapor retarder. Also, tie the roof air-vapor retarder to the roof membrane (i.e., wrap the insulation).
- Avoid right-angled bends in membrane flashings.
- Nail the edges of roof membranes into wood blocking that is firmly secured to the roof deck.
- Never attach roof flashing membranes directly to parapet walls. Attach vertical membrane flashings to wood blocking that is anchored to the roof deck and unanchored to the wall (unless the roof and wall structure is monolithic).
- Nail vertical flashing membranes 200 mm (8 inches) (minimum) above finished roof surfaces.
- Design counterflashings to allow for movement between vertical membrane flashings and walls.

Product Development

The lack of first-time success in roofing product development in Canada and elsewhere deserves special attention.

Some roof membrane manufacturers are willing to sell product that will experience temperatures between 80°C (176°F) and -40°C (-40°F) without first having tested products at these temperatures. One example of this was glass-reinforced two-ply modified bitumen membranes imported into Canada from Europe around 1980. The glass reinforcements in these materials were weak, but manufacturers claimed that they only acted as a carrier sheet during the manufacture of the high-quality modified bitumen sheet.

The problem in Canada was that the glass transition point temperature of these modified bitumen products was typically -30°C (-22°F), and below these temperatures, the membranes behaved like weakly reinforced two-ply oxidized bitumen built-up roof membranes. As roof temperatures in much of Canada drop below -30°C (-22°F), cold-temperature splitting of this type of membrane was widespread. This problem could have been foreseen if realistic laboratory testing or test roof programs had been undertaken.[21]

Evaluating products using laboratory tests requires care and attention to ensure that test methods are relevant, realistic, and reproducible. Otherwise, results can be misleading.

One example of how problems can arise is in the measurement of strain energy. Strain energy is a good measure of a membrane's ability to work, and strain energy of a roof membrane can be measured at any temperature. In addition, laboratory evaluation of strain energy is reproducible and relevant, and at first sight, it appears to be realistic.

However, bituminous roof membranes can develop considerable shrinkage forces when they are cooled, and this is often overlooked in laboratory tests. Laboratory membrane specimens are free to contract when they are cooled but membranes on roofs are not free to contract. A significant part of strain energy can be consumed by contractional stresses that build up within a roof membrane.

By clamping a roof membrane specimen in a universal tester at 25°C (77°F) and then cooling it to -40°C (-40°F), the contractional load within the material can be evaluated. The useable strain energy of the membrane (i.e., its ability to work on a roof) at -40°C (-40°F) is the strain energy left in the material at this point. Unfortunately, many laboratories simply cool their test specimens in a freezer where they are free to contract and then measure the strain energy. This procedure overstates the membrane's real life performance (Figure 9).

Because of poor experiences with new product introductions, the provincial roofing contractor association of Alberta requires that products be tested on roofs in Alberta for two years before the association accepts them in their roof warranty program. On a less formal basis, most roofing contractor organizations adopt a similarly cautious approach to new products.

The insulation industry has been debating design R-values for two decades without concensus. In Canada, different insulation materials undergo different R-value test procedures. Product users are confused and frustrated because they cannot confidently compare R-values of different products, and there is a mistrust of manufacturers' R-value claims. Some manufacturers have not been straightforward in this area, and it has taken much effort from organizations such as the Thermal Insulating Systems: Standards and Quality Consortium to develop a benchmark for comparing R-values. This benchmark is the R-value of products after two years of exposure in end-use conditions.

The cost of product evaluation using laboratory tests and test roof exposures is typically less than the cost of one large failed roof. This author suggests that manufacturers and consumers would be further ahead if they heeded the lessons of history; a two-year assessment of all new products in end-use would be a fine start.

CONCLUSION

Numerous new roofing product and roof system introductions over the latter half of this century have provided useful information on commercial-sized roofs. Some of these roofshave, inadvertently, been experiments in what not to do in roofing. This paper reported, in a qualitative way, lessons learned from new roofing product and system performance in Canada. This paper also reported the results of an experiment with five small test roofs in Montreal. The advantage of small test roof experiments is that they are more controlled than commercial-sized roofs, yield more quantitative information and can tie together field experience and laboratory test results.

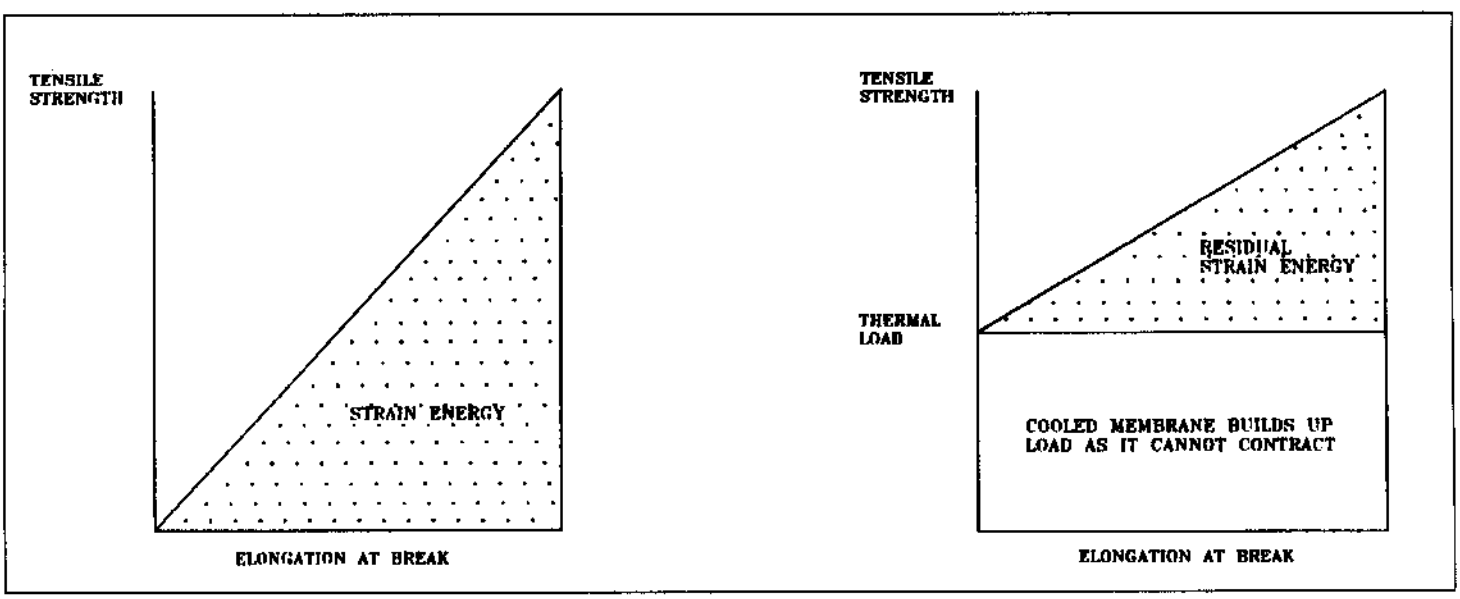


Figure 9. Residual strain energy.

Some examples of good roofing practices that have resulted from a combination of field experience and controlled experiment have been discussed, as have the lessons that are becoming more widely appreciated by the Canadian roofing industry as the next century approaches.

REFERENCES

1. *Fixed Capital Flows and Stocks Methodology Introduction National Wealth and Capital Stock Selection,* Investment and Capital Stock Division, Statistics Canada, 1990.
2. CSA S478-95, *Guidelines in Durability in Buildings: Structures Design,* Canadian Standards Association, December 1995.
3. Zdanowicz, A. "Flat Roof Performance," *Proceedings of Third Conference on Building Science and Technology,* Canadian Society for Civil Engineering, November 1985.
4. Cullen, W. C. "Survey compares practices to problems. Project Pinpoint uncovers successes and failures," *Roofing Spec,* October 1984.
5. "Bitumen and built-up felt roofings: Durability," *UK Building Research Station Digest 144,* August 1972.
6. Booth, R. J. "Life History of Built-up Roofs Bonded by Domtar in 1958," *Comtar Research Memorandum,* July 1979. [This document is not openly available. Excerpts provided with permission of Domtar Inc.].
7. Cullen, W. C. *Project Pinpoint Analysis: Ten-Year Performance Experience of Commercial Roofing 1983-1992,* U.S. National Roofing Contractors Association, 1993.
8. Holmes, R., et al. *Maintenance costs of flat roofs,* Building Research Establishment, U.K., Current paper 4/81, 1981.
9. Baker, M. C. "Building Science and Roofing Design," *Roofing, Siding and Insulation Magazine,* August 1969.
10. Solvason, K. R. and G. O. Handegord. *Ridging, Shrinkage and Splitting of Built Up Roofing Membranes,* NRC of Canada, Division of Building Research, Note No. 112, 1976.
11. Laaly, H. O. *Temperature of Bituminous Roofing Membrane and Its Relation to Ambient Conditions,* NRC of Canada, Division of Building Research, Note No. 758, 1977.
12. Baker, M. C. *Roofs,* Multiscience Publications, Montreal 1980.
13. Cullen, W. C. *Solar Heating, Radiative Cooling, and Thermal Movement Their Effects on Built-Up Roofing,* U.S. Dept. of Commerce, NBS Technical Note 1963.
14. Johnson, J. E. and J. P. Sheahan. "The Role of Temperature on the Splitting of Built-Up Roofing Systems," *Proceedings of the Second International Symposium on Roofs and Roofing,* September 1981.
15. Stephenson, G. *Mathematical Methods for Science Students,* Longmans, London 1965.
16. Hedlin, C. P., H. W. Orr, and S. S. Tao. "A Method for Determining the Thermal Resistances of Experimental Flat Roof Systems Using Heat Flow Meters," *Thermal Insulation Performance,* ASTM STP 718, 307 1980.
17. Treado, S. J. "Measuring Roof System Thermal Resistance," *Proceedings of the 6th Conference on Roofing Technology,* NBS/NRCA, 1981.
18. Beech, J. C. and R. W. Hudson. "Joint Movements in Foam Plastics Flat Roofing Insulation," *Second International Symposium on Roofs and Roofing,* September 1981.
19. "Profits up but workmanship is poor," *RSI* magazine, February 1979.
20. Cullen, W. C., E. C. Shuman, P. L. Morris, and W. E. Kugler. *Reports on Ten Years of Roofing Research,* Midwest Roofing Contractors Association, Kansas City, Missouri, 1976.
21. Booth, R. J. "Evaluation, Testing and Standards for Modified Bitumen," *Proceedings of the 8th Conference on Roofing Technology,* NBS/NRCA, 1987.