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Thermal Considerations in Roof Design

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Please note

Thermal considerations in the design of roofs can be divided into two general categories: control of heat loss and heat gain of the space below the roof, and the effects of extremes and variations of temperature on the roof system. In Canadian buildings where temperature control through winter heating and summer cooling is common, heat gain and heat loss are of economic importance. Some roofs may only control heat gain by providing shade from the sun, but all roofs exposed to the weather experience wide variations of temperature. The effects of extremes and variations of temperature are of major importance because they influence the durability of the total roof system. It must also be recognized that all materials interposed between environments, including ceilings and air spaces, are considered part of the roof system because all influence the thermal performance of the total construction.

Control of Heat Loss/Gain

The size, capacity and cost of heating and cooling systems are determined on the basis of maximum rates of heat loss and heat gain, and can be reduced by increasing the over-all resistance to heat flow through the roof. Savings in annual cost for fuel and mechanical maintenance can also be made by increasing the heat flow resistance. This is normally achieved by the inclusion of insulation in the roof system. Summer heat gain can be further reduced by using a light coloured roof surface. Light colours reflect more solar radiation than dark colours so that their heat gain is less.

The economic thickness of insulation, considering only heat loss and heat gain, can be determined on the basis of the installed cost of increased thermal resistance, the reduced cost of mechanical equipment and operation, and the difference in taxes and interest on the investment. Because of the many potential problems, however, insulation thickness and position in the construction should be determined by a study of its influence on the temperatures throughout the roof.

Temperature Effects

Durability or service life of a roof is to a large degree dependent upon the temperatures it experiences. A knowledge of the thermal response of materials, the variations and extremes of

temperature and how to modify or compensate for them, is essential for the design of durable roofs.

High temperatures increase the rate of deterioration of many roof materials through acceleration of the photo-oxidative processes, softening bitumens and, under extreme conditions, softening plastic insulation. A temperature rise may produce sufficient expansion of small quantities of air or moisture trapped between layers of a roof membrane to cause blisters that can destroy the waterproof characteristics of the membrane.

At low temperatures the coefficient of expansion of bituminous membranes is high and the material tends to be brittle and vulnerable to cracking under stress. Both high and low interior surface temperatures influence comfort conditions, and low values may determine the relative humidity permissible in the space below.

As a result of daily and seasonal changes in air temperature, solar heating and radiative cooling, temperature variations occur that cause building materials to change their dimensions. Each layer in a roof experiences a different temperature cycle and under these conditions differential movements can occur. If this is restrained it produces stress and perhaps warping in the restrained materials, and may in turn result in cracking or wrinkling and ultimate failure. These are but a few examples of the thermal response of roof materials and constructions.

Determination of Temperatures

The temperature distribution through a roof can be determined by the simplified procedure described in **CBD 36**. As explained there, two of the major assumptions made for simplification may lead to inaccuracies in the temperature values gained for constructions exposed to solar radiation. The first is that heat transfer (at a surface) by convection and radiation can be combined and expressed in terms of a thermal resistance. As the thermal resistance values normally used do not make adequate allowance for solar heating and radiative cooling, there may be sizable errors in the extreme values gained.

The second assumption, of steady state heat flow, seldom occurs in heavy constructions because of heat storage and rapid fluctuations of air temperature, solar heating and radiative cooling. Near steady state conditions can obtain, however, in light constructions. The errors resulting from this assumption are usually on the safe side, showing a slightly wider spread of temperature than actually occurs provided allowance has been made for radiation effects. The simplified procedure of **CBD 36** gives acceptable temperature values when a realistic exterior surface temperature is used in lieu of the outside air temperature and surface film resistance

Surface temperature values for use in determining temperatures for roofs to be built in Canada (taking into consideration solar heating, heat storage and radiative cooling) can be approximated by the following simple formulae. With a low heat capacity material (insulation) immediately below the roof surface, the maximum temperature is $t_A + 100a$, and the low temperature under a clear night sky at all seasons is t_A -20°F, where t_A is the air temperature in degrees Fahrenheit and a is the coefficient of solar absorption.

The high and low temperatures for a roof surface on a high heat capacity substrate (concrete) are $t_A + 75a$ and t_A - 10°F. Recommended design values of a for representative colours and some weathered metals are given in Table I. The value of a, however, changes with the changing colour that results from accumulations of dirt. It should also be recognized that when a light coloured wall reflects solar radiation onto a roof the incident radiation is increased. To allow for this the constants in the above formulae for summer high temperatures should be increased by approximately 30 per cent to $t_A + 130a$ and $t_A + 100a$.

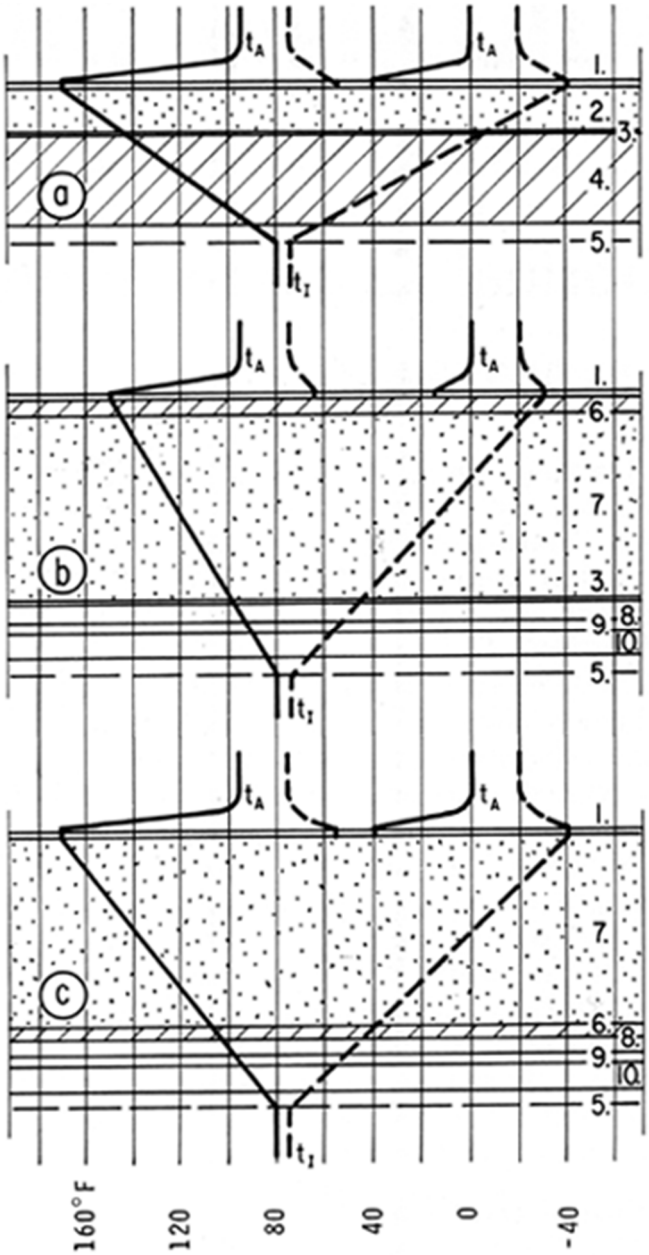
Table I. Recommended Values of The Solar Absorption Coefficient, *a*

Surface Colour	*a*

black	0.95
dark grey	0.80
light grey	0.65
white	0.45
Weathered metals	
copper - tarnished	0.80
- patina	0.65
aluminum	0.60
galvanized iron	0.90

The graphic determination of temperature distribution (**CBD 36**) is presented in Figure 1, where the thickness of each material has been drawn to the scale of its thermal resistance. The straight line joining the exterior surface temperature and the inside air temperature gives the temperature distribution. The temperature at any plane in the construction can be read from the temperature scale where the temperature gradient line intersects that plane in the construction.

SUMMER		WINTER
95°F	Air Temp. Day (t_A)	0°F
75	Air Temp. Night	-20
80	Inside Air Temp. (t_I)	75



LEGEND FOR MATERIALS

		Resistance
1.	Roof Membrane a = .75	.3
2.	1" Fibre Insulation	1.8
3.	Vapour Barrier	0
4.	3" Cedar Deck	3.8

5.	Inside Surface Film	.6
6.	4" Concrete Deck	.4
7.	2" Insulation	8.0
8.	Dead Air Space	.8
9.	Gypsum Board	.3
10.	Acoustic Tile	1.2

Figure 1. Temperature gradients through three roofs.

The reader should be cautioned that the surface temperatures used in Figure 1 do not represent extreme conditions. They are based instead on temperatures for a roof with a clear view of the sky and a medium grey surface having a coefficient of solar radiation absorption, *a*, of 0.75.

Control of Temperatures

The temperature of each material in a roof is influenced by both the temperature at the roof surface and its position with respect to the major thermal resistance. Insulation in a roof has the effect of causing the materials on the warm side of it to be warmer and those on the cold side to be colder than they would be if no insulation were used. In Figure 1b it can be seen that the roof deck and membrane with insulation below experience a wide variation of temperature, while the ceiling temperature is more nearly constant. When the insulation is outward of the roof deck as in Figure 1c, the temperature variation in all materials except the membrane is small. The position of the insulation also has an appreciable effect upon the extremes of exterior surface temperature, as is indicated by the surface temperature formulae.

Two separate layers of insulating material in a roof may produce undesirable conditions such as low temperature in winter at the vapour barrier, as is illustrated in Figure 1a. Acoustic treatments frequently produce this situation because of their thermal resistance.

Temperatures can be controlled by other measures. The maximum exterior surface temperature of a roof, being dependent upon solar heating, can be reduced by judicious selection of the surface colour, by shading with other materials, and by ventilation below the surface. It can also be reduced by using a high heat capacity substrate, but care must be taken to avoid the many problems associated with differential movements. The minimum exterior surface temperature can be increased slightly by use of a high heat capacity substrate or by ventilation below the surface.

The daily high temperature for winter cannot be determined by the formulae presented for the summer maximums because the incident solar radiation is considerably less. It has however, been indicated on Figures 1 and 2 to assist a designer to recognize the effect of solar heating on the short term expansion and contraction of a roof membrane.

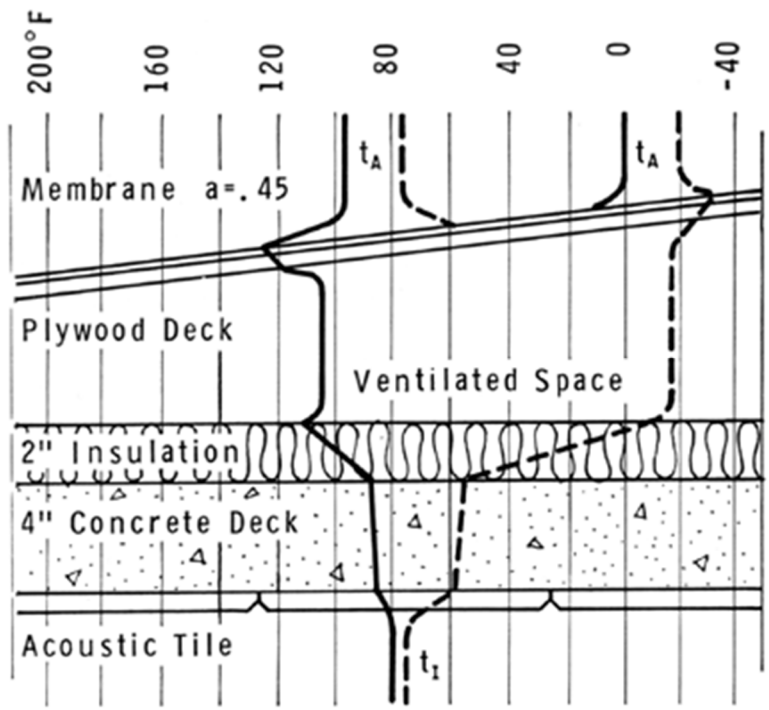


Figure 2. Temperature gradients for a roof with white surface and a ventilated space.

Thermal bridges (**CBD 44**) produce localized cold zones on the warm side of the roof and warm zones on the cold side because they have less thermal resistance than the adjacent construction. A low interior surface temperature may cause condensation and dirt marking, whereas a warm zone in a cold membrane may contribute to ridging over insulation joints. Thermal bridges can best be eliminated by using a continuous layer of insulation. Their effect can also be greatly reduced by separating the roof surface from the remainder of the construction by means of a ventilated air space and a high heat conductivity material on the under side of the insulation.

Control of Thermal Problems

To minimize thermal problems in roofs it is necessary to minimize, wherever possible, the range of temperature variation and to allow for the differential movements that will inevitably occur. In the roof of Figure 2 (drawn to its physical scale) a white membrane (a = 0.45) on a light plywood deck has been used. If the air space were not ventilated the extreme surface temperatures would be 140 and -40°F. When ventilated, however, the surface temperatures approach 125 and 40°F. With this portion of the roof sloped for drainage and acting as a rain screen, the construction below is protected from the weather and a relatively continuous layer of insulation can be placed on the exterior of the structural deck. As the solar/rain screen will experience a greater variation of temperature than the construction below, it should be free to move. The acoustic tile in this case causes the temperature variation in the structural deck to be 12 F degrees higher than would occur if the ceiling were plastered. This variation, however, can be reduced by increasing the insulation above the deck.

A ventilated space in a roof is of considerable value in controlling both thermal and moisture problems, but because night sky cooling can cause the under side of the rain screen deck to be colder than the air, condensation or dew formation may occur under some conditions. This and other moisture problems in roofs will be discussed in a future Digest. It should be noted that all points of this discussion may not apply to roofs of refrigerated spaces because of their special thermal and moisture conditions.

Conclusion

The design of roofs inevitably involves many compromises, but the most successful solution can only be achieved when the designer is aware of all the factors influencing performance. Thermal performance plays a major role in determining the success or failure of a roof system, and it can be controlled to a high degree by the designer.