DESIGN HEAT REQUIREMENTS FOR EMBEDDED SNOW-MELTING SYSTEMS IN COLD CLIMATES

G. P. Williams, Division of Building Research, National Research Council of Canada

Methods of calculating design heat requirements of embedded snow-melting systems are assessed, particularly for those operating in cold climates. Formulas for estimating design heat requirements developed from snow-melting tests carried out during three winters at Ottawa, Canada, are compared with those recommended in the Guide and Data Book of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the only comprehensive guidelines available in North America. The relation between convective coefficients and wind speed at an exposed site compares reasonably well with that recommended by ASHRAE, provided adjustments are made for the size of the heated area, the exposure to wind, and the height at which wind speeds are measured. Evaporative coefficients recommended by ASHRAE also need to be adjusted for the size of heated area and the exposure to wind. Radiative coefficients need to be adjusted for cloud conditions. The design heat requirements for systems operating in cold climates are determined by the maximum rate of surface heat loss from bare, wet pavements for weather conditions that will probably prevail immediately after snowstorms. Design heat requirements calculated for an exposed site at Ottawa by using the heat transfer coefficients obtained are 170 Btu/ft^2-hour (536 W/m^2). This agrees quite well with current practice in this region. Two case histories of snow-melting tests are presented to illustrate that the use of insulation will practically eliminate ground heat loss and the need to allow for it in design calculations.

•ONE of the more difficult determinations in the design of embedded heating systems in pavements is the calculation of the heat needed to prevent ice from forming or snow from accumulating. Designers must provide sufficient heat capacity for effective melting but must not overdesign the system and unnecessarily increase the cost of an already expensive operation.

Published information on procedures for calculating design heat requirements is limited and can be misleading. Some of the procedures are based on field tests of snow melting during mild weather (1, 2) and do not necessarily apply to systems operating under severe winter weather. The procedure recommended in the ASHRAE Guide and Data Book (3), the only comprehensive guideline available in North America, has proved to be of uncertain value. A comparison of calculated design heat loads, based on procedures of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), with actual installed heat capacities for five cities in the northern United States (4), shows that the installed heat capacities are often quite different from the theoretical values (Table 1). The information on installed capacities, shown for Canada, was obtained from unpublished and published reports (5, 6). Installed heat capacities are generally somewhat lower in Canada than those reported in the United States, a surprising development considering the more severe climatic conditions under which Canadian systems usually operate.

The purpose of this paper is to assess methods of calculating design heat requirements of embedded snow-melting systems, particularly those operating in cold climates. The study is based on an extensive review of the literature and on snow-melting tests

carried out on heated pavements, over three winter periods, on the grounds of the National Research Council of Canada in Ottawa.

TEST SLABS, INSTRUMENTATION, AND WEATHER OBSERVATIONS

Test sites A, B, and D are shown in Figure 1. Most of the observations were made at site A, a 16-ft^2 (1.5-m^2) electrically heated, insulated snow-melting system at an exposed location. Electric heating cables, spaced 4 in. (10.2 cm) apart, were embedded 3 in. (7.6 cm) deep in a 7.5 in.-thick (19-cm) concrete slab that rested on 2 in. (5.1 cm) of expanded polystyrene insulation. The heating cables were laid out in two separate circuits, providing two heated areas: an inner 10-ft^2 (0.9-m^2) area in the center of the slab and an outer 2.5-ft-wide (0.75-m) area extending around the inner area. Three levels of power input were available for each circuit. Temperatures were measured by thermocouples at several locations in the concrete slab and in the insulation under the slab. Heat loss through the insulation was measured by heat flow meters installed at three locations in the insulation. A data logging system was used to record output from the thermocouples and heat flow meters.

Observations were also made at two heated 3-ft^2 (0.3-m^2) concrete test slabs: One was located at an exposed site B, the other at site C, sheltered from the wind. The two slabs were identically constructed: 1-in.-thick (2.5-cm) concrete with embedded electric heating cables and with 1-in.-thick (2.5-cm) polystyrene bead board insulating the bottoms and sides. Temperatures were measured at several locations in both concrete and insulation by thermocouples attached to recorders. The power input was recorded and controlled to maintain the surface temperature of each slab at about 38 F (3.3 C) during test runs. Site B was located on the north side of a small building a few hundred feet (meters) from site A. The slab at site C was located on the south side of the same building, almost completely sheltered from wind by the building and by a fence built for that purpose. Observations at these sites were used to determine the effect of size and exposure on the heat requirements of snow-melting systems.

Limited observations were also obtained at site D, an electrically heated ramp leading to the basement of a building located on the grounds of the National Research Council of Canada. This uninsulated snow-melting system is operated intermittently, and the power is automatically turned on at 5 p.m. and off at 8 a.m. during the winter season. Surface temperatures were measured at several locations on the ramp by means of thermocouples connected to a recorder, and surface heat loss was determined by a heat flow meter installed in the asphalt surface. The power input was measured by the household types of wattmeters on the circuits supplying power to the ramp. Observations were used to determine the magnitude of heat loss to the ground at this site.

Standard weather records obtained on the grounds of the National Research Council of Canada, the only kind of weather information normally available for design calculations, were used in the analysis. Air temperature was measured with a thermocouple located in a Stevenson screen about 200 ft (61 m) from site A; wind speed was recorded with an anemometer located at a height of 50 ft (15.2 m); snowfall measurements, obtained by standard meteorological methods, were checked with a recording gauge equipped with a windshield; and net radiation, measured with an all-wave radiometer installed about 2 ft (0.6 m) above the center of the slab at site A, was used to check radiation formulas. Surface conditions on the heated slabs (whether they were dry, wet, snow- or ice-covered) during tests runs were obtained by visual observation supplemented by time-lapse photographs taken at site A.

SURFACE HEAT LOSS FROM BARE PAVEMENTS

Designers of snow-melting systems must estimate surface heat loss from bare pavements when determining the heat required to maintain operating temperatures for systems run continuously or the heat needed to raise the temperature of a slab to operating

Table 1. Heat requirements.

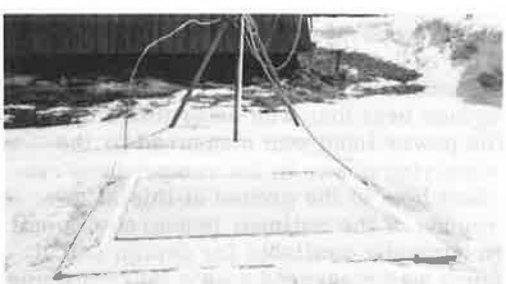
Area	Class 1[a]		Class 2[b]		Class 3[c]		
	Installed	ASHRAE[e]	Installed	ASHRAE[e]	Installed	ASHRAE[e]	Installed[d]
Northern United States							
Spokane	30 to 40	36	30 to 45	52		78	
Minneapolis-St. Paul	42 to 75	26	60 to 75	64	70 to 75	104	
Detroit	40 to 60	28	60	57	60	105	
Burlington	50	37	50	58	75	100	
Hartford	30	47	50	104	70	107	
Canada							
British Columbia							15 to 25
Prairie Provinces							30 to 55
Southern Ontario							20 to 40
Ottawa-Montreal							45 to 55
Atlantic Provinces							35 to 55

Note: All values are in British thermal units per square foot-hour. 1 Btu/ft^2-hour = 3.2 W/m^2.

[a]Residential. [d]ASHRAE calculations are not available; no information on class of installation.
[b]Commercial. [e]Calculated; includes adjustment for loss of ground heat.
[c]Critical.

Figure 1. Test sites.

test slab, site A



test slab, site B

heated ramp, site D

temperatures for systems run intermittently. This total heat loss, which depends on weather conditions, is composed of convective, radiative, and evaporative heat losses.

Convective Heat Loss

The rate of transfer of convective heat is proportional to the temperature difference ΔT between the surface and the air and the area in contact with the air flow as follows:

$$\frac{dQ}{dt} = h_c A \Delta T \qquad (1)$$

where h_c = heat transfer coefficient, a function of many variables, shape, roughness, and dimensions of the surface that will not be uniform over a surface. For design calculations an average coefficient is used.

Convective heat loss Q_c of dry surfaces was determined at site A for the selected periods for the central heated area of the slab from the following equation:

$$Q_c = Q_T - Q_R - Q_q \tag{2}$$

where

Q_T = electrical power,
Q_R = net radiation, and
Q_q = heat flow through the insulation under the slab.

All of these values were measured. Heat loss from the edge of the pad was kept to an insignificant level by maintaining an appropriate level of heat input to the outer circuit of the slab. The periods analyzed were for steady state conditions when temperature changes within the concrete were slight and the contribution of heat storage to surface heat loss could be neglected. Average hourly coefficients for convective heat transfer ($Q_c/\Delta T$) were then obtained and plotted against average hourly wind speeds for site A. A calculated value of convective coefficient for free convection (7) in the absence of winds is also shown.

A similar procedure was used to obtain convective coefficients for the small slabs at sites B and C (Figure 2). Those obtained by Chapman and Katunich (1) for 3.5-ft-diameter (1.1-m) snow-melting test panels agree quite well with measured values at site B if adjustments are made for the height at which wind speeds were measured. It was not possible to compare other convective coefficients reported in the literature on snow melting because convective and radiative coefficients are combined and are not reported separately.

These results show that the size of a heated area must be taken into consideration in calculating heat loss by convection. Convective heat coefficients obtained for the small slab at site B are almost double those at the larger slab at site C for the same wind speed. The effect of size on convective coefficients is particularly important for areas with short characteristic length, such as narrow sidewalks or heated wheel tracks, but does not appear to be too significant for larger heated areas with characteristic lengths varying from 10 to 100 ft (3.1 to 30.5 m) (8).

These results also show the effect of exposure to wind. The reduction in heat loss observed at the sheltered site C is approximately the same as that recommended by Watkins (9) for sheltered sites. Adjustments for the degree of exposure to wind should be made with caution, however, because wind speeds are difficult to predict at specific sites, especially in urban areas (10). The relation shown in Figure 2 for site C should only be used for sites that are completely sheltered from wind.

Radiative Heat Loss

Net long-wave radiation (downward atmospheric minus upward terrestrial) is the only radiative component considered in the design of snow-melting systems. The heat received from short-wave radiation during daylight hours is usually not taken into consideration in the design calculations because melting systems must perform satisfactorily under the worst conditions, e.g., at night when air temperatures are lowest and surface heat losses usually greatest.

A formula developed by Swinbank (11) for estimating incoming long-wave radiation under clear sky conditions and a procedure outlined by Budyko (12) for taking into account surface temperature and cloud conditions provided the basis for two equations for estimating net long-wave radiation:

$$Q_{R_{\text{clear sky}}} = -17.09 + 0.235\sigma T_A^4 - 4\sigma T_A^3 \Delta T \quad (3)$$

$$Q_{R_{10/10\text{ cloud}}} = -3.25 + 0.045\sigma T_A^4 - 4\sigma T_A^3 \Delta T \quad (4)$$

Temperatures are measured in kelvins, and the Stephan-Boltzman constant σ is measured in milliwatts/square centimeter • kelvins (the units used by Swinbank).

Equations 3 and 4 were used to calculate the long-wave radiation coefficients, $h_r = (Q_R/\Delta T)$, for both clear and cloudy conditions and a range of air temperatures for a bare concrete pavement at 32 F (0 C). The calculated long-wave radiation coefficients are compared with measured coefficients obtained from measurements of Q_R over the heated test slab at site A for selected periods when the sky was either clear or completely overcast and when surface temperatures varied from 32 to 50 F (0 to 10 C) (Figure 3). Some of the variation in the measurements can be attributed to uncertainties associated with cloud cover, i.e., whether or not the sky was completely clear of high clouds or completely overcast. The reasonable agreement between calculated and measured values indicates that equations 3 and 4 are satisfactory for estimating radiative heat loss in design calculations using the two extreme cloud conditions.

The average radiation coefficient (1) used by ASHRAE is also shown in Figure 3. This value will give good results if used for cloudy conditions and large surface-air temperature differences. It should not be used for clear sky conditions or when ΔT is less than 18 F (-10 C).

Radiative and convective coefficients are often combined in a surface or film coefficient. The combined coefficients for site A give considerably lower combined heat loss by convection and radiation at high wind speeds than that calculated by using ASHRAE coefficients. The magnitude of this overestimate will become apparent in the next section of the paper where total surface heat loss calculated by the ASHRAE formula is compared with the results obtained at site A.

Evaporative Heat Loss

Numerous empirical equations are available for estimating the rate of evaporation from water surfaces under atmospheric conditions. The simple equations developed for engineering use are of the following form:

$$E = k f(v) \Delta e \quad (5)$$

where

E = evaporation rate;
k = empirical constant, including air density, air pressure, and roughness factors;
$f(v)$ = function of wind speed; and
Δe = difference in vapor pressure between the saturation vapor pressure at the temperature of the surface and the vapor pressure of the air above the surface.

The evaporation rate E can be converted to heat by multiplying it by the latent heat of vaporization. Difficulties in the measurement of evaporation rates proved insurmountable at test site A, and it was necessary to rely on existing formulas to estimate evaporative heat loss from wet pavements.

The empirical evaporation formula used by ASHRAE was compared with one recommended by Penman (13), which is well accepted for estimating evaporation from small water surfaces (Figure 4). The agreement between the two formulas is quite good if it is assumed that wind is measured at the 6.6-ft (2.1-m) level. These results suggest, however, that the ASHRAE formula would have considerable error if wind speeds ob-

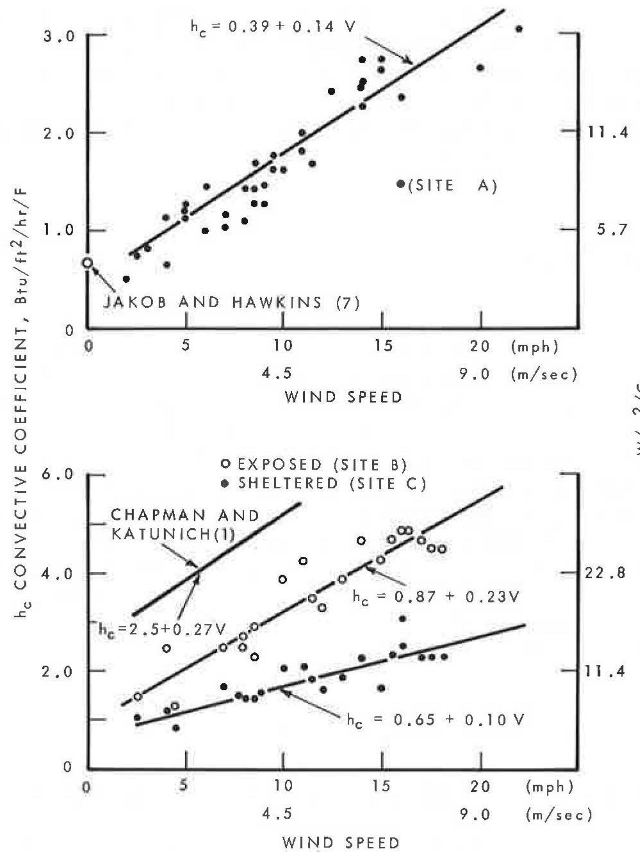


Figure 2. Convective coefficients.

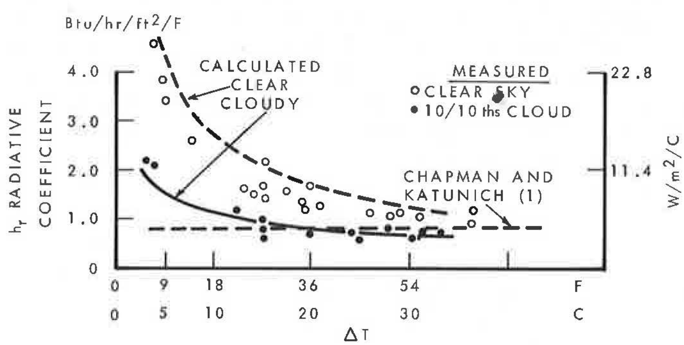


Figure 3. Long-wave radiative coefficient versus change in temperature.

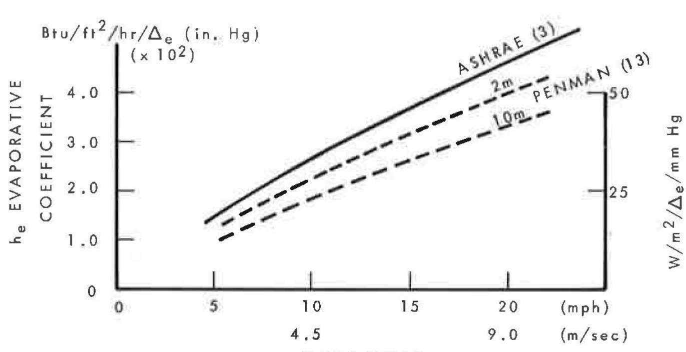


Figure 4. Evaporative coefficient versus wind speed.

tained from standard weather records [usually measured at the 3.1-ft (10-m) level] were used to calculate evaporation. The importance of allowing for the height at which wind speed is measured has frequently been stressed in the literature (14).

Evaporative coefficients need to be adjusted for the size of the evaporating area and the exposure to wind in the same way as convective coefficients. One way of doing this is to assume that Bowen's ratio (15) is valid, i.e.,

$$\frac{Q_c}{Q_e} = R\frac{\Delta T}{\Delta e} \qquad (6)$$

When convective heat loss has been calculated by using the relations shown in Figure 1, evaporative heat loss can be estimated by using Bowen's ratio.

The total surface heat loss from wet pavements by convection, long-wave radiation, and evaporation was calculated for completely cloudy conditions for ΔT = 18 F (-10 C) and Δe = 0.13 in. (3.3 mm) of mercury, by using the coefficients obtained at site A and the Penman evaporation formula. The total heat loss was then compared with values obtained by using the ASHRAE formula and that recommended by Watkins (9) for the design of snow-melting systems in Britain (Figure 5). Both formulas give higher values for total surface heat loss. If evaporative and convective heat loss terms in these formulas are recalculated and the height at which wind speed is measured at standard weather stations is taken into account, they agree reasonably well with the results obtained at site A.

SURFACE HEAT LOSS DURING SNOWSTORMS

Heat Required to Maintain Bare Pavement During Snowstorm

Maintainance of completely bare pavement during a snowstorm requires that sufficient heat be supplied to melt snow as it falls and to offset surface heat loss by convection, radiation, and evaporation. The heat required for melting equals the heat of fusion multiplied by the hourly rate of snowfall (water equivalent/hour). Information on the maximum hourly rates that can be expected at a site is therefore needed. The problem of measuring snowfall rates accurately under windy conditions has not been solved, however, and reliable data on hourly rates are not usually available. The few estimates available indicate that maximum hourly snowfall may be two to three times the hourly rate, averaged over the entire period of a snowstorm (16). For an average rate of snowfall during a storm of 1.0 in./hour (2.5 cm/hour), the estimated maximum hourly rates range from 2 to 3.5 in./hour (5.1 to 8.9 cm/hour), and a heat input of 170 to 275 Btu/ft^2-hour (536 to 867 W/m^2) would be required to melt the snow as it falls. Sites that are subject to drifting snow require even larger heat inputs since the rate at which snow can drift into a site can be several times the average rate of snowfall. Because of the large amounts of heat required, snow-melting systems are seldom designed to maintain completely bare pavements during snowstorms. This becomes evident when class 3 installed capacities are compared with ASHRAE calculated values (Table 1).

Design Heat Requirements for Snow-Covered Surfaces

Surface heat losses by convection, radiation, and evaporation are reduced in direct proportion to the percentage of heated pavement covered by snow. If the area is half covered, surface heat losses are reduced to about one-half those of a completely bare area; if the pavement is completely covered by even a thin layer of snow, the only surface heat loss is the small amount of heat transferred upward by conduction from the pavement surface through the snow cover.

In the ASHRAE procedure for calculating design surface heat losses, three levels

are chosen (level 1, complete snow cover; level 2, 50 percent snow cover; and level 3, completely bare) to allow for the percentage of area covered by snow. For most snow-melting systems in cold climates, however, only level 1 need be considered because level 3 gives unrealistically high heat requirements and the arbitrarily chosen level 2 will not necessarily apply at specific sites.

Snow-melting systems designed to melt the average rate of snowfall occurring during snowstorms, assuming complete snow cover, will prevent excessive snow accumulation, provided drifting snow is not a problem. Many of the earlier snow-melting systems were designed to melt snow at a certain design rate of snowfall without consideration of any other factors. Even record snowstorms (17), with 29.9 in. (76 cm) in 24 hours, only require about 90 Btu/ft^2-hour (284 W/m^2) to melt all the snow over the period of the storm, assuming no ground heat loss.

The design heat requirements for snow-melting systems should not, however, be based only on their ability to melt snow during a storm. If too low a design value is used, bridging can occur under undisturbed snow on sidewalks or driveways with little traffic, and subsequent poor heat transfer from the heated pavement to the snow cover will result. Where there is vehicle traffic, a portion of the heated pavement will be kept free of snow, and surface heat loss from the bare portion of the pavement will increase heat requirements accordingly. In addition, the limiting condition in cold climates is not so much the melting of snow during a storm as the maintenance of an ice-free surface afterwards.

Design Heat Requirements After Snowstorm

Preventing ice from forming on a heated pavement immediately after a storm requires that the heat input to the surface be equal to or exceed the rate of surface loss from a wet surface. This heat requirement usually exceeds that during a storm because the pavement is free of snow and surface heat loss can be quite high, particularly in cold climates where snowstorms are often followed by extremely cold weather.

Observations at site A showed that conditions after a storm were always the limiting factor in determining the required heat input. Figure 6, a series of time-lapse photographs taken at site A on January 6, 1973, shows a typical example of ice formation under severe weather conditions after a storm. Immediately after the storm on the evening of January 5, the slab was essentially bare and wet. By late evening it was partially covered with a thin layer of crusted ice, resulting partly from light snow blowing on the wet surface. By 4 a.m. on January 6, the slab was still covered because the rate at which heat was supplied to the surface was insufficient to maintain a bare surface. At 6 a.m. on January 6, hoar frost began to form and completely covered the slab by 8:00 a.m. The heat input during this period of observation, 135 Btu/ft^2-hour (426 W/m^2), was not sufficient to maintain a bare pavement.

Design heat requirements for conditions after snowstorms can be estimated by calculating the maximum rate of surface heat loss for the weather conditions that will probably prevail. The simplest way is to examine the weather records of a station, select representative or design storms, and thus establish the design weather data to be used in calculations. The elaborate method of obtaining design weather data recommended by ASHRAE is usually not justified because of the approximate nature of calculations of surface heat loss.

The design storm approach was used in an earlier study (16) to obtain design weather data for Ottawa. Surface heat loss from a wet surface at an exposed site was calculated to be 170 Btu/ft^2-hour (536 W/m^2) for a design air temperature of 5 F (-15 C) and wind speed of 18 mph (8.1 m/s). This heat input will not ensure bare pavement during heavy snowfalls nor prevent ice from forming on some occasions during extremely cold weather but should maintain an ice-free surface for most of the storms that occur in the region.

When a design value has been obtained, it may be desirable to adjust it for the standard of operation desired or for special site conditions. For example, the calculated design value for Ottawa might well be reduced for a residential system where the main

Figure 5. Comparison of formulas for heat loss from wet, bare pavements.

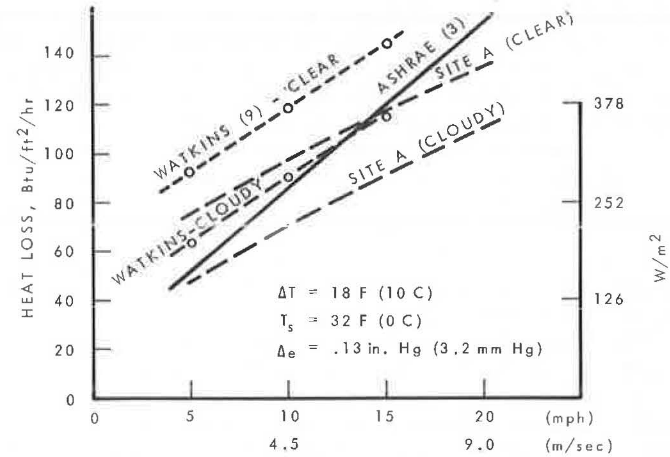
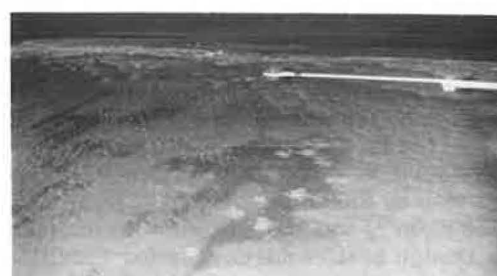


Figure 6. Conditions after snowstorm.

beginning of ice formation, TA = 15 F (-9.4 C)

ice formed, TA = -5 F (-20.5 C)



beginning of hoar frost formation, TA = -8 F (-22.2 C)

objective might be to melt snow rather than to maintain an ice-free surface. The effects of traffic, heat available from solar radiation, and heat stored in the concrete are factors that may influence the choice of design value at a particular site although they are difficult to allow for in calculations.

GROUND HEAT STORAGE

The importance of allowing for heat loss into the ground surrounding snow-melting systems when design heat requirements are calculated has long been recognized. For a continuously heated slab, ground heat losses are often assumed to be negligible; for

intermittent operation, arbitrary allowances of 30 to 50 percent of the surface heat loss are recommended (18). The role of the heat stored in a concrete slab in maintaining slab operating temperatures has been recognized, but the limitations of this heat source have not been investigated to any extent. Although there is no doubt that ground heat losses can be reduced substantially by the use of insulation, there is little information on the subject.

Edge Heat Loss

A substantial amount of heat can be lost from the edges of a heated area to the soil or pavement surrounding it. It will be greatest when the system has just been turned on after a period of cold weather and there is no snow on the ground, for then the ground temperatures at the edge are much lower than the temperature of the heated slab. The edge heat loss is difficult to calculate because it depends on variable thermal properties of the material around the slab, on weather conditions occurring before the heat has been turned on, and on past history of operation (past operating temperatures and duration of period when slab is unheated). For design purposes, it is probably sufficient to know the approximate value of the edge heat loss, the circumstances under which it will be greatest, and how to minimize it.

Edge heat loss was estimated for the inner heated area of the slab at site A for a period when a large temperature difference existed between the heated area and the unheated portion of the slab surrounding it [average gradient = 23 F/ft (0.4 C/cm)]. It was calculated by assuming a realistic value for the thermal conductivity of concrete and assuming steady state conditions. The average edge heat loss, estimated to be 130 W, was about 6 percent of the total heat supplied. A second estimate, based on a solution of the heat balance equation for the inner circuit, gave a value of 220 W or about 10 percent of the total heat supplied. It is considered that an estimated range of heat loss of from 6 to 10 percent is representative of the probable maximum edge heat loss at this site.

Edge heat loss can be reduced appreciably by the use of insulation. Heat loss from the perimeters of the small insulated heating slabs at sites B and C was always less than 1 percent of the total surface heat loss. Use of insulation to reduce edge heat loss is especially recommended for narrow heated areas with long perimeters, for example, sidewalks or vehicle tracks, because not only will the edge loss be reduced but also operating temperatures will be more easily maintained at the edge of the heated area.

Ground Heat Loss

Heat loss downward to the ground under heated slabs is difficult to calculate because of the variable thermal properties of the material under the slab and because of variable, non-steady-state temperature conditions. An approximate method of calculating this heat loss is available (19), but it does not appear to be used much.

Two case histories of ground heat loss during the operation of snow-melting systems are discussed to illustrate its relative value and how it can be reduced by the use of insulation. The first history is of ground heat loss at site D, an uninsulated snow-melting system; the second is of losses at site A, an insulated system. Total ground heat loss in both cases includes edge heat loss, heat loss or gain in the slab, and heat loss downward to the ground under the heated slabs. Both systems were operated on an intermittent basis, and power was turned on in the late afternoon and off in the morning.

Figure 7 shows the estimated total ground heat loss for the system at site D for one period considered fairly typical of losses that can occur at this site. The electrical energy used during the periods of operation was determined from wattmeters read at regular intervals. Surface heat loss was obtained in two ways: from measurements of the heat flowmeter installed near the surface and from calculations using the heat transfer coefficients developed for a sheltered site. The difference between heat sup-

Figure 7. Estimated ground heat loss for uninsulated snow-melting system, site D.

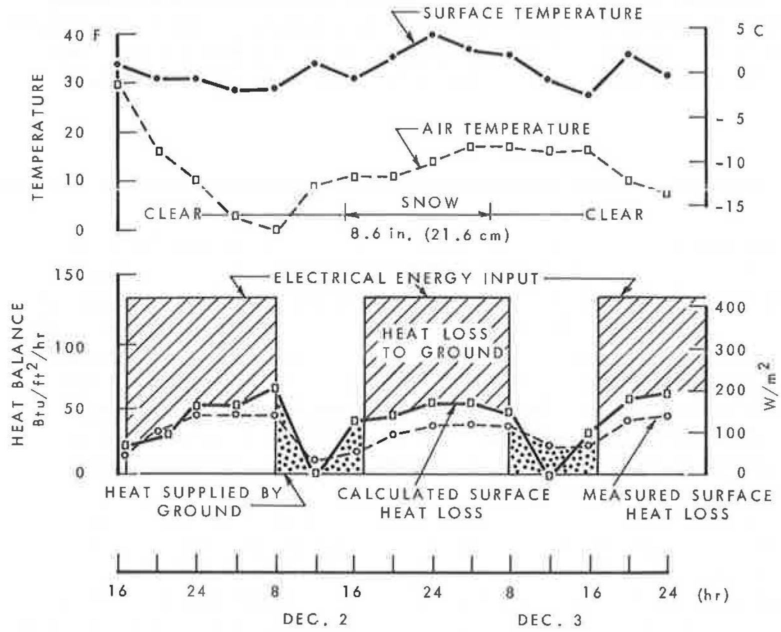
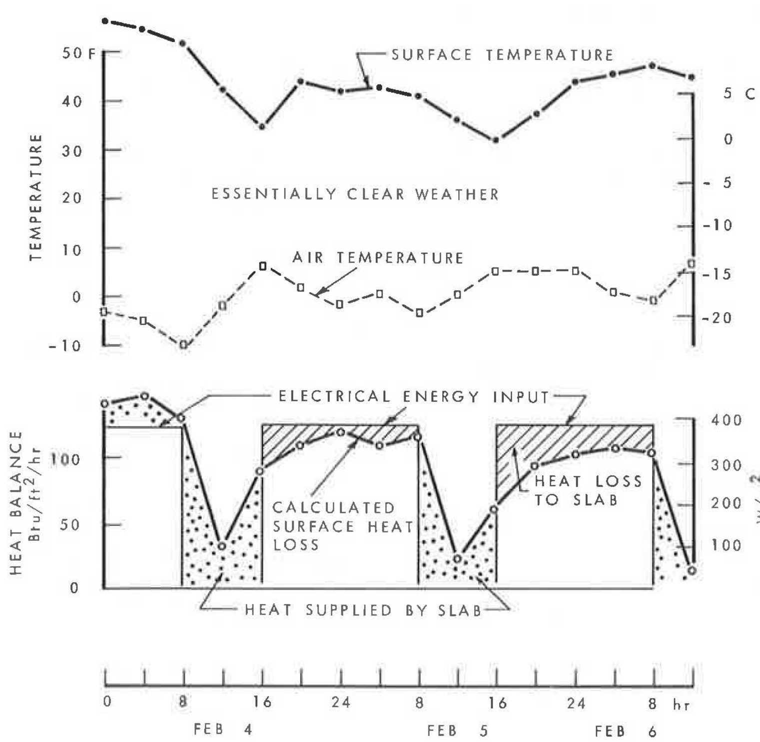


Figure 8. Estimated ground heat loss for insulated snow-melting system, site A.



plied and surface heat loss represents the total ground heat loss or gain. These results show that during the period when power was on, 50 percent or more of the electrical energy went to warming the slab and the ground surrounding it. During the day when the power was off, some of the heat stored in the slab and the ground became available for maintaining operating temperatures.

Figure 8 shows the estimated total ground heat loss at site A, with the system operating under quite severe weather conditions. The difference between electrical energy used and surface heat loss (estimated by using the appropriate heat transfer coefficients) was primarily edge loss plus heat lost or gained by the slab when it underwent temperature change. Heat loss through the insulation under the slab was less than 1 percent of the total heat loss.

The results from the two case histories illustrate the advantage of installing insulation under embedded snow-melting systems. Not only is the loss to the ground reduced to a small amount (this was verified under a wide range of operating conditions), but also the heat stored in the concrete appears to become more readily available for maintaining operating temperatures. The technology of insulated roadways is now reasonably well established (20) and could be applied to embedded snow-melting systems. Use of insulation would practically eliminate the heat loss downward to the ground under the slab and the need to make allowances for it in design calculations.

CONCLUSIONS

1. The ASHRAE formulas (3) for calculating design heat requirements for snow-melting systems are reasonably satisfactory, provided adjustments are made to take into account the size of the heated area, the exposure to wind, and the height at which wind speeds are measured.
2. The limiting condition controlling design heat requirements of snow-melting systems operating in cold climates is the maintenance of an ice-free surface immediately after snowstorms rather than the effective melting of snow during a storm. These heat requirements can be estimated by calculating the rate of surface heat loss from bare, wet pavements and by using weather data obtained from representative or design storms.
3. The use of insulation reduces edge and ground heat losses to insignificant amounts and eliminates the need to make allowances for such losses in design heat calculations.

ACKNOWLEDGMENTS

I am indebted to several colleagues in the geotechnical section for help in the preparation of this paper and to A. Laberge for taking many of the field observations. This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the director of that division.

REFERENCES

1. W. P. Chapman and S. Katunich. Heat Requirements of Snow Melting Systems. Trans., American Society of Heating and Air-Conditioning Engineers, Vol. 62, 1956, pp. 359-372.
2. P. J. Williamson. The Estimation of Heat Outputs for Road Heating Installations. Road Research Laboratory, Crowthorne, Berkshire, England, RRL Rept. LR 77, 1967.
3. ASHRAE Guide and Data Book—Systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York, 1970, chapter 36.
4. W. G. Potter. Electric Snow Melting Systems. Journal American Society of Heating, Refrigerating, and Air-conditioning Engineers, Vol. 9, No. 10, 1967, pp. 35-44.

5. A. E. Kobold and G. H. West. Snow Melting by Electrical Means. Ontario Hydro Research News, Vol. 12, No. 37, 1960, pp. 18-24.
6. J. D. George and C. S. Wiffen. Snow and Ice Removal From Road Surfaces by Electrical Heating. Highway Research Record 94, 1965, pp. 45-51.
7. M. Jakob and G. A. Hawkins. Elements of Heat Transfer. John Wiley and Sons, New York, 3rd Ed., 1958.
8. R. G. Coulter and S. Herman. Control of Snow and Ice by Induced Melting. City College Research Foundation, New York, 1964.
9. L. H. Watkins. Control of Road Snow and Ice by Salt and Electrical Road Heating. HRB Special Rept. 115, 1970, pp. 146-156.
10. Building Research Station Digest—Wind Environment Around Tall Buildings. Building Research Station, Garston, Watford, England, Digest 141, May 1972.
11. W. C. Swinbank. Long-Wave Radiation From Clear Skies. Journal, Royal Meteorological Society, Vol. 89, 1963, p. 339.
12. M. I. Budyko. The Heat Balance of the Earth's Surface (N. A. Stephanova, tr.). U.S. Department of Commerce, 1956.
13. H. L. Penman. Evaporation: An Introductory Survey. Netherlands Journal of Agricultural Science, Vol. 4, No. 1, 1956.
14. G. E. Harbeck. Discussion of Evaporation Computations for Prairie Reservoirs. Proc., Hydrology Symposium 2, National Research Council of Canada, 1961, p. 164.
15. I. S. Bowen. The Ratio of Heat Losses by Conduction and by Evaporation From Any Water Surface. Physical Review, Vol. 27, 1926, pp. 779-787.
16. G. P. Williams. Heat Requirements of Snow Melting Systems in Canada. Proc., National Conference on Snow and Ice Control, Roads and Transportation Association of Canada, Ottawa, April 1973.
17. R. V. Dexter. Nova Scotia's Record Snow Storm on 2-3 February 1960. Weatherwise, Vol. 13, No. 4, 1960, pp. 153-157.
18. P. A. Schaerer. Melting Snow and Ice by Heating Pavements. Division of Building Research, National Research Council of Canada, Building Research Note 55, 1966.
19. R. Jorgensen and Associates. Non-Chemical Methods of Snow and Ice Control on Highway Structures. NCHRP Rept. 4, 1964.
20. E. Penner, M. D. Oosterbaan, and R. W. Rodman. Performance of City Pavement Structures Containing Foamed Plastic Insulation. Highway Research Record 128, 1966, pp. 1-17.