Surface Heat Losses from Heated Pavements during Snow Melting Tests

Williams, G. P.

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ABSTRACT

This paper deals with the problem of estimating surface heat losses from heated pavements used to melt snow. The study is based on an extensive review of the literature and on tests carried out over three winter periods on an embedded snow melting system located on the grounds of the National Research Council, Ottawa. Formulae for estimating surface heat loss are compared with those recommended in the ASHRAE Guide and Data Book, the only comprehensive guidelines available in North America for calculating the design heat requirements of embedded snow melting systems. Several case histories of snow melting tests are presented to illustrate the problems of estimating surface heat loss during and immediately following snowstorms. It was found that the ASHRAE formulae gave reasonable results, provided adjustments were made for the height at which wind speeds are measured. The limiting condition controlling design surface heat loss for snow melting systems operating in cold climates is the maintenance of an ice-free surface immediately following snowstorms rather than the effective melting of snow during a storm.

LES PERTES DE CHALEUR SUPERFICIELLES DES CHAUSSEES CHAUFFANTES AU COURS D'ESSAIS DE FONTE DE NEIGE

par

G.P. Williams

RESUME

L'auteur examine le problème de l'évaluation des pertes de chaleur superficielles des chaussées chauffantes faisant fondre la neige. L'étude se fonde sur un examen détaillé de la littérature et sur des essais effectués durant trois périodes hivernales sur un système enrobé de chauffage des chaussées situé dans le campus du Conseil national de recherches à Ottawa. Les formules d'évaluation de la perte de chaleur superficielle sont comparées à celles que recommande le "ASHRAE Guide and Data Book", qui contient les seules directives d'ensemble, en Amérique du Nord, pour le calcul des exigences thermiques de base des systèmes enrobés de chauffage des chaussées. L'auteur décrit plusieurs essais de fonte de neige pour montrer les difficultés d'évaluer la perte de chaleur superficielle durant et immédiatement après une tempête de neige. Les formules ASHRAE donnent des résultats satisfaisants, pourvu qu'on tienne compte de la hauteur à laquelle la vitesse du vent est mesurée. Le but à atteindre quant à la perte de chaleur superficielle des systèmes de chauffage des chaussées en climat froid est d'assurer une surface libre de glace immédiatement après une tempête de neige plutôt que de faire fondre la neige durant une tempête.

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by

G.P. Williams

I. INTRODUCTION

Embedded melting systems are used to keep sidewalks, loading docks, garage ramps, driveways and bridge approaches free of snow and ice. Although there has been a substantial increase in the use of these systems during the past ten years, there is little published information in Canada on the subject. Most of the design information available is from foreign sources and does not necessarily apply to systems operating under the severe winter conditions experienced in Canada.

One of the more difficult determinations in the design of these systems, is the prior calculation of the heat needed to prevent ice forming or snow accumulating. Designers must provide sufficient heat to effectively melt snow and ice but not over-design the system and thus increase unnecessarily the cost of an already expensive operation. The only published procedures available for calculating design heat requirements are those presented in the ASHRAE Guide and Data Book (1970). This method is not generally used in Canada because it is not suited to Canadian meteorological records; also, the formulae upon which these procedures are based were obtained from limited field tests (Chapman and Katunich, 1956) during snowfalls with air temperatures close to 0°C (32°F). Formulae for estimating heat outputs for snow melting systems have also been developed in Britain (Williamson, 1967), but these were also developed for use under mild weather conditions. The only published information on design heat requirements for Canadian conditions, based on experimental snow melting tests, is for specific locations (Kobold and West, 1960; George and Wiffen, 1965). No attempt was made to generalize the results from these studies so that they could be applied to other locations in Canada.

In response to a need for more factual information on heat requirements for snow melting systems operating under severe winter weather, the Division of Building Research initiated, in 1971, a study of embedded snow melting systems. An experimental, electrically-heated concrete slab was constructed at an Ottawa site and instrumented to measure heat inputs and heat losses from the surface during snowfall and for periods in between snowfalls. This paper presents the detailed observations, analysis and results from these tests carried out during three winter seasons (1971-72, 1972-73, 1973-74).

Particular attention was given to the problem of estimating surface heat losses during the operation of snow melting systems, using available meteorological records. Formulae, relating surface heat losses to weather elements, were developed and compared with those recommended by the ASHRAE Guide and Data Book (1970).

1. Description of test slab and instrumentation

The heated concrete test slab, 4.9 by 4.9 m (16 ft by 16 ft), was constructed on the grounds of the National Research Council, Ottawa. Five centimetres (2 in.) of expanded polystyrene bead board insulation was placed over 1 m (3.3 ft) of crushed gravel. Ten centimetres (4 in.) of air-entrained concrete was poured directly over the insulation. Electrical heating cables were laid on this concrete base and covered with about 8 cm (3 in.) of concrete to form the finished surface of the test pad. The surface was built with a slight slope so that melt water would run off into a natural drainage channel west of the site. Figure 1 shows a general plan and cross-sectional view of the experimental slab.

The heating cables were laid out in two separate circuits: an inner circuit about 3 m by 3 m (10 ft by 10 ft) and an outer circuit .75 m (2.5 ft) wide extending around the inner area. The inner circuit had a rating of 6000 watts, the outer 7500 watts, both at 575 volts. Each circuit could be controlled to maintain three different levels of heat input: 18.5, 37 and 55.5 $cal/cm^2/hr$ (20, 40 and 60 watts/sq ft*). The electrical energy was metered in the first trials with household type kilowatt-hr meters; in later tests the power was metered and recorded with a data logging system using the household type meters as independent checks.

Temperatures were measured in the concrete slab and in the gravel pad under the insulation with thermocouples. Three thermocouple probes were installed during construction at the centre of the pad and at distances 1.2 m (4 ft) and 0.44 m (1.3 ft) from its edge (Figure 1). The thermocouples in each probe were located at depths of 1.2 cm (0.5 in.), 7.6 cm (3 in.) and 17.9 cm (7 in.) in the concrete. Additional thermocouples were placed beneath the insulation; one immediately beneath it, one at 15 cm (6 in.), and another at 60 cm (24 in.) deep in the gravel base.

Three heat flow meters were placed near the thermocouple probes between the two 2.5 cm (1 in.) layers of insulation board to measure heat loss from the slab into the ground. The calibration of the meters was checked by comparing their outputs under steady state conditions with the calculated heat flow through the insulation. The value of the thermal conductivity of the insulation used in this calculation was obtained by measurement of the thermal conductivity of samples of insulation. Agreement between the two methods was reasonable (Figure 2a); differences were not significant in terms of the total heat balance for the heated slab.

A heat flow meter was also installed just beneath the upper surface of the slab to obtain an independent check of surface heat loss. The agreement between heat flow measured with the meter and heat flow obtained by measurements of net radiation and convection was not too satisfactory (Figure 2b). It was considered that the results from the heat flow meter were not accurate enough to use in the analysis. (The meters were calibrated for much lower heat outputs and may not be reliable at high heat flows).

* 1 watt/ sq ft = 0.93 $cal/cm^2/hr$ = 3.4 $Btu/ft^2/hr$

Net radiation was measured with a C.S.I.R.O. all-wave radiometer installed about 0.6 m (2 ft) above the centre of the slab. The calibration of the radiometer was checked by comparing its output with the outputs of three other net radiometers positioned over the heated slab during clear nights when net radiation was quite constant. The agreement between the radiometers was quite reasonable (Table I), particularly for this type of instrument.

Air temperatures used in the analysis were obtained with a thermocouple located in a Stevenson screen about 61 m (200 ft) from the concrete slab. Wind speed was measured with an anemometer located on the nearby roof of the Building Research Centre. Hourly averages of these measurements were compared with wind speed measurements made at the 2-m level near the slab. The relationship between the two anemometers (Figure 3) followed approximately the power law:

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^a$$

where V_2 is the velocity at ht 2 m (h_2)

V_1 is the velocity at ht 15 m (h_1).

$a = 1/7$

The rate of snowfall was measured with a standard tipping bucket rain-gauge modified to record snowfall. An adapter was built which fitted over the tipping bucket gauge. The adapter was filled with antifreeze to melt snow as it fell. The bucket tipped when .0254 cm (.01 in.) water equivalent of snow accumulated. The number of times the bucket tipped during a storm was recorded on a modified event recorder. An Alter type (Warnick, 1956) windshield was installed to improve the efficiency of the catch of the snow gauge during high winds.

Figure 4 is a general view of the site showing the location of some of the weather instruments used in the study.

A data logging system, supplemented by chart recorders, was used to record the outputs from all the instruments. The outputs were recorded on tapes every 10 minutes and then fed through a computer to obtain the hourly averages used in the analysis.

2. Heat balance of test slab

During periods of snowfall, a melting system must provide sufficient heat to raise the temperature of the snow to the melting point, melt it, and offset surface heat loss by evaporation, convection and radiation; heat loss to the ground from around and under the slab, must also be allowed for. In between snowfalls sufficient heat must be supplied to keep the surface temperature above a specified design level if the slab is operated with continuous power input. If the slab is operated on an intermittent basis, sufficient heat must be available to raise the slab to the required operating temperature in time to melt expected snowfalls.

The heat balance of an insulated snow melting system can be expressed by the following equation:

$$Q_T = Q_m + Q_t + Q_e + Q_c + Q_r + Q_q + Q_p + \Delta Q_s$$

where Q_T = heat supplied by electric heating cables

Q_m = heat required to melt snow

Q_t = heat required to raise the temperature of the snow to the melting point

Q_e = heat loss by evaporation (from portion of pavement not covered with snow)

Q_c = heat loss by convection from bare portion of pavement

Q_r = heat loss by radiation from bare portion of pavement

Q_q = heat loss to the ground through the insulation under slab

Q_p = edge heat loss into ground at the perimeter of the slab

ΔQ_s = changes in heat stored in the concrete slab above the insulation.

Several of the terms in the above equation can, under some circumstances, add heat to the system, e.g. condensation can take place instead of evaporation, heat can be gained from the ground under the insulation, internal heat can be added to the system if the concrete slab is cooling down. The heat needed to raise the temperature of the snow to the melting point (Q_t) is a small percentage of the total heat requirements and can be ignored.

For dry pavement, the equation simplifies to:

$$Q_T = Q_c + Q_r + Q_q + Q_p + \Delta Q_s$$

The original objective of this research project was to measure Q_T, Q_m, Q_r, Q_q, Q_p and ΔQ_s so that Q_c could be calculated from the heat balance equation. Convective heat losses could then be related to weather elements to obtain formulae for determining design heat requirements for snow melting systems. If formulae could be developed for estimating Q_c, evaporative heat loss (Q_e) could then be calculated from the heat balance equation during periods when the pavement is wet.

Because of difficulties in measuring the actual rate at which snow fell on the slab, variations in surface temperature and depth of snow accumulations, and uncertainties associated with estimating the thermal capacity of the concrete with heating cables embedded in it, reasonably consistent heat balances were obtained only under relatively stable, steady-state conditions for a bare, dry pavement. A qualitative analysis was necessary when the pavement was wet or when snow was falling on it.

II. HEAT LOSS FROM BARE, DRY, HEATED PAVEMENTS

1. h_c - Convective heat transfer coefficient

(a) General

Convective heat transfer from a surface is of two types: (a) free or natural convection in which heat flow results from density differences within the fluid and (b) forced convection in which flow is caused by wind blowing along the surface. In both cases the rate of heat transfer is proportional to the temperature difference, ΔT, between the surface and the air, and the area A in contact with the air flow, i.e.

$$\frac{dQ}{dt} = h_c \, A \, \Delta T$$

The heat transfer coefficient h_c is a function of many variables, such as shape, roughness and dimensions of the surface; direction and velocity of flow; and physical properties of the fluid. Its numerical value is, in general, not uniform over a surface, but depends on boundary conditions and variations in velocity and air temperature profiles over the surface. For most applications an "average" coefficient is used to calculate convective heat losses.

Analytical procedures are available for calculating coefficients for both free and forced convection for surfaces of different shapes and sizes under laboratory conditions, for relatively simple cases, such as that of estimating the convective coefficient for a heated, horizontal plate, facing upwards under free convection. The solutions obtained for forced convection problems cannot, however, usually be used for field problems because measurements of velocity and temperature profiles are seldom available and the flow characteristics and the development of a thermal boundary layer along a heated plate are not usually well defined.

The analytical procedures are, however, of value for assessing the probable effect of size of heated area on convective coefficients (Mukammel, 1961). Coulter (Coulter and Herman, 1964) estimates a forced convection coefficient of 1.2 cal/sq cm/hr/°C for a plate of 3 metres (10 ft) characteristic length, compared to .85 cal/sq cm/hr/°C for a plate of 30 metres (100 ft) length under the same wind flow conditions. These results suggest that the size of heated area may have to be considered in estimating coefficients, especially for areas with a short characteristic length, such as narrow sidewalks or heated wheel-tracks.

The measurement of convective coefficients under field conditions presents almost as many difficulties as their calculation from theory. The original investigations of heat requirements for snow melting by Chapman and Katunich (1956) is one of the few cases reported in the literature in which convective coefficients were measured under field conditions. The coefficients obtained in their tests are high when compared with other investigators (Schaerer, 1966) possibly because they used very small test panels and no adjustment was made for the height at which wind speeds were measured. These tests provide the basis for the empirical formulae used in the chapter on snow melting in the ASHRAE Guide and Data Book.

(b) Experimental results

During the three winter seasons of observation the test slab was operated under various combinations of heat input and weather conditions. Convective coefficients were calculated for selected periods for the 9 sq m (100 sq ft) central, heated area using the heat balance equation for a dry surface. For the periods analysed, temperature changes within the concrete slab were slight and the heat storage term (ΔQ_s) could be neglected. Edge heat losses from the central area (Q_p) were also kept at an insignificant level by maintaining the temperature of the perimeter at an appropriate value using the outer heating circuit. Under these conditions, convective heat losses could be calculated from the following equation:

$$Q_c = Q_T - Q_r - Q_q$$

as Q_T (the heat input), Q_r (net radiation) and Q_q (heat flow through the insulation) were measured. The convective coefficient was determined for different wind speeds from the equation:

$$h_c = \frac{Q_c}{(T_s - T_A)}$$

where h_c = coefficient (cal/sq cm/hr/°C)

Q_c = convective heat loss (cal/sq cm/hr)

T_s = average surface temperature (°C)

T_A = average air temperature (°C)

Figure 5 shows the relationship between wind speed and convective heat transfer coefficient for this test slab ($h_c = 0.19 + 0.146$ V, "V" in m/sec). A calculated value of the coefficient for free convection from a heated plate at 0°C (32°F) with air temperature equal to -18°C (0°F) (Jakob and Hawkins, 1958), is shown as well as that obtained by Chapman and Katunich. It is not possible to compare other coefficients reported in the literature for snow melting systems because the convective and radiative components were not reported separately.

2. h_r - long-wave radiation coefficient

(a) General

Net radiation consists of short-wave radiation associated with sunlight and long-wave radiation. The heat received from shortwave radiation during daylight hours is usually not taken into consideration in the design of snow melting systems because of the need to design for worst conditions, i.e. night-time when air temperatures are lowest and surface heat losses usually greatest. Long-wave radiation can be broken down into incoming long-wave radiation from the atmosphere (R_{in}) and long-wave radiation emitted by the surface (R_{out}); the two components are often combined and called net long-wave radiation (R_n). Numerous empirical formulae have been developed to estimate net long-wave radiation from surface temperature and meteorological records such as air temperature, air vapour pressure and percent cloudiness. Such formulae are not highly accurate because of the difficulty in allowing for the effect of cloud conditions on incoming long-wave radiation and the fact that they were not developed for use over short periods of time.

(b) Development of formulae

Incoming long-wave radiation under clear sky conditions can be related to screen air temperature by the equation (Swinbank, 1963):

$$R_{in} = (-17.09 + 1.195\ \sigma\ T_A^4) \text{ milliwatts/sq cm}$$

where T_A = air temperature °K

σ = Stefan-Boltzmann constant (milliwatts/sq cm °K)

As the outgoing long-wave radiation (R_{out}) is equal to $E\sigma\ T_s^4$ (Stefan-Boltzmann Law) where T_s is surface temperature °K, and E, the emissivity, the net long-wave radiation for clear skies is equal to:

$$R_n = (-17.09 + 1.195\ \sigma\ T_A^4) - E\sigma\ T_s^4$$

for the case where $T_A = T_s$ and the emissivity E = 0.96 (for a concrete surface)

$$R_n = (-17.09 + 0.235\ \sigma\ T_A^4)$$

This equation can be adjusted for cloudy skies by a factor ($1 - CN^2$) where C is a coefficient that varies with latitude and N is the cloud cover in tenths (Budyko, 1956).

For 10/10 cloud and latitude 45°N, (C = .81 and N = 1):

$$R_n = (-3.25 + 0.045\ \sigma\ T_A^4)$$

For the situation where the surface temperature is not equal to air temperature an approximate adjustment, $- 4\ \sigma\ T_A^3\ \Delta T$ (where $\Delta T = T_s - T_A$) can be made (Geiger, 1965). The equations for estimating R_n, then become:-

$$R_n = -17.09 + 0.235\ \sigma\ T_A^4 - 4\ \sigma\ T_A^3\ \Delta T$$

clear sky milliwatts/sq cm

$$R_n = -3.25 + 0.045\ \sigma\ T_A^4 - 4\ \sigma\ T_A^3\ \Delta T$$

10/10 cloud milliwatts/sq cm

(c) Comparison of formulae with measurements

These formulae for R_n were used to calculate $h_r \left(h_r = \frac{R_n}{\Delta T} \right)$, the long-wave radiation coefficient, for essentially clear sky and cloudy sky conditions for a bare concrete pavement at 0°C (32°F) for different air temperature. Some values of h_r, obtained from measurements of R_n over the test slab for selected periods when cloud conditions could be defined, are compared with the values calculated (Figure 6). The surface temperature of the heated slab was not always at 0°C (32°F) for these periods (varying from 0-10°C (32-50°F)). The calculated valued for h_r agree reasonably well with the measured values indicating that the method of calculating long-wave radiation should be satisfactory for use in the design of snow melting systems. The two extremes of cloud conditions, essentially clear and 10/10ths cloud, give limits which are adequate for design purposes. Some of the variation in the measurements probably can be attributed to uncertainties associated with cloud cover, i.e. whether or not the sky was completely clear of high cloud, and the fact the surface temperature of the heat slab was not held constant at 0°C (32°F).

In practice, the heat loss from long-wave radiation should be calculated using the formulae given rather than the coefficient h_r, to avoid the problem that $\frac{R_n}{\Delta T}$ approaches infinity as ΔT approaches zero. The only reason it is plotted in this form in this paper is to illustrate the fallacy of using a constant value for h_r, as has been done in many of the formulae developed for use in the design of snow melting systems (Chapman and Katunich, 1956).

3. $h_r + h_c$ - combined long-wave and convective coefficient

In some papers on snow melting, radiative and convective coefficients are combined to obtain a surface or film coefficient (h_{rc}). The original study by Champan and Katunich gave $h_{rc} = 0.27\ V + 3.3$; the ASHRAE Guide and Data Book gives $h_{rc} = 0.23\ V + 0.63$ (V = wind speed (mph) with units in Btu/hr/sq ft/°F). The ASHRAE combined coefficient is considerably lower but no information is given on how the coefficient was obtained. Neither reference specifies the height at which wind speeds should be measured, but by implication it is assumed wind speeds measured at standard heights at meteorological stations should be used. The combined coefficient from both these references are plotted against wind speed (Figure 7). These values are compared with the combined coefficient (obtained from measurements of the convective coefficient and calculated radiative coefficient) for clear and cloudy conditions for ΔT = 10°C (18°F) and ΔT = 20°C (36°F).

The ASHRAE equation underestimates heat loss by radiation and convection at low wind speeds and clear sky conditions; at high wind speeds the equation overestimates heat losses, particularly for cloudy conditions. The equation does, however, give a good average value for the combined coefficient. The coefficients given by Chapman and Katunich are considerably higher which, as mentioned previously, may be due to the small test panels used in the tests and the fact that no allowance was made for the height at which wind speeds were measured. These results indicate the need to define cloud conditions and height at which wind speeds are measured in the application of empirical formulae to estimate heat losses by convection and radiation from a dry surface.

III. HEAT LOSS FROM WET, HEATED PAVEMENTS

1. h_e - evaporative coefficient

(a) General

Numerous mass transfer equations are available for estimating evaporation from water surfaces under atmospheric conditions. Some of these require measurements of wind speed and air vapour pressure at two levels, as well as of surface roughness. Simpler forms of mass transfer equations have been developed for engineering use of the form:

$$E = K f(V) \Delta e$$

where E = evaporation rate

$f(V)$ = function of wind speed

$\Delta e = e_s - e_a$

e_a = vapour pressure of air above the surface

e_s = saturated vapour pressure of air at temperature of the surface

K = an empirical constant (which includes air density, air pressure and roughness factors).

The evaporation rate E can be converted to heat used in evaporation (Q_e) by multiplying it by the latent heat of vapourization.

This type of formula which lumps several variables into K is necessarily approximate and cannot be expected to give highly accurate results. An additional complication is the "mid-desert" condition described by Penman (1956). Under these circumstances the size of the wet, heated surface becomes a factor as the temperature and vapour pressure of the air are modified as air passes from the dry, cold surface surrounding the heated slab, over the wet evaporating surface.

The problem of measuring the rate of evaporation from a wet, heated pavement during periods of snowfall is most difficult. It is necessary not only to measure the precipitation rate accurately, and the rate of runoff from the heated slab, but also the amount of infiltration into the concrete which may be significant. The difficulties in the measurement of evaporation proved insurmountable at the test slab and it was necessary to rely on existing formulae to estimate evaporation for the snow melting tests described in this paper.

(b) Comparison of evaporative coefficients

The empirical formula recommended for wet surfaces at 33°F by ASHRAE is:

$$Q_e = h_{fg} (0.0201 V + 0.055)(0.185 - p_{av})$$

where h_{fg} = latent heat of evaporation (Btu/lb)

V = wind speed, (mph)

p_{av} = vapour pressure of air (in. of Hg)

Q_e = Btu/sq ft/hr

Another formula recommended by Penman (1956) for estimating evaporation from evaporation pans is:

$$E_o = (0.35)(\Delta e)\left(0.5 + \frac{V_2}{100}\right)$$

where E_o = evaporation (mm/d_A)

$\Delta e = e_s - e_a$

V_2 = mean wind speed (miles/d_A)

Evaporative coefficients in cal/sq cm/hr/Δe (mm Hg) (with suitable conversion of units) were calculated using the Penman formula and compared with similar calculations using the ASHRAE formula (Figure 8).

The Penman formula, using wind speed at the two metre (6.6 ft) level, agrees reasonably well with the ASHRAE formula. If, however, the formula is adjusted for wind speed measurements at the 10 metre level (33 ft), there are substantial differences. These results suggest that the ASHRAE formula does not allow for adjustment for the height at which wind speed is measured. The importance of allowing for the height at which wind speed is measured in using empirical evaporation formulae has been stressed in the literature on evaporation (Harbeck, 1961).

2. Total heat loss from wet, heated pavements, during periods of no snowfall

The total surface heat loss from wet pavements by convection, long-wave radiation and evaporation was calculated for completely clear and completely cloudy conditions for ΔT = 10°C (18°F) and ΔT = 20°C (36°F), using the coefficients measured and calculated for the experimental test pad. The total heat loss was then compared with values using the ASHRAE procedure (Figure 9). Total heat losses for ΔT = 5°C were also calculated and compared with heat losses, using formulae prepared by Watkins (1970) (Figure 10), designed for use in Britain, where only small surface-air temperature differences would be encountered. The Watkins formula agrees quite well with the calculated values; the ASHRAE formula gives higher values at high wind speeds and lower values at low wind speeds.

3. Heat loss from wet pavements during a snowstorm

In order to maintain a completely bare pavement during a snowstorm sufficient heat must be supplied to melt snow as it falls as well as off-set heat losses by convection, radiation and evaporation. The heat required for melting equals the heat of fusion multiplied by the hourly rate of snowfall (water equivalent/hr). Information on the maximum hourly rates of snowfall that can be expected at a site is, therefore, needed to determine the heat required to maintain a bare pavement. This information is not available for Canada as maximum hourly rates of snowfall are not measured at Canadian meteorological stations.

One reason hourly rates of snowfall are not available is that the problem of obtaining accurate measurement of snowfall rates has not been solved. Under windy conditions an unshielded snow gauge may only catch a small percent of the actual snowfall; even snow gauges equipped with special shields may underestimate the actual catch by a significant amount (Rechard and Larson, 1971).

The few available estimates of maximum hourly rates of snowfall indicate they are 2 to 3 times the hourly rate averaged over the entire period of a snowstorm. Adlam (1950) estimates maximum hourly rates of 8.1 - 8.9 cm/hr (3.2 - 3.5 in./hr) for two storms in New York where the average rates were 2.8 and 3.5 cm/hr (1.1 and 1.4 in./hr) respectively throughout the storm period. Dexter (1960), in describing a record snowstorm in Nova Scotia, indicated the rate of snowfall as 5.9 cm/hr (2.33 in./hr) (averaged over 6 hr) for a snowfall of 76 cm (29.9 in.) occurring in 24 hr (average rate 2.7 cm/hr (1.25 in./hr)). The ASHRAE Guide (1970) indicates that the maximum hourly snowfall can be about twice the 6-hour average. Limited information on hourly snowfall rates obtained at the experimental test site indicated that this is a reasonable estimate.

The information available in the literature was used to obtain the following estimate for the heat required to melt snow as it falls:

Average Rate of Snowfall during Storm		Estimated Maximum Hourly Rate of Snowfall		Heat Required	
cm/hr	in./hr	cm/hr	in./hr	$cal/cm^2/hr$	watts/sq ft
.7	(0.25)	1.3-2.3	(0.5-0.9)	11-19	(12-20)
1.3	(0.5)	2.8-4.6	(1.1-1.8)	22-37	(24-40)
2.5	(1.0)	5.6-9.2	(2.2-3.6)	45-75	(48-80)

An estimate of the total heat required to maintain a bare pavement during a snowfall can be obtained by adding these approximate values to heat losses by convection, radiation and evaporation using the coefficients defined previously.

Because of the large amount of heat required to maintain a pavement completely free of snow during periods with high rates of snowfall, melting systems are seldom designed to melt snow as it falls. This is particularly true for sites subject to drifting snow. The rate at which snow can drift into a site is highly variable, depending on local conditions, but can probably be several times the average rate of snowfall.

IV. HEAT LOSS FROM SNOW AND ICE COVERED HEATED PAVEMENTS

1. General

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 with snow, surface heat losses are reduced to about one half that 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 transferred upward by conduction from the pavement surface through the snow cover.

Chapman and Katunich (1956) introduced the term "free area ratio" in calculating heat losses from heated pavement completely covered or partly covered with snow. The free area ratio, A_r, equals $\frac{\text{Area free of snow}}{\text{Total heated area}}$ ($A_r = 1$ for a snow-free pavement and $A_r = 0$ for pavements that are completely covered with snow), and surface heat losses equal $A_r\ (Q_c + Q_r + Q_e)$. In the design procedure recommended by ASHRAE three levels of design heat input are calculated: Class I ($A_r = 0$), Class II ($A_r = 0.5$) and Class III ($A_r = 1.0$). In order to determine the limitations to this method of calculating design heat requirements for snow melting systems, a series of snow melting tests were conducted at the test slab, commencing in December 1971.

The snow melting system was operated under continuous power at two levels of input: approximately 18.5 and 37 cal/cm^2/hr (20 watts/sq ft and 40 watts/sq ft). The lower heat input is considerably less than that generally used for design in the Ottawa region; the higher heat input is close to the design value used in practice. The results are presented in the form of a few, selected case histories to evaluate not only the procedure recommended by ASHRAE but also to illustrate the limitations to operating snow melting systems under the climatic conditions experienced at the exposed test site.

2. Snow melting tests at low heat input

(a) Case History, 30-31 December 1971

Snow began near noon on 30 December with the surface temperature of the slab from 1.7 - 4.5°C (35 - 40°F). Snow continued for several hours with a total accumulation of about 12.7 - 15.1 cm (5 - 6 in.) under quite strong winds and relatively low air temperatures (Figure 11). The slab was completely covered with about 5 cm (2 in.) of snow during the afternoon of 30 December which would have not been sufficient to impede traffic. No surface cover observations were made during the night but considerable hoar frost was observed on the slab at 0800 hours, 31 December (Figure 12). The hoar frost which may have been preceded by an ice layer formed a protective insulating layer preventing the surface temperature of the slab from cooling much below 0°C (32°F). Even though the concrete temperature at 1.2 cm (0.5 in.) depth did not drop below the freezing point it is possible that the surface temperature went below 0°C (32°F) in the early morning of 30 December. If the slab had been subject to vehicular traffic the hoar frost layer would probably not have been able to form and the surface would have cooled below the freezing point with a good possibility of freezing of melt water on the slab.

This case history illustrates that conditions after the storm often determine whether the heat input is sufficient to keep ice from forming on the slab. Surface heat loss from a wet surface under the meteorological conditions that prevailed in the early morning of 31 December was estimated to be about 25 - 30 cal/sq cm/hr (27 - 32 watts/sq ft) exceeding the heat input of 18.5 cal/sq cm/hr (20 watts/ sq ft). The case history also illustrates the problem of using test slabs without vehicle traffic, to determine the heat requirements for operational snow melting systems.

(b) Case History, 13-14 January 1972

This test period started with mild weather and surface temperature of the heated slab above 15.5°C (60°F) (Figure 13). In the afternoon of 13 January light rain commenced, changing to light snow. During the early morning of 14 January rapid clearing took place with low air temperatures, strong winds and drifting snow. By 0800 hours, 14 January, the pad was covered with a layer of ice about 1.2 cm (0.5 in.) in thickness.

This case history illustrates that even small amounts of drifting snow can be melted and subsequently changed to ice if sufficient heat is not available to prevent ice formation. (Heat loss from a wet surface was estimated to be from 50 - 60 cal/sq cm/hr (54 - 65 watts/sq ft) for the weather conditions that prevailed during the early morning of 14 January). It also illustrates that high initial operating temperatures are not sufficient to prevent ice from forming.

(c) Case History, 16-17 January 1972

During the morning of 16 January strong surface cooling prevailed resulting in the surface temperature of the heated test slab dropping to a minimum of about -9.5°C (15°F) by 0800 hours. Snow that began near midnight of 16 January and ended about midday 17 January, amounted to about 11.7 cm (4.6 in.). The slab was essentially clear of snow on the morning of 17 January, even though air temperatures had only reached a high of about -12°C (10°F) (Figure 14).

This case history illustrates that even when the initial temperature of the slab is well below 0°C (32°F), it quickly warms up when it is covered by an insulating layer of snow. Under these circumstances most of the available heat goes into melting, so that snow is melted efficiently. No ice or hoar frost formed after the storm because the weather was relatively warm, and the low power was enough to keep the slab above freezing.

(d) Case History, 3-7 February 1972

The 32 cm (12.7 in.) of snow that fell on 3 February established a new record for daily snowfall in February in Ottawa. The storm can be considered a "design" storm for the Ottawa area with high rates of snowfall occurring with relatively high winds and low air temperatures (Figure 15). Unfortunately, a record of surface conditions on the test slab was not obtained until the morning of 7 February. Surface temperature records do indicate, however, that the slab surface was at least partially clear during the evening of 4 February. The record high net radiation during the daylight hours of 5 and 6 February indicated that much of the pad must have been bare of snow, but it probably was either wet or had slushy ice on it as the surface temperature remained constant at about (1.1°C) 34°F. By the morning of 7 February the slab was observed to be essentially clear of snow.

This storm illustrates that low heat input will melt and prevent large amounts of snow from accumulating even under relatively high rates of snowfall. During the period of heavy snow, almost all the heat available went into melting snow, as heat loss through the insulation and edge heat were insignificant and changes in heat storage in the concrete were slight under the steady-state conditions that prevailed. If all the heat at low power (20 watts/sq ft) went into melting, the 42 cm of snow (assuming 4.2 cm water equivalent) would have melted in about 18 hours. This case history also illustrates the significant contribution incoming solar radiation can make to the surface heat balance under clear sky conditions.

In summary, it can be stated that the limiting condition in the use of low heat input for the insulated slab was not the melting of snow but the maintenance of an ice-free surface after a snowstorm. If surface heat losses exceeded the rate at which heat was supplied to the surface, melt water would freeze resulting in ice formation.

3. Snow melting tests at medium heat input

(a) Case History, 17-23 February 1972

The summary of snowfall and weather conditions for this period shows that snow occurred every day from 18 - 21 February, with a maximum of 15.8 cm (6.2 in.) occurring 19 February (Figure 16). Air temperature remained below -18°C (0°F) for much of the period after 19 February, with considerable blowing snow. Observations of surface conditions were not available 20 Feb but by the morning of 21 Feb the slab was clear of snow or ice but had a substantial deposit of hoar frost on it. During the night of 21 - 22 February severe drifting took place and the slab was covered with snow (Figure 17). Snow piled up by clearing operations on the roadway near the slab acted as a fence resulting in drifting onto the site. By the morning of 23 February the surface was essentially clear of snow except for hoar frost deposits.

This case history effectively illustrates the difficulty of melting snow at sites subject to drifting snow. It further demonstrates the importance of weather conditions after snowstorms in determining whether the surface of a heated pavement can be maintained free of ice.

(b) Case History, 15-17 December 1972

Snow commenced about 1600 hr , 15 December and the surface temperature dropped rapidly from above 15.5°C (60°F) to below 4.5°C (40°F). Altogether 19 cm (7.5 in.) of snow fell, mostly during the evening of 15 December and early morning of 16 December. Air temperatures averaged about -9.5°C (15°F) during the storm with wind speeds from 9 - 11.3 m/sec (20 - 25 mph); during the night of 16 - 17 December air temperatures dropped to -18°C (0°F) with quite high winds (Figure 18).

A sequence of time-lapse photographs during the period showed that the surface quickly covered with snow at the beginning of the storm, with considerable accumulation. By mid-morning of 16 December, however, the slab was only partially snow covered. In the late afternoon and evening of 16 December, drifting snow started to accumulate on the slab. During the night considerable ice had formed, with some drifting snow on top of it. By the morning of 17 December, the slab was essentially clear again, with portions of it still wet from the drifting that had taken place.

This case history illustrates that even with medium heat input the slab becomes snow covered and remains that way during storms with significant snowfalls. It also demonstrates that sufficient heat must be available to prevent ice from forming during the drifting of freshly fallen snow (night of December 16 - 17). This case history also illustrates the importance of solar radiation in clearing the slab of snow and ice during the day. (Note that the temperature just below the surface rose above 19°C (66°F) for a brief period during the midday of December 17th).

4. Hourly heat balance during snow melting test, 6 - 7 January 1973

A heavy snowfall occurred on the morning of 5 January followed by clear, very cold, windy weather on 6 - 7 January (Figure 19). A sequence of photographs taken during the night of 6 - 7 January (Figure 20) shows surface conditions during the period following the storm. In the late afternoon of 6 January the pad was wet from melted, drifted snow. During the night a crusted snow layer developed which by the morning of 7 January had become covered with hoar frost.

Hourly surface heat balance calculations were made for the slab for the period 2200 hours of 6 January to 0800 hours 7 January to illustrate the unstable situation that exists when an ice layer starts to form. The heat input (Q_T) was measured, the heat gained from the ground (Q_q) under the insulation was obtained from the heat flow meters and the heat available from changes in heat stored in the slab ΔQ_s was estimated from temperature changes in the slab and assuming values for the heat capacity of the concrete. The heat lost by long-wave radiation (Q_r) was measured. Heat lost by convection (Q_c) was calculated by estimating surface temperatures and using values previously obtained for the convective coefficient. Edge heat losses (Q_p) were kept to an insignificant level by controlling the heat supplied to the outer electrical circuit. The difference between the heat supplied and the heat lost represents the heat available for melting snow and ice as well as heat loss or gain by evaporation or condensation.

The results of the detailed hourly heat balance, shown in Table 2, illustrate the following points:

(i) The insignificant heat gain (or loss) through the insulation under the concrete slab.

(ii) The contribution of heat stored in the concrete even when the slab is cooling at relatively slow rates. This term becomes a major factor if the concrete slab undergoes rapid temperature change.

(iii) The difficulty in measuring the different terms in the heat balance equation accurately enough to obtain meaningful values for the heat used in melting or gained by freezing.

(iv) The unstable situation that exists when the heat available almost balances heat losses. If surface heat losses start to exceed the heat available at the surface, the snow or mixture of slush starts to freeze, but only slowly if the net heat losses are small.

(v) The surface heat balance is complicated by the process of evaporation and condensation. Evaporation adds vapour to the air which will condense on colder parts of the surface cooled down to dew point temperature. As the rate of evaporation or condensation cannot be measured at the test slab, it is futile to attempt detailed heat balance calculations except to illustrate the processes involved.

V. GENERAL DISCUSSION

Only two situations need to be considered in estimating design surface heat losses for snow melting systems: (1) a completely snow covered surface during a storm providing sufficient design heat capacity to prevent snow accumulations that will impede traffic and (2) an ice free surface after the storm providing sufficient heat to prevent ice formation.

The total heat requirements during a snowstorm can be calculated from estimates of the average rate of expected snowfall. In the absence of drifting snow, accumulations on a heated pad will not be great if average values for snowfall rates are used in calculations. Many of the earlier snow melting systems were designed simply to melt snow at a certain rate of snowfall without considering any other factors. For example, one of the first electrical snow melting systems in Canada (Kobold and West, 1960) was designed to melt snow falling at a rate of 2.54 cm/hr (1 in./hr), which required a heat input of 28 cal/cm^2/hr (30 watts/sq ft) after some allowance for other losses. A previous study (Williams, 1973) of heat requirements for completely snow-covered heated pavements, designed to handle severe snowstorms occurring at 6 locations in Canada (Halifax, Quebec City, Toronto, Ottawa, Winnipeg and Edmonton), indicated that 18.5 - 28 cal/cm^2/hr (20 - 30 watts/sq ft) was sufficient for all locations.

In general, the heat required to prevent ice from forming on a heated pavement after a storm must equal or exceed the rate of heat loss from a wet surface, under the weather conditions likely to prevail after snowstorms. The snow melting tests show that ice often formed on the heated slab after storms with relatively small amounts of snowfall, if drifting snow is blown onto the surface. This fact will probably limit the use of snow melting systems in cold climates to sites where drifting is not a problem.

Elaborate procedures to obtain the design weather data needed to estimate heat losses from wet surfaces after snow storms are not justified because of the approximate nature of the coefficients used to calculate these losses. Also, many of the factors affecting surface heat loss are difficult to allow for in design calculations, e.g. the heat available from short-wave radiation during daylight hours; the heat stored in the concrete which becomes available if the concrete slab is cooling; the effect of traffic on surface heat exchange processes, including salt transported onto the slab.

Two approaches have been given for establishing the design weather condition. A frequency analysis of all occurrences of snow over a period of years can be made for a site and the system designed to handle a certain percentage of any snowfalls that will occur (ASHRAE Guide and Data Book, 1970). In the other approach a "design" storm is chosen that is reasonably representative of weather conditions expected at a site (Williams, 1973). This method is simpler and probably produces results accurate enough for most situations.

VI. SUMMARY

Empirical equations have been developed in this paper for estimating surface heat loss from bare, dry, heated pavements during periods between snowfall when snow and ice melting systems are "idling". A comparison of total heat loss by convection and radiation with similar equations recommended in the ASHRAE Guide and Data Book (1970) indicates that the ASHRAE equation underestimates heat loss at low wind speeds and clear sky conditions and overestimates at high wind speeds under cloudy conditions.

The total surface heat loss from bare, wet, heated pavements can be estimated with reasonable accuracy by using convection and radiation coefficients and available empirical evaporation formulae. The ASHRAE formulae for estimating evaporation loss for snow melting systems is satisfactory, providing adjustments are made for the height at which wind speed is measured.

The heat required to melt snow as it falls in order to maintain a completely bare pavement during a storm can be calculated if maximum hourly rates of snowfall are available. Only very approximate estimates are possible, however, because these rates are usually not known. Because of the large amount of heat required to maintain a completely bare pavement, such systems are not economical, particularly for sites subject to drifting snow.

Sufficient heat to prevent excessive snow accumulations will be provided, in most cases, if the system is designed to melt the average rate of snow that falls during a storm. A relatively low heat input of from 18.5 - 28 $cal/cm^2/hr$ (20 - 30 watts/sq ft) is sufficient for an exposed site in Ottawa if drifting snow is not a problem.

The prevention of ice formation on heated pavements after a snowstorm is the limiting condition which determines heat requirements for snow melting systems in cold climates. Heat losses from bare, wet pavements for the weather conditions that occur after the storm must not exceed the rate at which heat is supplied to the surface. At the Ottawa site a heat input of 37 $cal/cm^2/hr$ (40 watts/sq ft) was not always sufficient to prevent water from freezing on the surface after a storm.

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TABLE I

COMPARISON OF RADIOMETERS ON CLEAR

NIGHT OVER CONCRETE SURFACE

Date of Comparison	Net Radiometer Output ($cal/cm^2/hr$) A No. 463	B No. 114	C No. 4/128	D A.E.S.
16/6/72	- 7.8	- 7.3		
18/6/72	- 9.1	-10.3		
4/8/72	-10.6		-8.9	
7/3/74	-12.9			-11.0

TABLE 2

HOURLY HEAT BALANCE TEST SLAB

(from 2200 hours, 6/1/73 to 0800 hours, 7/1/73)

	Heat Available				Heat Lost			(Heat Available -Heat Lost)	
Time	Q_T	ΔQ_s	Q_g	Total	Q_r	Q_c	Total		Surface Condition
		(cal/cm^2/hr)				(cal/cm^2/hr)		(cal/cm^2/hr)	
6/1/73									
2200	33.9	3.2	0.2	37.3	-13.2	-22.6	-35.8	+1.5	
2300	33.6	2.4	0.2	36.2	-13.3	-25.2	-38.5	-2.3	partially covered snow-slush
2400	33.9	3.1	0.2	37.2	-13.4	-24.2	-37.6	-0.4	
7/1/73									
0100	34.3	0.8	0.2	35.3	-13.4	-22.6	-36.0	-0.7	
0200	34.3	1.4	0.2	35.9	-13.7	-23.0	-36.7	-0.8	completely covered snow-slush
0300	34.1	2.7	0.2	37.0	-13.2	-27.4	-40.6	-3.6	
0400	34.0	3.6	0.3	37.9	-12.8	-26.8	-39.6	-1.7	
0500	34.1	2.7	0.3	37.1	-12.7	-27.5	-40.2	-3.1	snow-ice
0600	34.3	2.4	0.3	37.0	-12.8	-27.2	-40.0	-3.0	hoar frost starting to form on surface
0700	34.3	2.0	0.3	36.6	-12.9	-25.4	-38.3	-1.7	
0800	34.3	2.0	0.3	36.6	-12.9	-25.6	-38.5	-1.9	

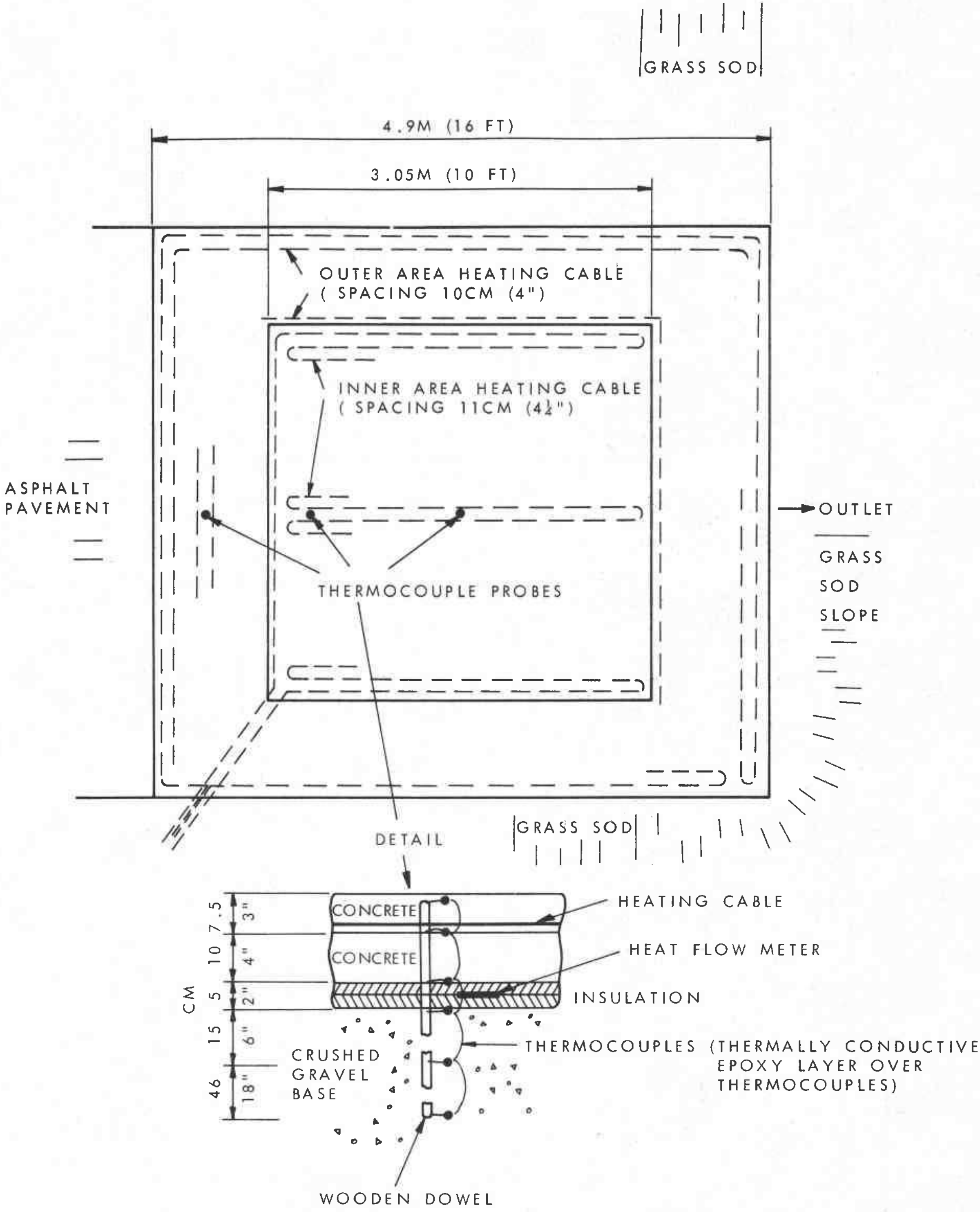


FIGURE 1

THE ARRANGEMENT OF HEATING CABLES AND THERMOCOUPLE CABLES FOR TEST SLAB

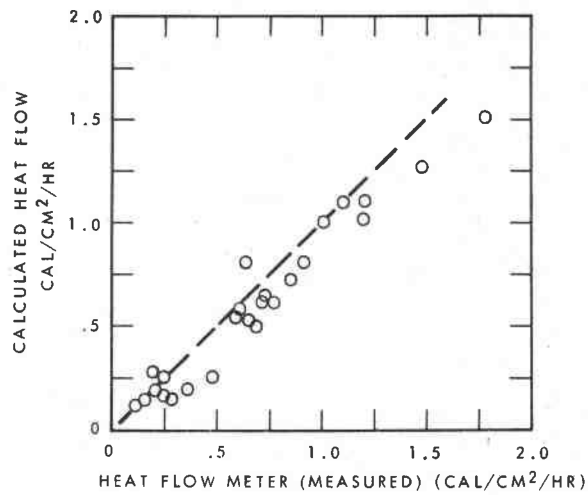


FIGURE 2a

COMPARISON OF CALCULATED AND MEASURED HEAT FLOW THROUGH INSULATION

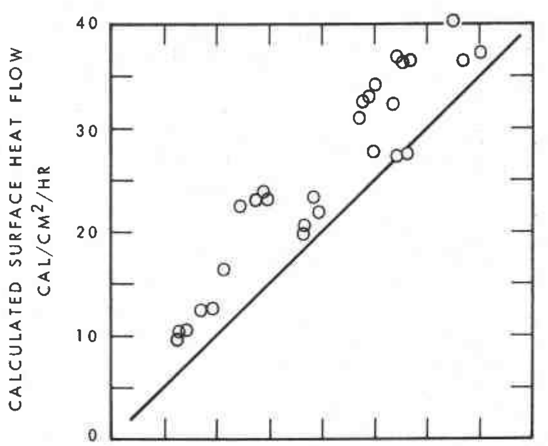


FIGURE 2b

COMPARISON OF CALCULATED AND MEASURED HEAT FLOW AT SURFACE OF HEATED SLAB

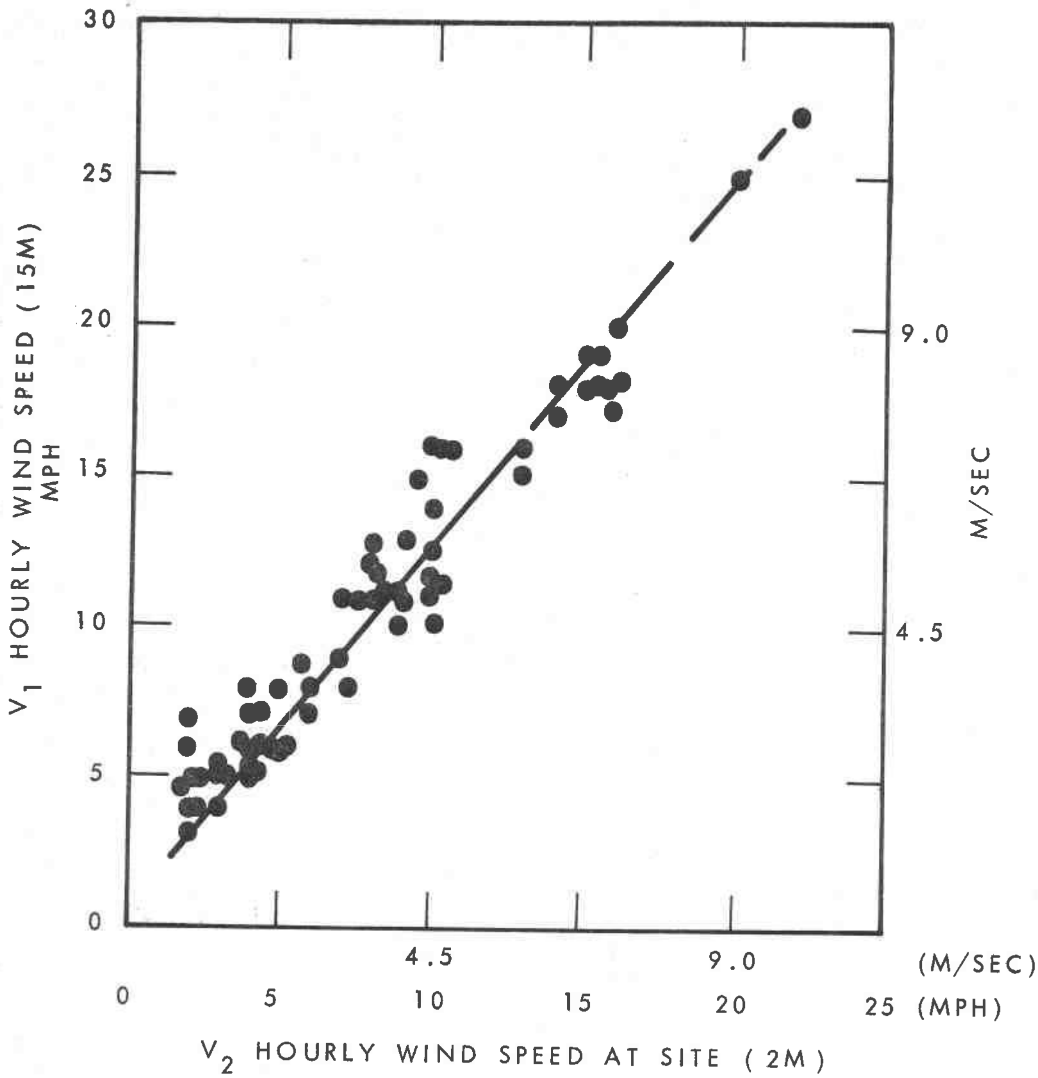
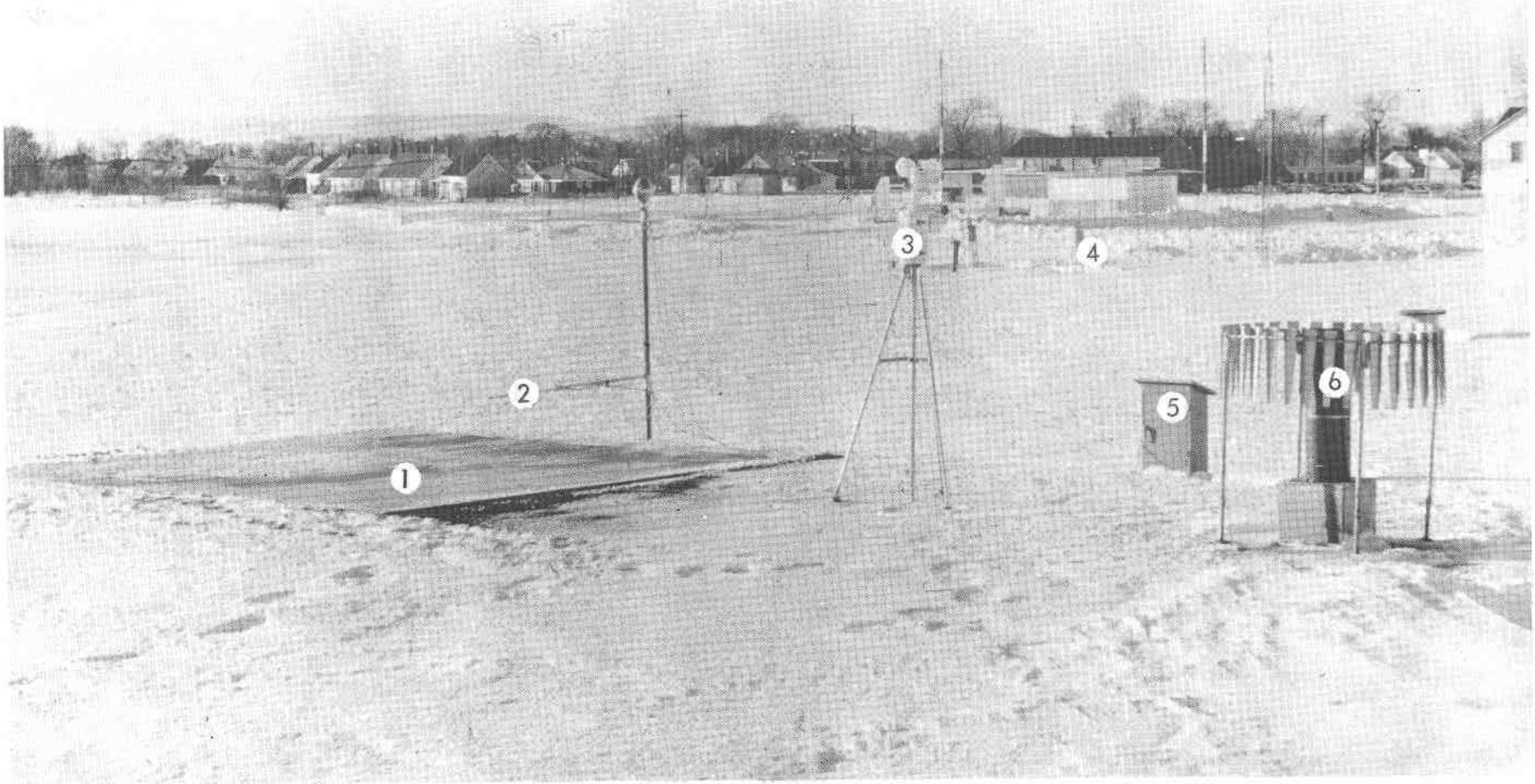


FIGURE 3

RELATION BETWEEN WIND SPEED AT SITE (2M) AND WIND SPEED USED IN ANALYSIS (15M)



1. Heated Slab
2. Radiometer
3. Anemometer
4. Stevenson Screen
5. Terminal
6. Snow Gauge

FIGURE 4 GENERAL VIEW OF TEST SLAB

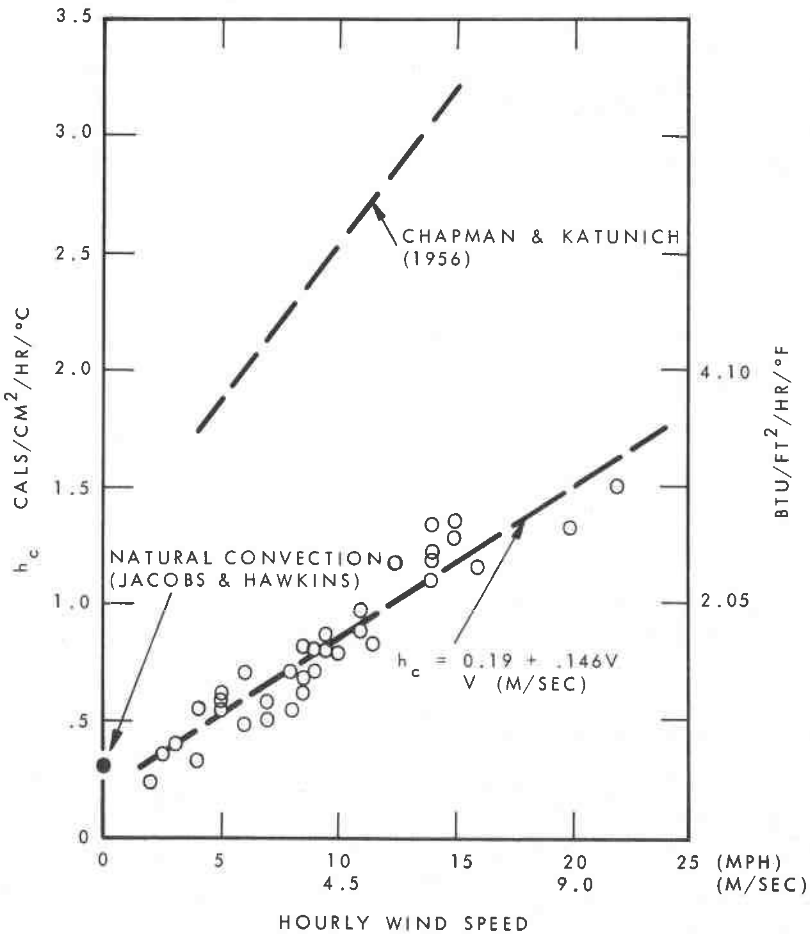


FIGURE 5

CONVECTIVE COEFFICIENT VS WIND SPEED

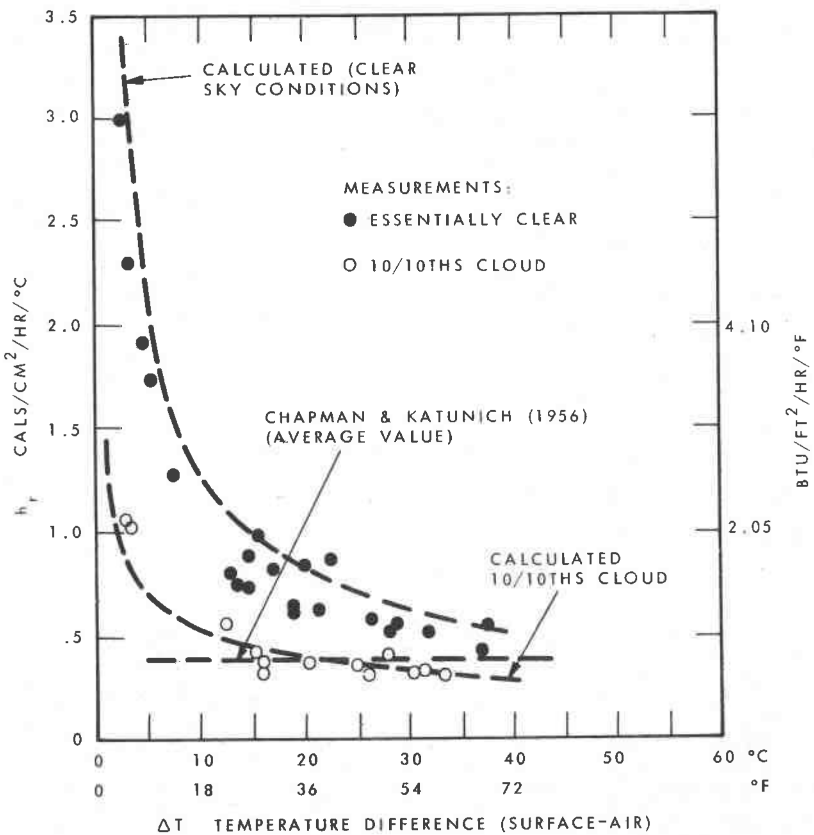


FIGURE 6

LONG-WAVE RADIATION COEFFICIENT VS TEMPERATURE DIFFERENCE

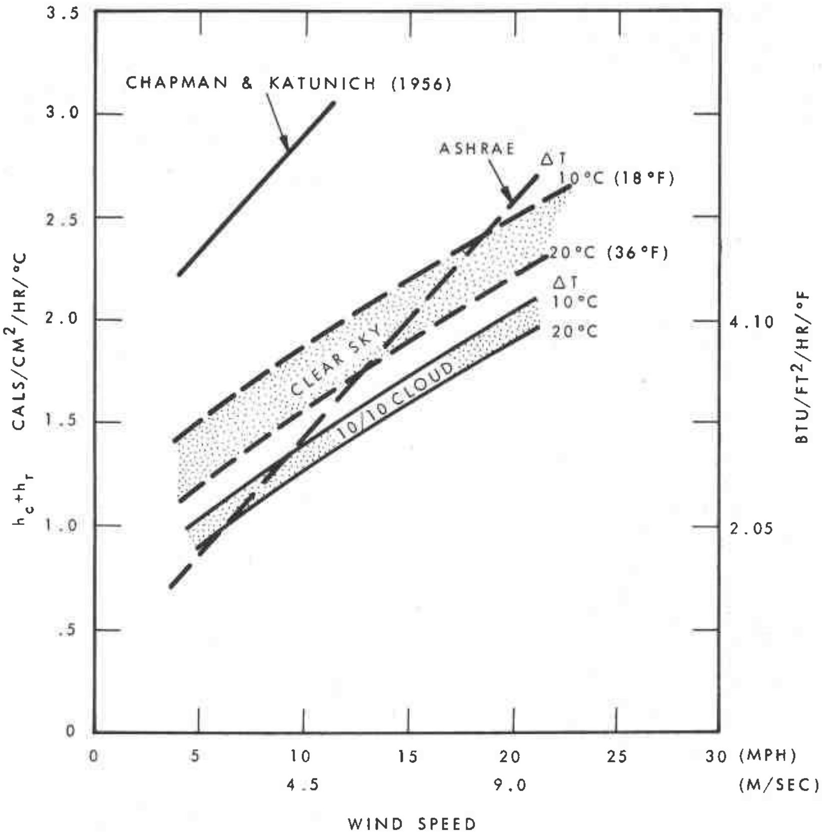


FIGURE 7

COMBINED CONVECTION AND RADIATION COEFFICIENTS FOR DRY CONCRETE PAVEMENT. (T_s = 0.5°C (33°F))

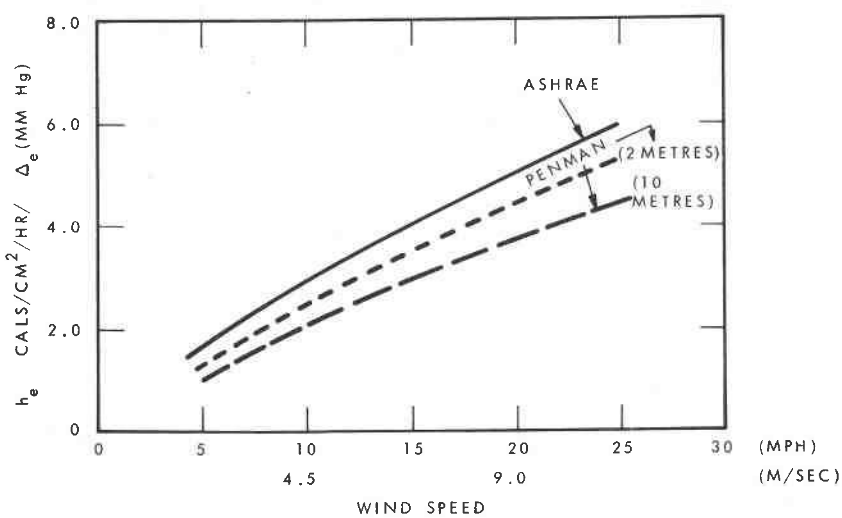


FIGURE 8

COMPARISON OF EVAPORATION COEFFICIENTS

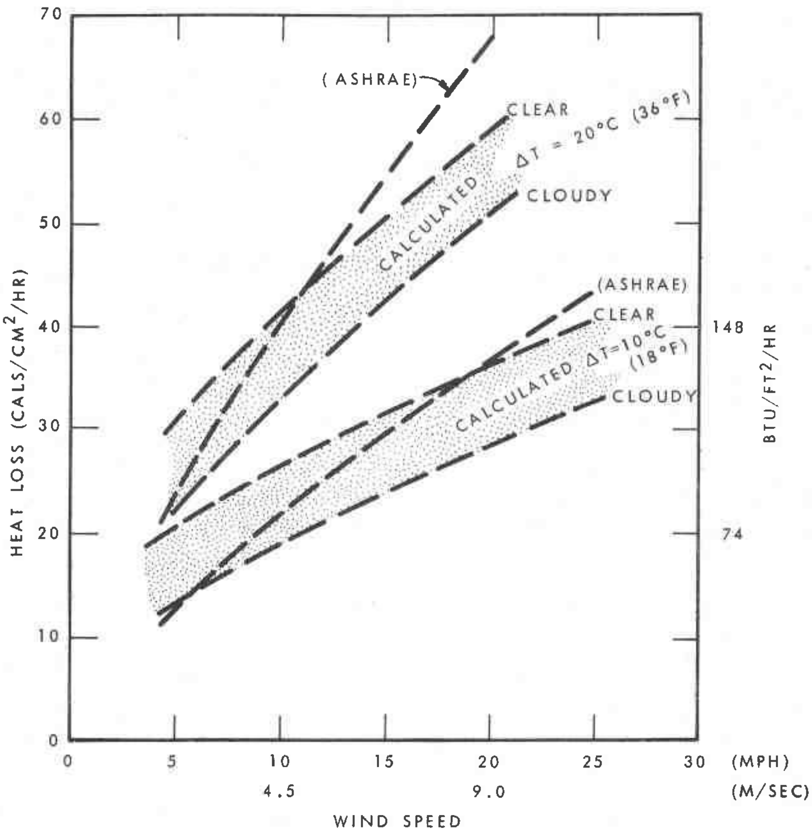


FIGURE 9

COMPARISON OF HEAT LOSS FOR WET PAVEMENTS (T_s = 33°F 0.5°C) Δ_e = 0.13 IN Hg (3.2 MM Hg)

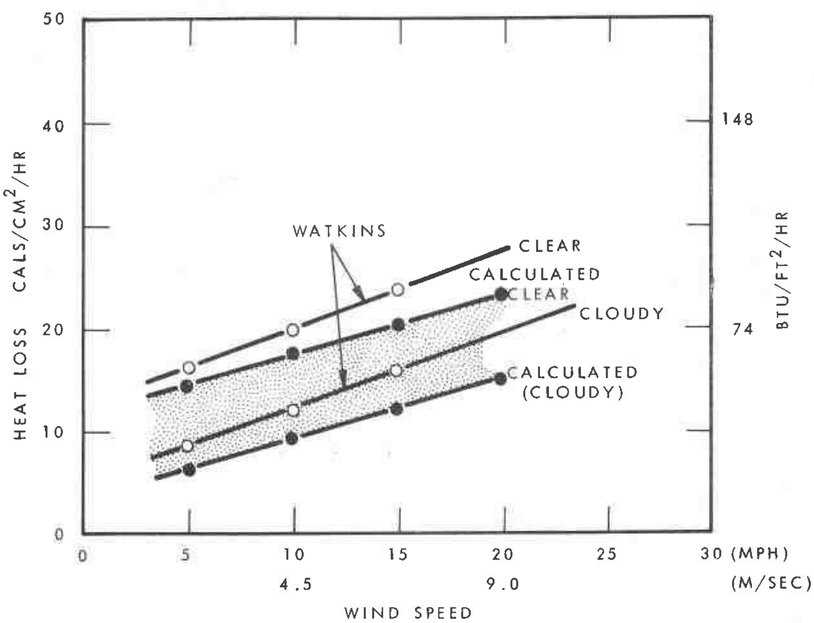


FIGURE 10

COMPARISON OF HEAT LOSS FOR WET PAVEMENTS AT ΔT = 5°C (9°F), T_s = 0°C (32°F)

Δe = 0.13 IN Hg (3.2 MM Hg)

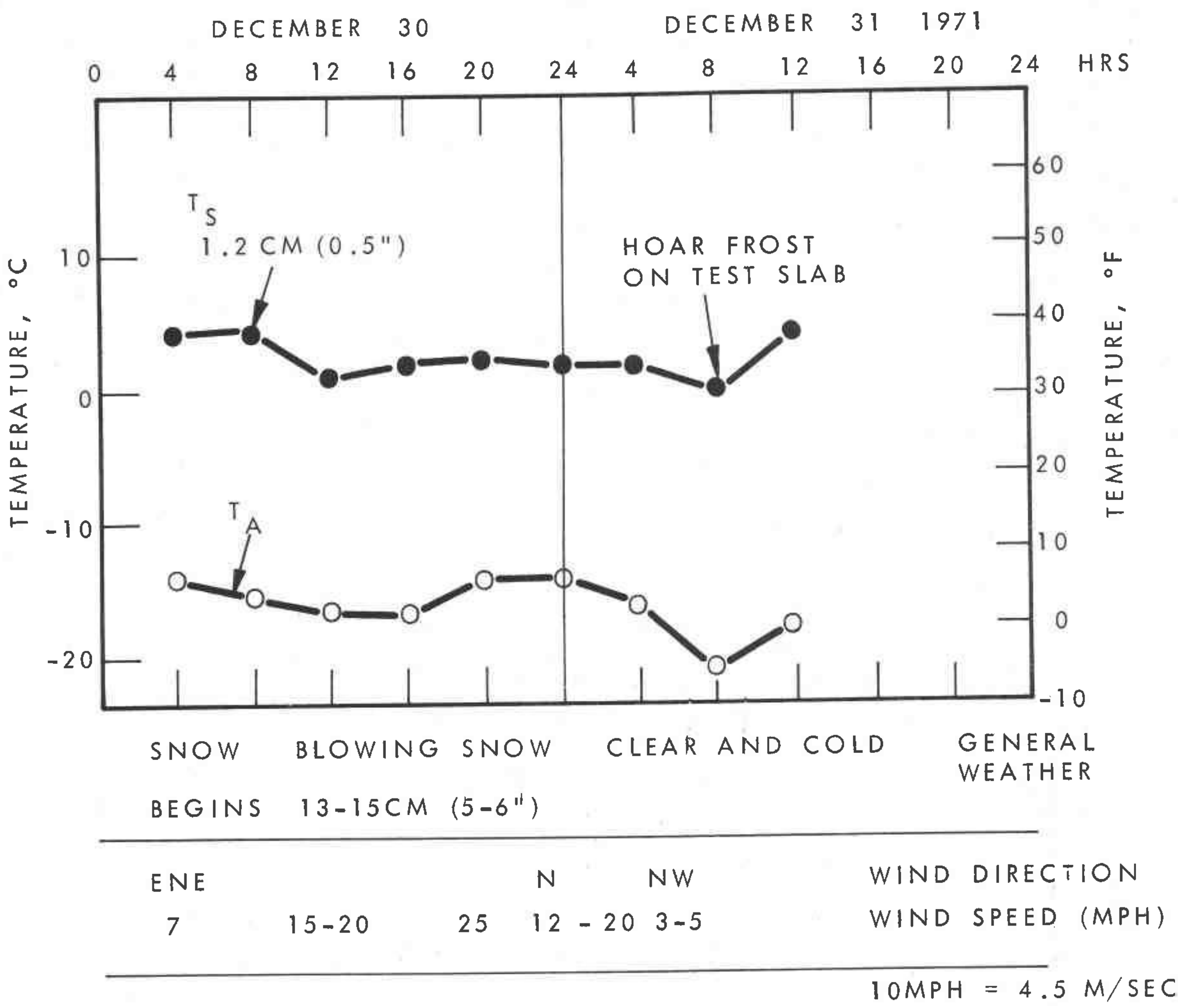


FIGURE 11

CASE HISTORY (BLOWING SNOW-HOAR FROST) DEC. 30-31, 1971

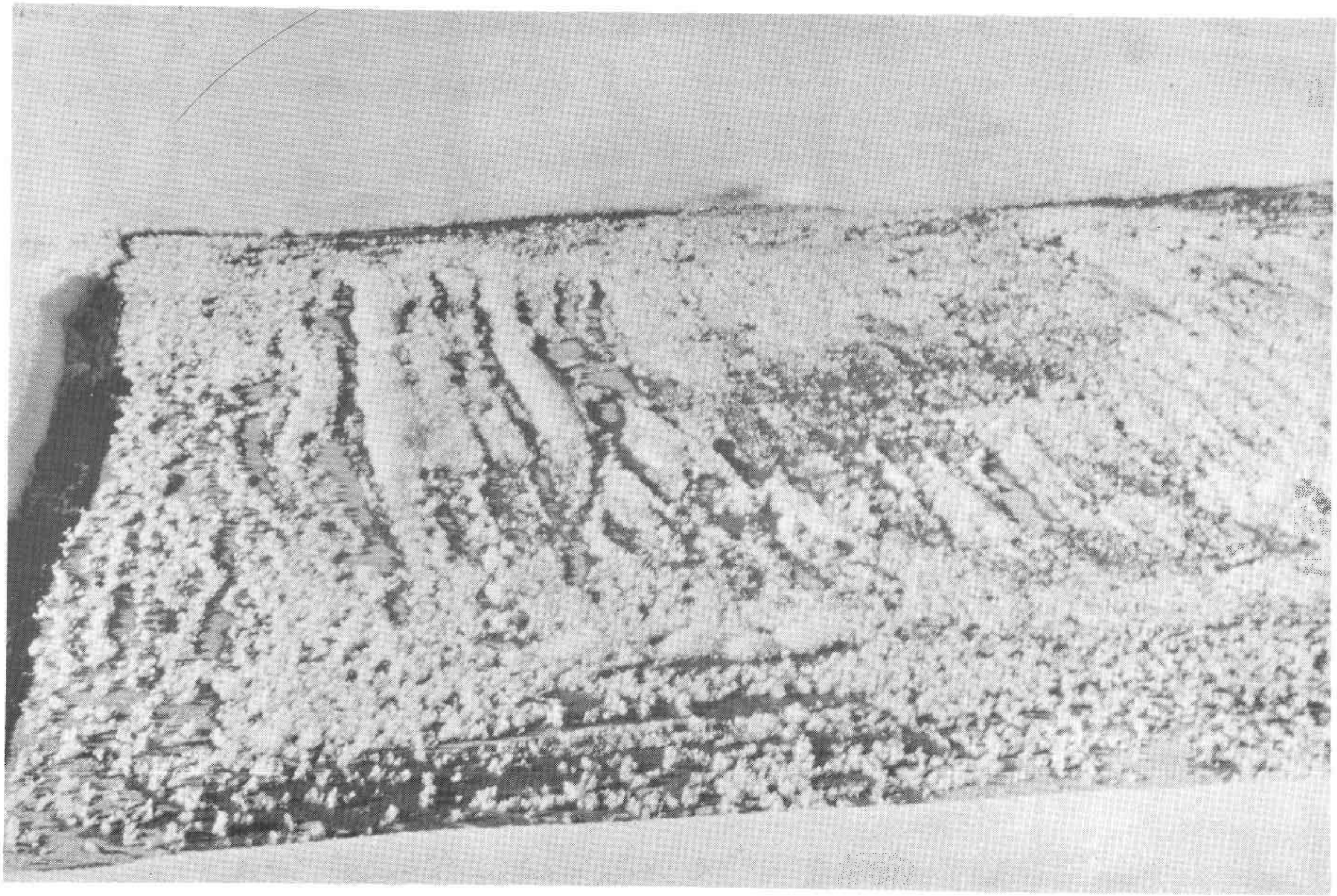


FIGURE 12 HOAR FROST ON TEST SLAB 0800 hr Dec 31, 1971

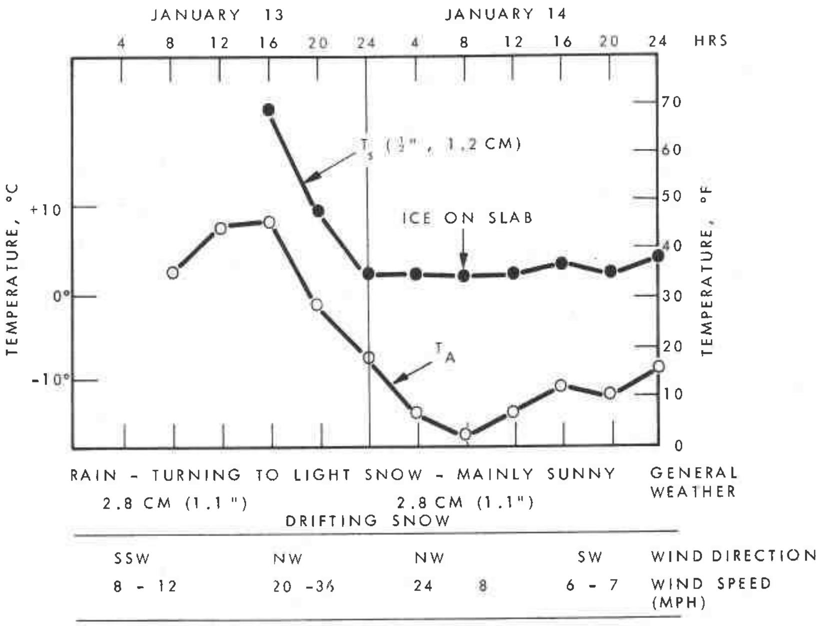


FIGURE 13

CASE HISTORY JANUARY 13 - 14, 1972 (HIGH INITIAL SURFACE TEMPERATURE - DRIFTING SNOW)

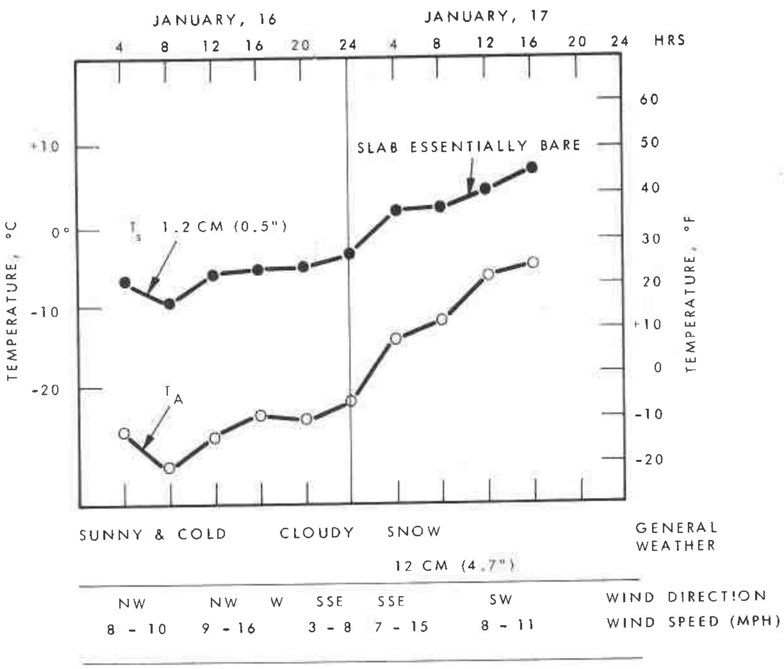


FIGURE 14

CASE HISTORY JANUARY 16 - 17, 1972 (LOW INITIAL TEMPERATURE - MODERATE SNOW)

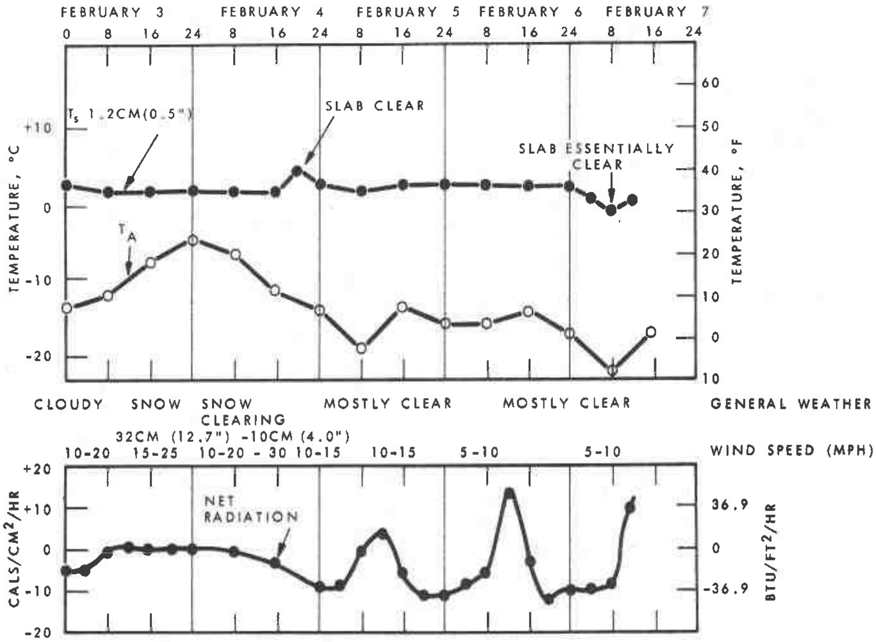


FIGURE 15

CASE HISTORY FEBRUARY 3-7, 1972 (RECORD SNOWFALL - FOLLOWED BY CLEAR WEATHER, HIGH SOLAR RADIATION)

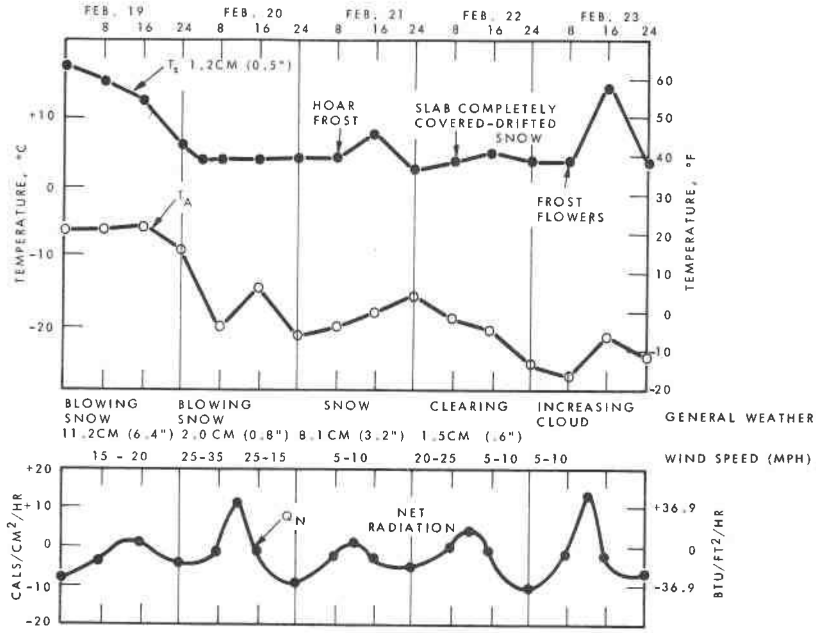


FIGURE 16

CASE HISTORY - FEBRUARY 19 - 23, 1972

FIGURE 17 TEST SLAB COVERED WITH DRIFTED SNOW
0800 hr Feb 22, 1972

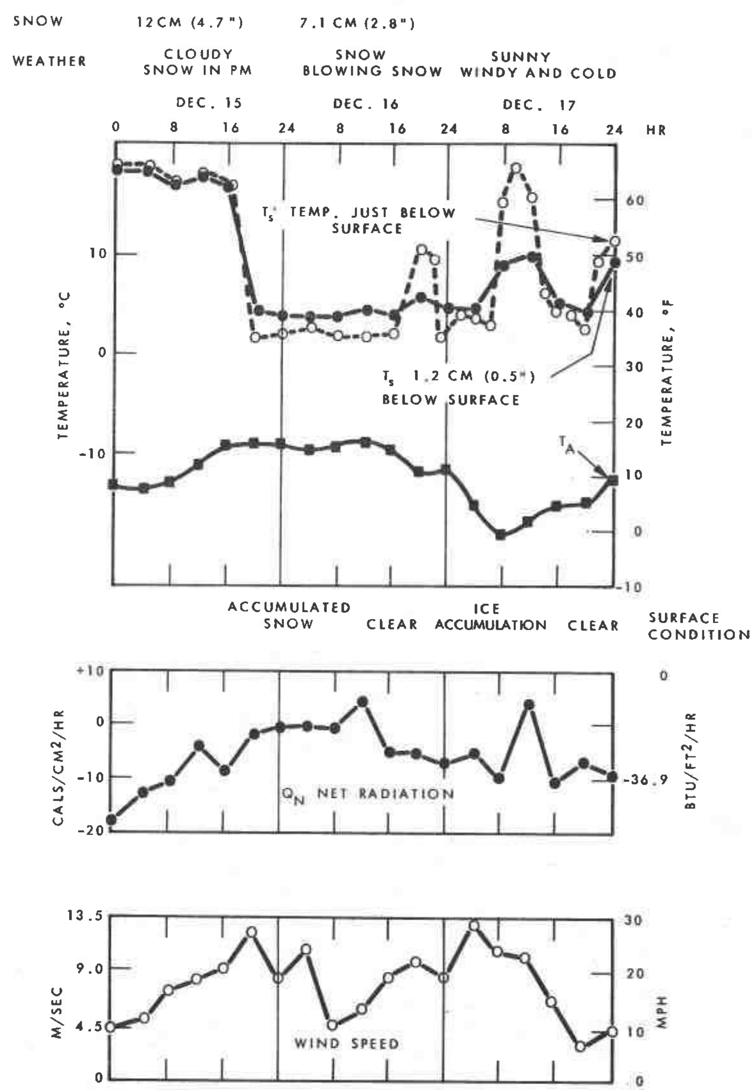


FIGURE 18
CASE HISTORY DECEMBER 15 - 16 - 17, 1972

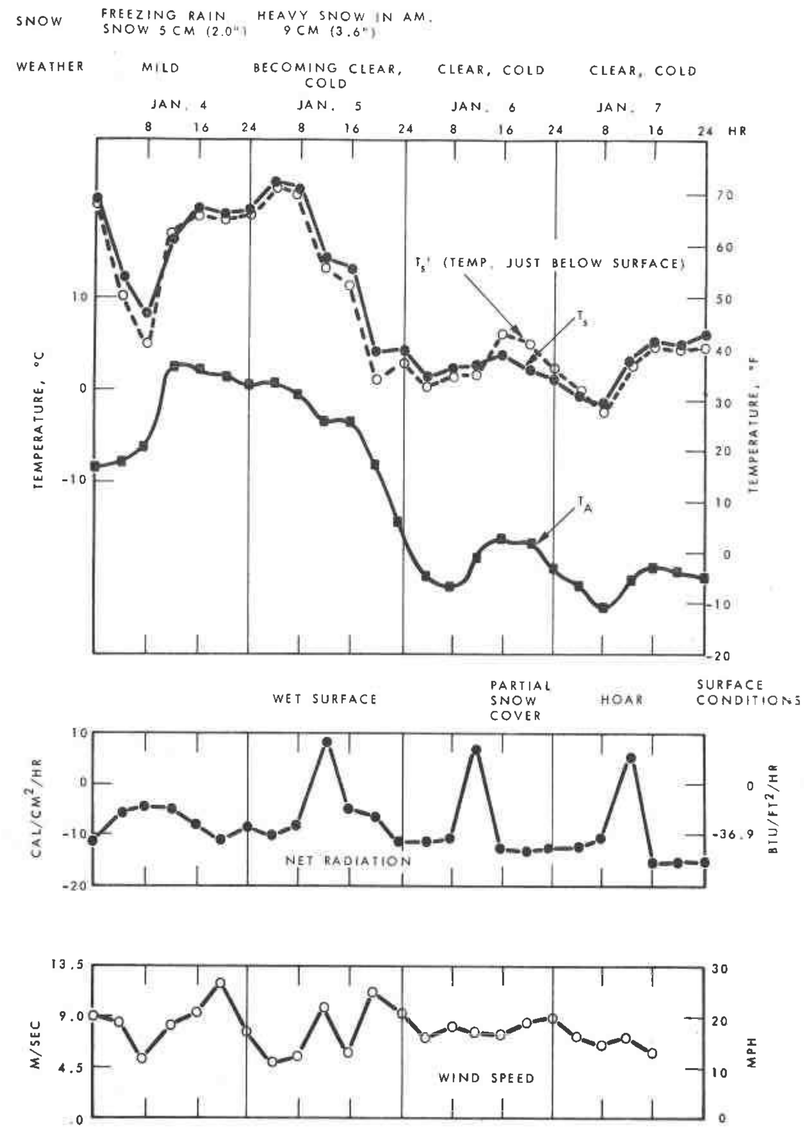
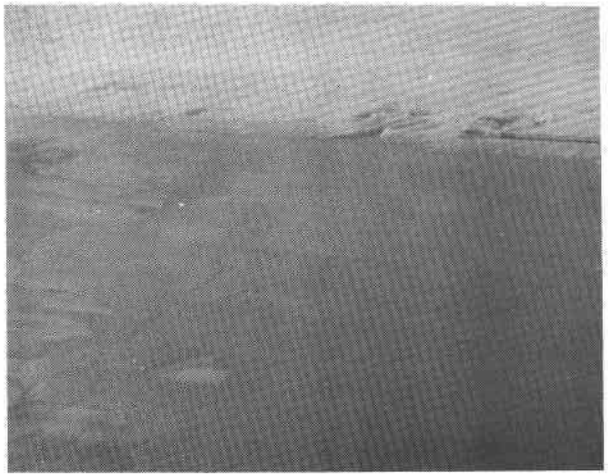


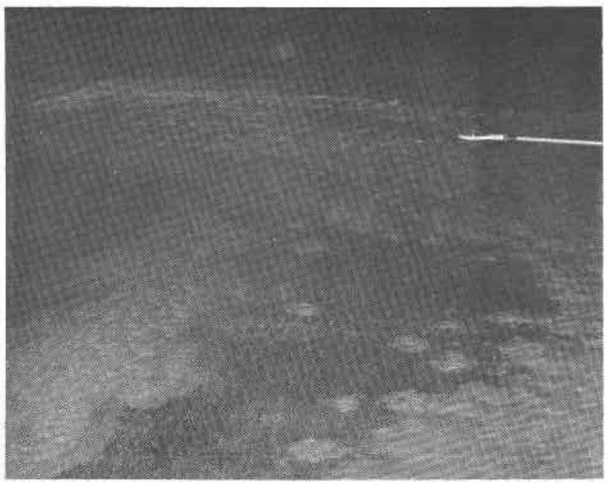
FIGURE 19
CASE HISTORY, JANUARY 4 - 7, 1973



1600 hr - T_A +2°F   Wind 28 mph

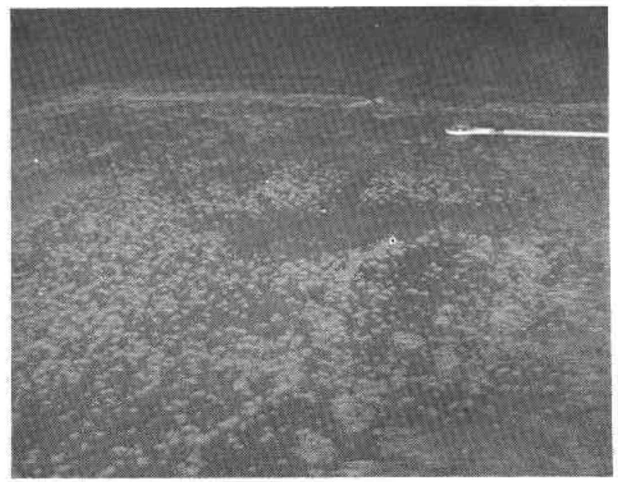
1800 hr - T_A -4°F   Wind 20 mph

0100 hr - T_A -7°F   Wind 18 mph



0400 hr - T_A -8°F   Wind 15 mph

0600 hr - T_A -9°F   Wind 15 mph



0900 hr - T_A -5°F   Wind 15 mph

FIGURE 20 SEQUENCE OF TIME-LAPSE PHOTOGRAPHS - Jan 6-7, 1973