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FOREWORD

The winter environment is the most difficult to control, and the automobile is quite adversely affected by the season. In dry conditions, the automobile can be safely maneuvered; however, when the road is covered with snow or ice, this maneuverability is decreased. Research, however, has improved winter driving. Past work has developed effective techniques for coping with many of winter's problems; if the citizens are willing to pay the price, traffic could move safely in nearly any condition. Current research should be directed to economically maximizing the periods of usable road conditions. The papers in this RECORD concern the maintenance of effective pavement surface conditions.

Four of the papers consider bridges as a class of pavement differing from pavements built on grade. Blackburn, Glennon, and Glauz discuss the problem faced by decision makers in assessing whether added design or extra maintenance costs are justified to prevent ice or frost formation on bridge decks by developing a cost-benefit methodology based on field observations. Raisanen presents the results of a survey of the incidence of premature bridge deck icing in Minnesota. He concludes that prediction of frosty bridge decks could be made sooner and that traveler safety could be increased if a frost detection sensor were used and its alarm were correlated with the visual observations of the dawn patrol. Pell, Nydahl, Cundy, Twitchell, and Weber look at the thermodynamics of a bridge surface with frequent temperature changes on top and bottom and develop a simulation model to describe the thermal response. Fox discusses observations of five installations of a frost and ice detection system for bridge decks, used experimentally in Iowa, that is based on the detection of the heat of fusion of ice. These papers will assist designers and maintenance engineers in decreasing the accident potential on bridge decks.

Two other papers are also concerned with engineering aspects of general winter maintenance of pavement surfaces and will also be of interest to design and maintenance engineers. Williams discusses the thermal requirements for snow-melting installations embedded in pavements and refines the recommendations of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Kuhajek and Fiedelman conclude that present levels of ferrocyanide used as a deicing salt and an anticaking agent are not high enough to present danger to aquatic or atmospheric environments.

—L. David Minsk

ECONOMIC EVALUATION OF THE EFFECTS OF ICE AND FROST ON BRIDGE DECKS

Robert R. Blackburn, John C. Glennon, and William D. Glauz,
Midwest Research Institute, Kansas City, Missouri

ABRIDGMENT

•THE objective of this research was to develop a comprehensive cost-benefit methodology, complete with a set of realistic parameter values, that can be used by a highway administrator to determine the added design or extra maintenance cost justified to prevent or remedy ice or frost on bridge decks. The emphasis, throughout, was on localized icing, that is, situations where the bridge deck and approach pavement conditions are dissimilar. Major activities included formulation and evaluation of a bridge classification or hazard model, the formulation of a cost-benefit methodology, and computation of illustrative examples of the cost-benefit methodology application.

The bridge classification model was developed for predicting the annual number of ice and snow accidents on a bridge, given various characteristics of the bridge. The prediction is based on average daily traffic, length, width, location (urban and rural), type of crossing (water and other), highway type (divided and undivided), and bridge type (concrete and other).

The cost-benefit methodology consisted of a benefit model and a cost model. The benefit model calculates a yearly dollar benefit that is the difference between accident costs without a special localized icing countermeasure and accident costs with the countermeasure. The cost model includes those costs incurred to combat localized ice or frost, including detection or prediction devices, the countermeasure, and repair and maintenance costs arising later because of the countermeasure.

Numerical examples of the cost-benefit methodology were calculated by using data from selected regions of the country. The benefit-cost ratio for the cases considered ranged from a low of 0.18 to a high of 2.27. Half of the benefit-cost values obtained for countermeasures applied to individual, selected bridges exceeded unity. However, all of the benefit-cost values associated with countermeasures appropriate to areawide groupings of bridges were less than unity. The occurrence of low values was rationalized in that areawide winter maintenance practices cannot be justified solely by accident reductions. It was concluded that the cost-benefit methodology developed is comprehensive and has the flexibility to represent a variety of situations and countermeasure systems.

SURVEY RESULTS OF THE INCIDENCE OF PREMATURE BRIDGE DECK ICING

Donald L. Raisanen, Minnesota Department of Highways

The occurrence of frost on bridge decks is a serious problem in Minnesota. So that we could become better acquainted with differential frosting, our maintenance personnel were asked to collect data. A total of 35,198 observations were made during two winters. Originally, we thought that we would be able to predict when a bridge deck would frost; this was not the case. Frosting occurred over a large temperature range and did not depend on any logical combination of variables. Since predictions of deck frosting cannot be made reliably by visual observations, we intend to install a frost detection sensor and to correlate the sensor alarm with the visual observations.

•THE problem of differential frosting between bridge decks and roadways has been in existence as long as there have been bridges. In the past, when the small amount of traffic was slow, frost was not too much of a problem. However, since the day of the 200 to 300-hp (149 to 224-kW) automobile, the speeds we travel at have been greatly increased. To maintain these speeds and increase the roadway user's safety, alignments and surfaces were improved, and many more bridges were constructed. The combination of increased traffic volumes and speeds along with the building of many more bridges made differential frosting of decks a traffic hazard. Since one of the most important functions of highway design is traveler safety, this project was begun with two objectives in mind:

1. To define the scope and extent of the problem, and
2. To investigate probable solutions to the problem.

In late 1972, we began to determine methods of eliminating, reducing, or at least forecasting the phenomenon of differential icing between bridge decks and adjoining roadways. The first step was to conduct a literature search. It appeared that the problem could not be solved from the information reviewed. We then listed a series of questions, whose answers we thought could lead us to a solution:

1. Under what atmospheric conditions could we expect frost? For example, was it only near freezing temperatures [32 F (0 C)] and, if not, under what temperature ranges could we expect problems?
2. Would we find frost only in the fall and spring?
3. Is differential frosting really a problem, or is it rare enough not to be a significant problem?
4. Are different types of construction, such as wood, concrete, and steel, more susceptible to frost?
5. Are bridges over rivers more likely to frost than others?

To investigate these questions, we thought we needed a statewide data base. Therefore, we asked each of our area maintenance engineers to have a daily check made between October and March of representative bridges in their areas. These checks showed only the month, day, and whether frost did or did not occur. In addition, one metropolitan area also reported the time of frost occurrence, temperature, wind direction and velocity, and sky cover. Their data were collected by the dawn patrol, a

Table 1. Observations of bridges over water and railroads or highway from November to March 1972 through 1974.

	Water			Railroad or Highway		
Month	Total	Frost	Percent	Total	Frost	Percent
November	2,148	221	10	3,236	308	10
December	3,205	264	8	4,015	371	9
January	3,708	603	16	5,519	742	13
February	2,808	149	5	4,635	206	5
March	2,586	65	3	3,338	67	2

unit that patrols the most heavily traveled roads during the night and early morning to look for problem areas.

During the two winters (November 1972 through March 1974) when we conducted this study, 35,198 observations were made (Table 1). Since they were made basically when frost should occur, night and early morning, and they were not timed, the total percentages of occurrences cannot be interpreted as the percentage of time or hours the decks were icy. However, some interesting conclusions can be made. If people were asked to describe when frost will occur, they most likely would cite spring or fall, a temperature near 32 F (0 C), a clear sky, no wind, and a time close to sunrise. This general consensus is regrettably only one of many combinations.

We found that differential frosting occurred during every month studied (October through March) and that the most frequent occurrences were during January. Other findings were as follows:

1. Temperatures varied from -22 to +36 F (-30 to +2 C),
2. Sky cover varied from clear to 100 percent cloud covered,
3. Wind blew from all points of the compass, at 0 to 30 mph (0 to 48 km/h), and
4. The time of occurrence covered our entire reporting time of midnight to 8 a.m.

Since other facts we found appear to be contrary to logic, they should be listed separately:

1. The type of superstructure of the bridges had no effect on frost formation;
2. The type of deck surface had no effect on frost formation; and
3. The location of the bridge, whether over land or streams, had no effect on frost formation.

We also found that differential frosting occurs on 2 to 15 percent of the days in a month; therefore, it can be a substantial problem. Regrettably, our accident information is coded into the computer in such a way that we cannot determine the exact cost of accidents on frosty decks. However, the Midwest Research Institute conducted a project that estimated the annual cost of nationwide accidents due to frosty decks to be about $70 million.

As stated above, we did not collect data that would show what structures would frost first during the day; we collected only data that showed which structures did frost.

The recurring pattern of all bridges in a geographic area being either frosty or nonfrosty is extremely noticeable when maps showing daily frost distribution are referred to. We tried correlating these data with the National Weather Service's forecasts but had no success. We felt this lack of success was due to two factors: Forecasts were, by nature, somewhat general because of their wide area coverage, and salt residue on the bridge decks changed the frost formation parameters.

Since we could not reliably predict frost conditions, we were forced to change our course. Our next objective was to determine methods or materials that could be applied to the decks and that could reduce or eliminate the frosting problem. Systems such as heating the concrete electrically or with radiant heaters were examined, but we felt the costs for over 13,000 decks statewide were prohibitive. The costs could have exceeded $250 million for the initial installations, and this did not include the yearly power requirements or maintenance. The standard salt solutions, air circulation, electroosmosis, and hydrated lime were also examined. These were quickly rejected because of expected poor performance. We did try insulating the underside of a few decks, but this proved to be of no value. Three chemicals were tried: propylene glycol, ethelyne glycol, and a formamide-based material. They were nonreactive with concrete or steel and could give up to 1 week's protection from frost. They were all liquids applied with a regular distributor truck and spray bar. The only thing we could agree on is that they did not attack the decks. Although they might have reduced frost if they had been applied at high rates, they would also have reduced skid resistance, our primary problem, and would have proved to be a pollutant. Therefore, we did not know what could be used effectively and ecologically to reduce or eliminate the frosting problem. Again the data were considered, and the only conclusion was that frosting appeared in regional areas and was not governed by structural characteristics or microgeography.

While we were testing various solutions, manufacturers were developing and refining frost detection sensors. We are now in the process of purchasing a sensor that will signal wet, frost warning, and frost conditions. This, in conjunction with our maintenance personnel's knowledge of which decks are the first to frost and our knowledge that it is likely that all within a given area will frost nearly at the same time, may finally give us the solution we have been looking for.

We intend to place a sensor on one bridge and connect it to an alarm at the maintenance headquarters. Of course, the maintenance dawn patrol will continue collecting their data as usual. We will then be able to correlate the sensor alarms to the visual observations. If the correlation proves satisfactory, we should then be able to detect or predict frosty bridge decks sooner than is now possible. We may also be able to reduce the personnel required by our dawn patrol to increase traveler safety.

THERMAL RESPONSE OF BRIDGES

Kynric M. Pell, John E. Nydahl, Vic A. Cundy, George Twitchell, and Mark Weber, Department of Mechanical Engineering, University of Wyoming

Interest in the control of ice on highway structures has resulted in a number of demonstration projects to investigate the effectiveness of both active and passive techniques to control the problem. Few of these experiments have incorporated any preliminary thermal modeling in their feasibility studies and, as a result, have met with mixed success. Research was initiated to develop, verify, and document a thermal model applicable to highway structures. This program would allow the design engineer to conveniently estimate the thermal performance of proposed ice control devices in a specific environment. The thermal model was developed and verified by simulating the thermal response of an instrumented bridge to within a mean deviation of 2.1 F (1.2 C) over a 12-day period of severe winter weather. The model is general since standard heat-transfer correlations rather than inferred correlations from the data were used. The utility of the simulation is demonstrated in a study of the effect that insulation would have on the freezing characteristics of a bridge. Insulation would reduce the number of freeze-thaw cycles by 34 percent and the total time frozen by 15 percent. Experimental results indicated that modifying the surface radiative characteristics can induce even larger reductions for the site investigated.

•TEMPERATURE variations, particularly around the freezing point, can strongly influence the performance of highway structures. Elevated highway structures such as ramps, interchanges, and bridge decks exhibit a different thermal response to the environment than the remainder of the roadway exhibits, and this results in possible preferential icing where either the deck surface is iced and the roadway is not or vice versa. The former case presents a more obvious safety hazard for the motorist. In addition, it has been recognized that concrete bridge deck deterioration is related to freeze-thaw cycles and the time the deck is frozen. The total time frozen is an important parameter because a structure's icing characteristics and, therefore, the application of salt are related to it.

Interest in the thermal design of bridges to ameliorate safety problems and inhibit deterioration related to freezing has recently increased. Both active and passive techniques have been explored. Studies related to preferential icing have been primarily experimental, and the results were often inconclusive and proved to be site specific. The inconclusive results were primarily due to insufficient data; however, the results were site specific because heat transfer on bridges is an extremely nonlinear function of climatic environment and material properties.

In view of these difficulties, it seemed desirable to develop an accurate thermal simulation of structures that could use available historical weather data to predict the thermal performance of a structure. This would be particularly valuable in preliminary design studies to characterize the effectiveness of possible control techniques minimizing icing conditions. For the program to be broadly accepted, it would have to possess documented accuracy and broad applicability and be user oriented. A program exhibiting these characteristics could also be used to predict preferential icing by using regional weather forecasts. The objective of this research is to develop and document such a program.

BACKGROUND AND SCOPE

One obvious method to minimize freezing is to actively heat the structures, and this has been attempted on some bridges, roads, and runways, by using heat sources such as electrical, oil, and gas-fired boilers or hot springs. A comprehensive review of this literature is given elsewhere (1, 2). Typical heating systems have included resistive heating elements, convective tubes, and infrared and convective heaters placed either above or below the surface. These methods appear to have a limited application for extreme situations because of prohibitive capital expense and operating costs or large induced thermal stresses.

The limited use of the earth as a low-temperature heat source for a convective system to melt snow on pavement in a mild climiate has been successfully demonstrated (3), and the use of heat pipes in a related application has been investigated (4). A demonstration project using ammonia-charged, gravity-operated heat pipes has been conducted recently at the Federal Highway Administration research facility in Virginia (5). The development of design procedures for heat pipe systems for both retrofit and new construction on bridges to inhibit preferential icing is also being investigated by FHWA.

Passive methods involving the alteration of the thermal properties of bridges have also been studied; for example, the bottoms of bridges have been insulated to reduce the convective heat transfer (6, 7, 8, 9, 10), and surface radiative properties have been varied (9). Essentially, all of the investigations to date have been strictly experimental, and the results in Table 1 do not provide the basis for general criteria for use of these techniques.

Passive techniques can be effective in significantly altering the freezing characteristics of a bridge (Table 1) and the amount of alteration and whether it is beneficial or detrimental depends strongly on the location. It is evident that if thermal designs of structures are to be optimized they must be optimized for their local environment, especially when elaborate schemes, such as geothermal heating, are being considered.

The evaluation and optimization of proposed freeze-thaw and icing control devices for bridges, roads, or runways require either a well-instrumented engineering development facility or an accurate thermal simulation. Engineering development facilities are traditionally expensive and exhibit inherent inflexibility as is demonstrated by many of the experimental studies previously mentioned. These facts have led to an increasing use of simulation in all areas of engineering. In view of this need for an accurate thermal model of broad applicability, the current study was initiated (11, 12, 13).

Development of a basic computer code for heat transfer that was applicable to highway structures began in 1972. The simultaneous development of an experimental facility to provide input data and model verification was initiated by using financial resources, equipment, and personnel of both the University of Wyoming and the Wyoming Highway Department.

EXPERIMENTAL INVESTIGATIONS

Experimental Facility

The overpass bridges and adjacent roadway at the Cooper Cove interchange located 40 miles (64 km) west of Laramie, Wyoming, on Interstate 80 were chosen as the test site because of the severity and variety of the local micrometeorology and the proximity of the U.S. Forest Service and Wyoming Highway Department field test site at Cooper Cove. The westbound lane has an asphalt overlay that will permit direct comparison of the thermal response of two bridges that are similar except for surface radiation properties (concrete versus asphalt).

The installed instrumentation can be divided into two groups to measure (a) the local micrometeorology and (b) the actual thermal response of the bridge and roadway. The weather data supply the input for the numerical simulations, and the thermal response data permit simulation verification. Figure 1 shows the rack, containing most of the meteorological instrumentation, that was mounted on the rail of the eastbound bridge and that includes two anemometers, two wind vanes, aspirated ambient air temperature gauge, time-lapse camera, and two Eppley pyrheliometers. The pyrheliometers are mounted on a 10-ft (3-m) pole; one unit measures the incoming solar radiation and the other unit is shielded and sees only the bridge so that the reflected solar radiation can be measured. The solar radiation absorbed by the bridge deck as well as the surface condition can be deduced from these two measurements since the solar reflectivity varies with wetness, icing, and snowpack. In addition, some indication of cloud cover can be obtained from the upward facing Eppley pyrheliometer. Barometric pressure, humidity, and precipitation are also measured. The temperature distributions in the bridges and adjacent roadway are measured as a function of time by using thermistors embedded in the bridge decks and the adjacent roadway. All of the transducers (thermistors and weather instrumentation) are cabled to an instrumentation shed located under the bridge of the eastbound lane of I-80. The instrumentation shed houses the various instrumentation controllers and the magnetic-tape-based data acquisition system. The bridges were instrumented by potting the sensors in $^3/_8$-in.-diameter (9.5-mm) epoxy rods of varying lengths, which could be inserted into holes drilled from the bottom of the bridge deck. A schematic of this installation is shown in Figure 2. The locations of all the temperature sensors are shown in Figure 3. Three road cables were installed to measure the temperature distribution down to 10 ft (3 m) below the surface of the adjacent road.

The data acquisition system was originally developed with the cooperation of the Electrical Engineering Department of the University of Wyoming. It is capable of sequentially sampling, digitizing, and recording 100 channels of analog input signals in less than 4 sec. The entire system, consisting of a line voltage regulator, digital system, and digital recorder, is mounted in one instrumentation rack. The digital system consists of an electronic multiplexing switch, an amplifier, an A-D converter, a digital clock, and a logic module. These components are mounted in functional arrays on printed circuit boards. A rack mounting unit with appropriate card guides and terminal strips houses the complete digital system. Data in 100 channels can be sampled at a predetermined rate, and the signals are recorded on an incremental digital recorder in a format that is compatible with the equipment in the University of Wyoming's computer center.

Results

The data acquisition system went into operation on January 24, 1974, and data were taken on an almost continuous basis until June 16, 1974. Power failures and data acquisition failures caused the system to be closed down 7½ days during this period. In addition, individual transducer malfunctions occurred during this period, but, because of the redundancy, these did not in general preclude simulation. On June 16, 1974, the data acquisition system failed because of overheating. Repair of the system and installation of an air-conditioning system were not completed until October 10, 1974, at which time the system started functioning continuously.

As long as the system is kept within operating temperature limits, it performs quite well, although noise on some of the instrumentation cables has been a consistent problem. The use of the isolation transformer to isolate the system from the power company ground has reduced this problem significantly. Throughout the program, the data acquisition system has been routinely subjected to calibration checks on all of the transducers.

An extensive computer-processing and data-reduction capability, providing a variety of tabular and graphical output formats, has been developed to provide convenient interpretation of the many parameters. All of the data processing is accomplished by using the program BRIDGEDATA, which incorporates 11 data-reduction modes. Input to the program includes the data tape generated in the field, a selection of the number of 1-min records that are to be averaged, and a specification of the particular mode to be executed.

Table 1. Passive techniques for control of icing on bridges.

Study	Time Observed (days)	Insulation Effects[a]		Surface Radiation Effects[a]	
		Freeze-Thaw Cycles	Total Time Frozen[b]	Freeze-Thaw Cycles	Total Time Frozen[b]
Nebraska (6)	80	-2	—	—	—
Texas (7)	41	+4	—[c]	—	—
New York (8)	147	-53	+2.6	—	—
Alabama (9)	245	+4	-7	+1[d]	-6
Missouri (10)	215	-15	+1	—	—
Wyoming	91	-34	-15	-37[e]	-36[e]

[a] Percentage reduction (-) or increase (+).
[b] Compared with control deck.
[c] 2-hour reduction in duration of cycle.
[d] Dark epoxy covering on deck.
[e] Asphalt-overlaid deck.

Figure 1. Meteorological instrumentation rack and instrumentation shed at field site.

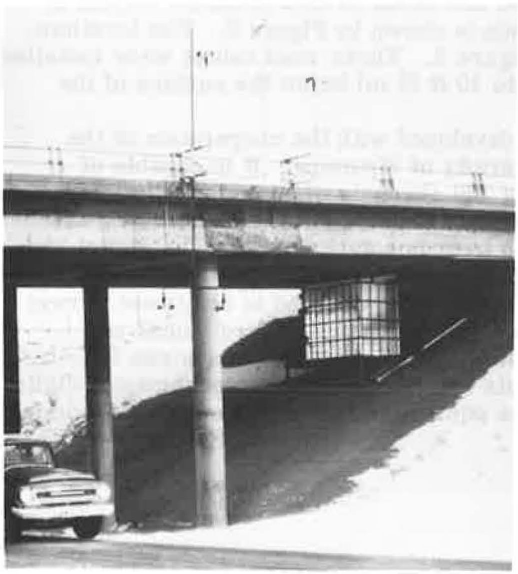


Figure 2. Thermistor installation on overlaid bridge.

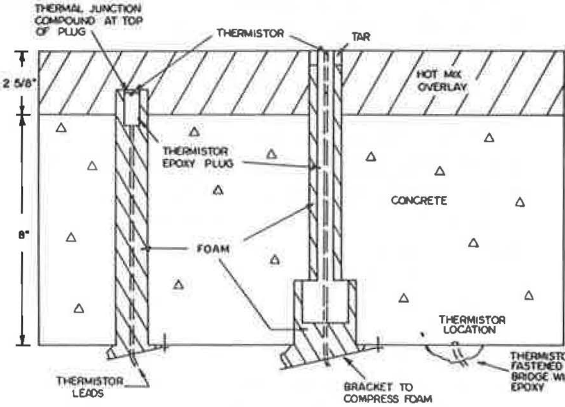
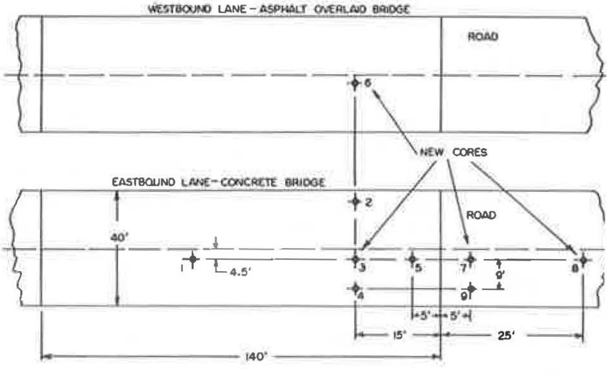


Figure 3. Thermistor locations in bridge decks and roadway.



A number of interesting results were obtained from a comprehensive data correlation study using BRIDGEDATA.

Over the 121-day period, a correlation between the surface temperatures measured at the five core locations on the concrete deck indicated that temperature differences of 3 F (1.67 C) could exist at the various locations. Location on the bridge does not appear to influence these temperatures with the exception of core 5, which appears to be warmed slightly by the proximity of the deck-road interface.

The asphalt-overlaid bridge deck is significantly warmer than the concrete bridge deck. During the period from February 1, 1974, when the asphalt bridge was instrumented, to June 15, 1974, there were 91 days when reliable comparisons could be made between the temperatures of the two decks. The surface temperatures were averaged for the day (6 a.m. to 6 p.m.) and for the night (6 p.m. to 6 a.m.). Since the tapes were generally changed around noon and the averaging was done on each tape as a unit, approximately 6 hours of data at the beginning and the end of each 8-day tape were neglected in the averaging process. These results showed that the concrete deck was 9.8 F (5.4 C) colder than the asphalt-overlaid deck during the day and 8.6 F (4.8 C) colder than the asphalt during the night for the 91-day period. A graphical representation of this data, along with air temperature, is shown in Figure 4. From the data averaged over the entire period, including that for both night and day, one can see that the asphalt-overlaid bridge was 9.2 F (5.1 C) warmer than the concrete deck. Graphic examples of this temperature difference are shown in Figure 5. A test of the effect of prevailing wind direction on this temperature difference did not result in any correlation. An additional test involving the simulated variation in internal thermal properties did not account for the observed differences. The difference in surface temperature of the two decks is therefore totally attributed to the difference in radiative properties of the two surfaces.

There was a positive indication that the number of freeze-thaw cycles was fewer and that the total time frozen (surface temperature) was significantly less for the asphalt-overlaid deck. Of the 91 days considered, the asphalt bridge experienced 18 freeze-thaw cycles, but the concrete deck experienced 40 freeze-thaw cycles. In addition, it is observed that the asphalt bridge was frozen an equivalent of 18 days, but the concrete bridge was frozen 26 days.

These results for the bridge can be contrasted with the roadway performance. During the 91 days when the surface temperature of the two bridges and the roadway could be compared, the roadway was 2 F (1.1 C) warmer than the concrete deck, and the asphalt deck was 7.2 F (4.0 C) warmer than the roadway. During the day, the concrete deck was an average of 1.5 F (0.8 C) colder than the adjacent road, and at night it was 2.5 F (1.4 C) colder. The observed range of variance for the ½-day averages was from 9.2 to -8.6 F (5.1 to -4.8 C). Similar data for the comparison of the asphalt deck with the roadway show that the asphalt bridge is an average of 8.3 F (4.6 C) warmer than the adjacent roadway during the day and 6.1 F (3.4 C) warmer during the night. In this case, the variance for the ½-day averages ranged from 16.4 to -2.5 F (9.1 to -1.4 C). Comparison of freeze-thaw performance indicates that the roadway exhibits 34 major freeze-thaw cycles during a 91-day period. This is significantly more than that experienced by the asphalt deck (24) but less than that experienced by the concrete deck (38). Table 1 gives some of these results.

The fact that the asphalt bridge is generally warmer than the adjacent roadway is surprising and contradictory to folklore. It is probably due to two factors. First, the temperature 10 ft (3 m) below the surface of the road varied from a low of 31 F (-0.56 C) to a high of 53 F (11.67 C) over the time interval studied. Obviously, this location is not below the frost line. Apparently the fill associated with the approach to the bridge [approximately 20-ft (6.1-m) elevation at the bridge] is subject to climatic variations to a much greater depth than the surrounding grade. As a result, the approach may be appreciably colder than the road at grade level. Second, note that, although the elevated structures may be expected to cool much faster than the roadway because of convection on the lower surface and their smaller thermal mass compared with that of the roadway, this smaller thermal mass also allows more rapid heating and, in fact, superheating with respect to the roadway.

Figure 4. Average ambient air temperature (top curve) and average temperature difference between the two bridge decks (bottom curve).

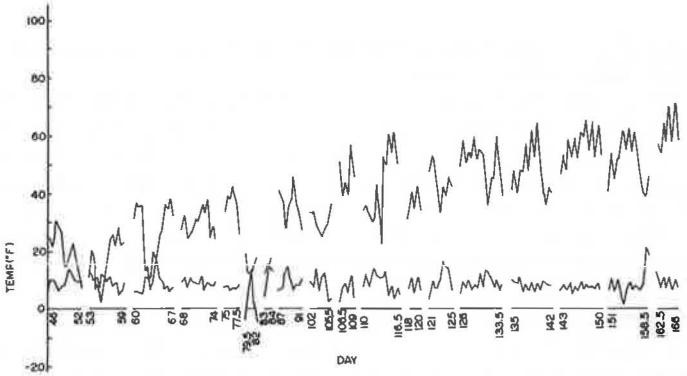


Figure 5. Comparison of surface temperature on asphalt and concrete bridge decks.

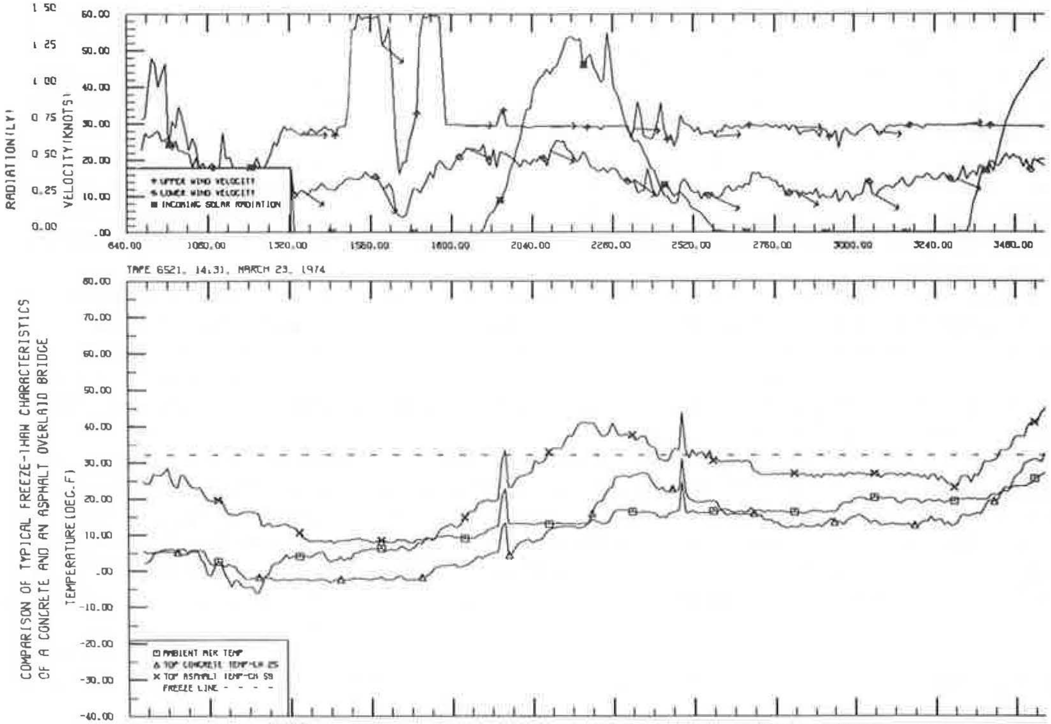
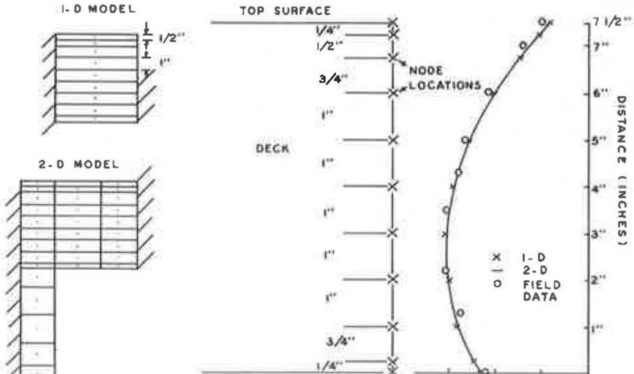


Figure 6. Temperature comparison of one- and two-dimensional models and experimental data.



LABORATORY EXPERIMENTS

A review of the literature indicated that the thermal conductivity of concrete can vary from 0.1 to 2.0 Btu/hour•ft•deg F (0.17 to 3.46 W/m•deg K) depending on the design of the mix. Similarly, the reported density and specific heat of concrete exhibit large variations. Investigations at the University of Wyoming confirmed these ranges of values (2, 14). It was found that the simulation was sensitive to the values used for these properties. This sensitivity necessitated that these properties be accurately determined for the actual materials found at the field site. A series of laboratory experiments were developed to evaluate the various properties.

The apparatus developed to measure thermal conductivity incorporates a guard heater, a specimen, a cooling reservoir, and the instrumentation for thermocouple temperature measurement. This standard arrangement provides a known heat flux through the specimen and allows a direct determination of the thermal conductivity from the temperature measurements. The value of thermal conductivity determined in this manner was combined with the known properties of steel to yield an effective value of thermal conductivity for the bridge. The values of the effective properties for concrete and asphalt are given below (1 Btu/lb•deg F = 4.18 kJ/kg•deg K; 1 Btu/hour•deg F = 1.7 W/m•deg K; and 1 lb/ft^3 = 1.6 kg/m^3):

Material	Heat Capacity (Btu/lb•deg F)	Conductivity (Btu/hour•ft•deg F)	Density (lb/ft^3)
Concrete	0.31	1.24	134.78
Asphalt	0.237	1.61	155.61

Density and specific heats of concrete and asphalt specimens were also measured by using standard techniques. These values were also combined with the known values for steel to obtain the values given above.

The comparison of the thermal response of the concrete and asphalt-overlaid decks presented previously indicates a strong dependence on the surface radiative properties. Generally these properties are a function of wavelength, and a wide range of values have been reported for the materials of interest (15). The short-wave (solar) radiative properties of the concrete deck have been characterized by using the Eppley pyrheliometers during the past year. There is no long-wave radiation instrumentation at the site; however, the excellent agreement between simulated and measured response of the concrete deck indicates that the models being used are probably adequate. In the case of the asphalt-overlaid deck, neither short-wave nor long-wave measurements have been made; as a result, the simulations suffer from this uncertainty.

SIMULATION

The simulation is based on a transient, three-dimensional, conductive heat transfer program developed by the Energy Research and Development Administration (16) and widely used by the National Aeronautics and Space Administration and industry. This program is now capable of handling inhomogeneous structures of arbitrary shapes, having internal heat generation that may differ at each internal node and vary with time. The heat transfer at the surface includes convection and radiation. The absorbed solar radiation was measured directly at the site, but the heat transfer between the atmosphere and the bridge surfaces was based on standard empirical correlations involving the measured environmental parameters.

The incident log-wave radiation from the atmosphere was calculated by using the empirical correlation (17, 18) for clear skies, which is based on air temperature and vapor pressure, as follows:

$$q_{L.W.} = \sigma T_a^4(a + b\sqrt{p}) \tag{1}$$

where

σ = Stefan-Boltzmann constant,
T_a = absolute air temperature at about 5 to 7 ft (1.5 to 2 m) above the surface,
a and b = constants, and
p = partial pressure of water vapor.

The long-wave radiation is also a strong function of cloud cover and cloud base height, but reasonable simulations were obtained if these parameters were ignored. Long-wave radiation emitted by the surface is calculated in the simulation by using the following equation:

$$q_{L.W.} = \epsilon_{L.W.}\sigma T_{surf}^4 \tag{2}$$

where

$\epsilon_{L.W.}$ = emissivity (0.80), and
T_{surf} = absolute temperature of the surface.

The long-wave radiation interchange between the ground and the bottom of the bridge deck was generally insignificant and was, therefore, ignored in the simple model presented here.

Calculation of the convective heat transfer depends on the flow structure around the bridge and is subject to large uncertainties. In spite of the fact that measurements indicate an appreciable difference between the mean flow velocities and directions above and below the bridge, parametric studies indicated that adequate simulations could be made without distinguishing between the upper and lower surface as far as convection is concerned. Both surfaces behave essentially as flat plates even though the bottom surface has a waffle structure. This is due to the very high Reynolds number of the turbulent flow. Kay's correlation for turbulent heat transfer from a flat plate was used in the simulation with good results (19):

$$q_{conv} = 131.6\rho c u Pr^{-0.4} Re_L^{-0.2}(T_{surf} - T_a) \tag{3}$$

where

u = free stream velocity in feet per second;
ρ = air density in pounds per cubic foot;
c = specific heat in British thermal units per pound·deg F;
Pr = Prandtl number; and
Re_L = Reynolds number based on L, the 40-ft (12-m) bridge width.

(If SI units are used in this equation, the numerical coefficient 746.8 should be used rather than 131.6.) Natural convection was incorporated in the simulation by using Vehrencamp's correlation (20):

$$q = 0.18(T_{surf} - T_a)^{1.3} \tag{4}$$

(For SI units, the numerical coefficient in this equation becomes 1.22.)

A study to determine the geometric complexity required for accurate simulation was undertaken to reduce the execution time of the computer simulations. One- and two-dimensional representations of the bridge were considered as shown in Figure 6. The two-dimensional model takes into account the web geometry below the concrete slab forming the deck, but the one-dimensional model represents just the deck slab. Results of the simulated temperature distribution for the one- and two-dimensional models and the measured temperature distribution are also shown in Figure 6. Although the data are for a particular time, they are typical of the results obtained throughout an 8-day simulation. It is apparent that a transient one-dimensional heat transfer model is sufficient for the type of investigations considered.

Most of the field data generated between January 24, 1974, and June 15, 1974, have been simulated by using the heat-transfer models previously described. This represents over 121 days of essentially continuous simulation including winter and spring environments. The mean deviation (based on absolute temperature difference) between the simulated and measured surface temperatures was only 2.1 F (1.2 C), in spite of the fact that this period encompassed many days when the upper surface was snowpacked, icy, or wet. It should be emphasized that the simulation does not treat these surface conditions explicitly but does directly incorporate into the program the fact that the solar radiation is absorbed.

Of a typical 8-day simulation, 1.5 days are shown in Figure 7. Mean deviation between the measured and simulated upper surface temperature for the full 8-day tape was 2 F (1.1 C); however, the mean deviation for the lower surface temperature was 2.2 F (1.2 C). Environmental conditions for the full tape included wind speeds of 60 knots (30.9 m/s) and ambient air temperatures below -10 F (-23.3 C). The upper surface, which was snowpacked for most of the 8 days, experienced five freeze-thaw cycles and was below freezing for 5.4 days. The first freeze-thaw cycle is included in Figure 7. It should be noted that the simulation accurately predicts the onset and termination of the freeze-thaw cycle. The excellent agreement between simulated and measured temperatures is surprising because the surface was snowpacked throughout most of the period.

Parametric studies were initiated to investigate the effect that an insulator, located at the bottom surface, would have on the freezing characteristics of the upper surface of the concrete deck. A perfect insulator was selected as the limiting case. The results of this study are given in Table 1, in which measured field site data are given for comparison. It was observed that insulation would be effective in reducing the number of freeze-thaw cycles (by 34 percent) and time frozen (by 15 percent) at this site under the prevalent environmental conditions and that the upper surface temperature was increased an average of about 1.92 F (1.1 C), and the lower surface temperature was increased 4.9 F (2.7 C). However, the average temperatures on both surfaces did decrease for one 8-day tape.

The results from part of a typical 8-day insulation study are graphically shown in Figure 8. Comparing the simulated temperature response of the insulated and uninsulated concrete decks for this 8-day period showed that the effect of insulation was to raise the average temperature of the upper surface by 2.1 F (1.2 C) and of the lower surface by 5.2 F (2.9 C). No reduction in freeze-thaw cycles occurred in this sample period. This result emphasizes the need to conduct comprehensive studies over extended periods of time. For this particular period of time, the average temperature of the bridge is well below freezing; therefore, a direct correlation can be made with the New York study (19). A result of this study indicates that the effect of insulation is minor during periods of hard freeze.

Insulation appears to be effective when the surface temperature is close to freezing and rapid alternate freezing and thawing cycles. In hard freeze or prolonged freeze situations, insulation is not effective in reducing the cycling. In Table 1, it may be seen that, at this site, asphalt overlaying is more effective in reducing freeze-thaw cycles and total time frozen than even a perfect insulator on the lower deck surface. It should be emphasized that these results for insulation should not be generalized to significantly different sites in view of the nonlinear dependence on geometry and environmental parameters.

Figure 7. Comparison of simulated and measured response of bridge with concrete deck.

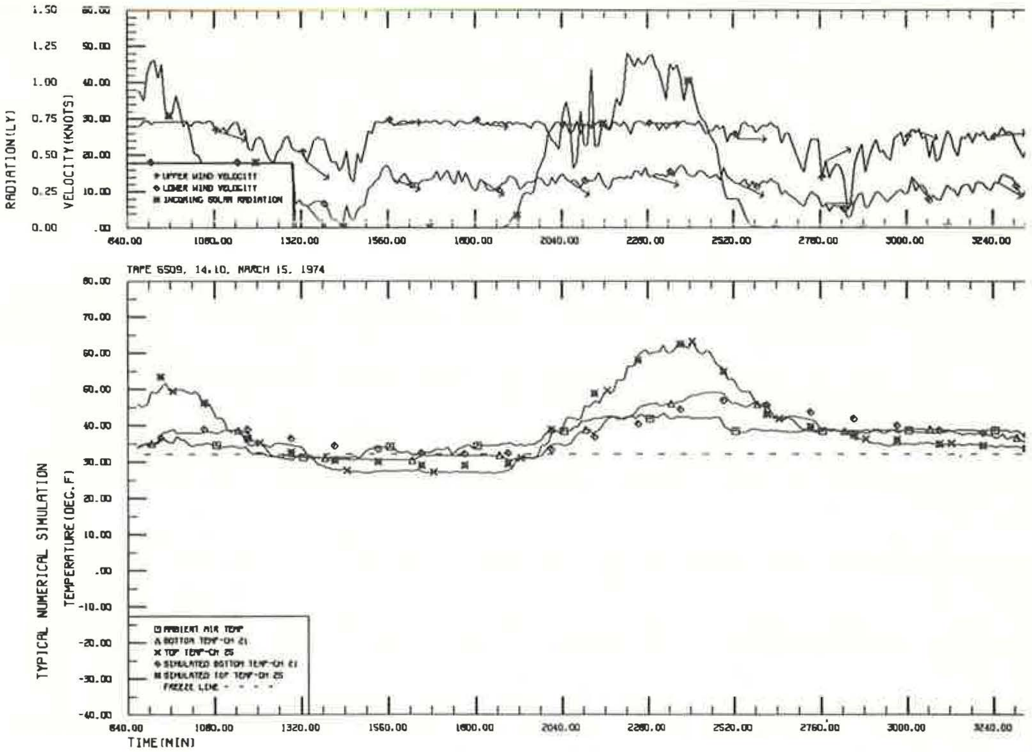
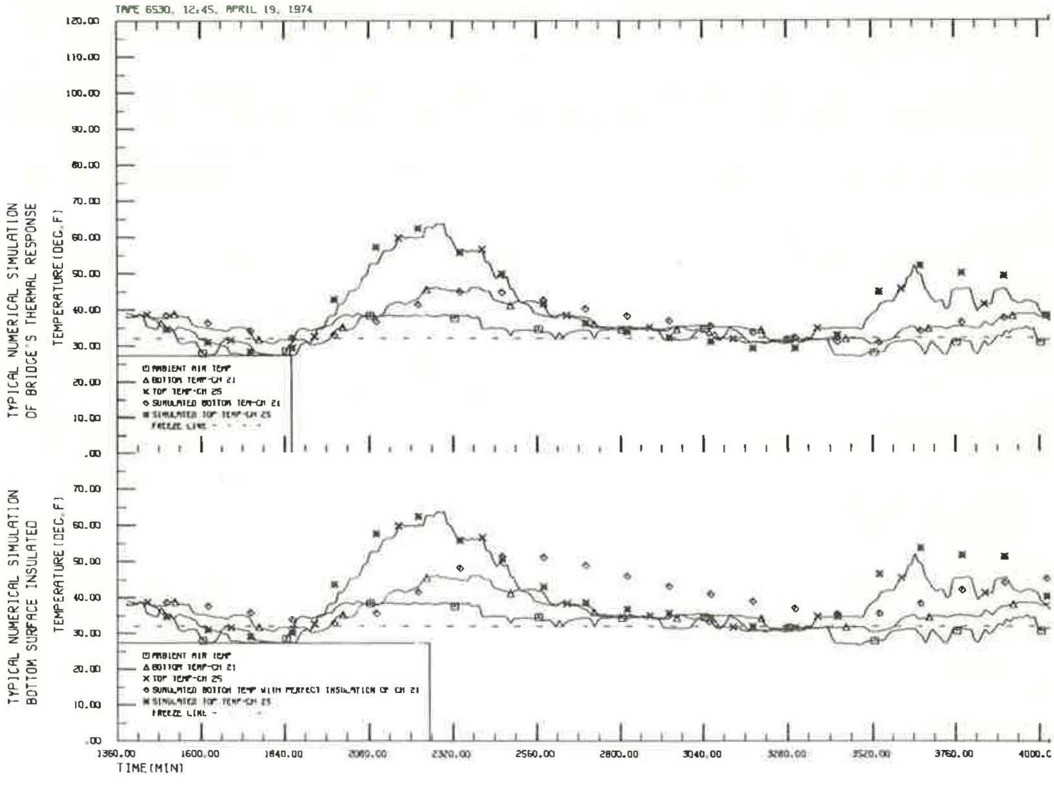


Figure 8. Comparison of bridge deck with and without insulation.



Parametric studies of the effect of modifying the surface radiative properties of the bridge were initiated by using the simulation. It was shown that large variations in the surface temperature can in principle be obtained by using this technique. This is qualitatively confirmed by the contrasting results obtained in the field site data for the concrete and asphalt-overlaid decks. In view of the uncertainty in the radiative properties previously noted, an exhaustive study was not pursued.

CONCLUSION

It has been demonstrated that accurate thermal simulations of highway structures can be obtained by using a relatively simple model. The environmental information needed for input (air temperature, wind speed, relative humidity, and solar radiation) is available for many regions in the form of a magnetic tape from the National Oceanographic and Atmospheric Administration.

The simulation has been verified by comparing simulation results to measured thermal response of a concrete bridge for 121 days. The mean deviation between measured and simulated temperatures was only 2.1 F (1.2 C) over the entire winter although this period encompassed many days when the upper surface was snowpacked, icy, or wet. In addition, the onset and termination of freeze-thaw cycles were accurately predicted.

Although the program was verified by using data obtained at a particular site, it incorporates correlations of standard heat transfer that should ensure applicability to other environments. Data obtained in Minnesota show that the response of bridges in rather large regions is similar inasmuch as all the bridges in a region exhibit icing at approximately the same time. This result indicates that the simulation used to study the parametric design of icing conditions could be based on regional historical weather data. The program, therefore, provides a convenient tool for optimizing the thermal design of highway structures for the local environment. Design alternatives that could be explored include radiative properties; insulation; material properties; composite structures; and active heating, including geothermal sources. Temperature distributions obtained from the program can also provide the basis for an analysis of thermal stress.

As an example of the utility of the simulation, a study was initiated to determine the effect that insulating the lower surface of the concrete bridge would have. Results indicate that the number of freeze-thaw cycles would be decreased by 34 percent and that the total time frozen would be decreased by 15 percent.

The experimental program to measure the thermal response of two bridge decks and the adjacent roadway as well as the local micrometeorological parameters has produced a number of important results in terms of contrasting thermal performance of various structures, in addition to providing the basis for development of the thermal simulation. Data obtained from January 24, 1974, through June 16, 1974, indicate that the asphalt-overlaid deck surface was generally warmer by 9 and 7 F (5 and 3.9 C) than either the concrete deck or the interfacing roadway respectively. The asphalt-overlaid deck was subject to 37 percent fewer major freeze-thaw cycles than the concrete deck and was below freezing for 36 percent less time than the concrete deck. In general, the concrete deck surface was 2 F (1.2 C) colder than the adjacent roadway surface.

A proposed icing control scheme for a particular site should be investigated by using a thermal simulation that incorporates historical weather data from the appropriate recording weather station even before a demonstration project is implemented.

ACKNOWLEDGMENT

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REFERENCES

1. R. Jorgensen. Non-Chemical Methods of Snow and Ice Control on Highway Structures. NCHRP Rept. 4, 1964.
2. V. A. Cundy. Thermodynamic Response of a Bridge Deck Under Various Climatic Environments. Univ. of Wyoming, thesis, Dec. 1974.
3. F. Winters. Pavement Heating, Progress Report. Project Bureau of Instrumentation Services, New Jersey Department of Transportation, Project 7722, Aug. 1971.
4. J. L. Pentecost et al. Development of a Pavement Heating System to Remove Snow From Airport Runway Inset Lights. Federal Aviation Administration, SRDS Rept. RD-65-109, Dec. 1965.
5. M. F. Pravda and P. L. Marjon. Snow and Ice Removal From Pavements Using Stored Earth Energy. Dynatherm Corp., July 1972.
6. G. L. Downey and R. T. Deloom. Effect of Bridge Deck Insulation on Icing Conditions. Bridge Design Section, Nebraska Department of Roads, 1965.
7. H. D. Butler. Insulation of Bridge Decks for Ice Prevention and Reduction of Freeze-Thaw Cycle. Texas Highway Department, Research Rept. 62-1 F, Feb. 1966.
8. M. D. Graham and I. F. Rizzuto. Effect of Bridge Deck Insulation on Icing Condition. Highway Research Record 94, 1965, pp. 77-98.
9. F. L. Homan. The Effectiveness of Darkening Surface and Insulating Bridge Slab to Reduce Unequal Icing. Bureau of Research and Development, Alabama Highway Department, July 1968.
10. E. O. Axon and R. W. Couch. Effect of Insulating the Underside of a Bridge Deck. Highway Research Record 14, 1963, pp. 1-13.
11. J. E. Nydahl and K. M. Pell. The Thermodynamic Response of Bridges. Department of Mechanical Engineering, Univ. of Wyoming, 1972.
12. J. E. Nydahl and K. M. Pell. A Tool for Thermal Design of Bridges, Roadways and Runways. Intersociety Conference on Transportation, Denver, Sept. 1973.
13. K. M. Pell, J. E. Nydahl, and V. A. Cundy. Thermodynamics of Bridges, Roadways and Runways. U.S. Department of Transportation, Rept. DOT-TST-75-41, Nov. 1974.
14. C. A. Howard. Thermal Conductivity of Concrete Made From Local Aggregates. Univ. of Wyoming, thesis, 1958.
15. G. G. Gubareff, J. E. Janssen, and R. H. Torborg. Radiation Properties. Honeywell Research Center, Minneapolis, 1960.
16. D. Bagwell. TOSS—An IBM 7090 Code for Computing Transient or Steady State Temperature Distributions. Atomic Energy Commission, Research and Development Rept. K-1494, 1961.
17. R. M. Goody. Atmospheric Radiation. Oxford Univ. Press, 1965.
18. K. Y. Kondratyev. Radiation in the Atmosphere. Academy Press, International Geophysics Series, Vol. 12, 1969.
19. W. M. Kays. Convective Heat and Mass Transfer. McGraw-Hill, 1966.
20. J. E. Vehrencamp. Experimental Investigation of Heat Transfer at an Air-Earth Interface. Trans., American Geophysical Union, Vol. 34, No. 1, 1953.

DEVELOPMENT OF A FROST AND ICE DETECTION SYSTEM FOR HIGHWAY BRIDGES

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A frost and ice detection system for bridge decks based on the detection of the heat of fusion of ice is being used experimentally in Iowa. Observation of the operation of 5 installations during the 1971-72 winter revealed that 57 alarms were genuine and 9 were false and that on 7 occasions the units failed to detect frost, ice, or snow.

•SYSTEMS for the detection of frost or ice on bridge floors have been commercially available for at least 8 years. In 1965, the Iowa State Highway Commission obtained two such systems, which were used experimentally during the winters of 1965-66 and 1966-67.

The two systems purchased by the commission distinguished between liquid water and frost or ice by detecting a difference in the electrical conductivity of water in its frozen and liquid forms. Investigation confirmed that a difference in electrical conductivity does exist, provided the water is relatively low in salt content. When the water contains an appreciable salt content, it is difficult or impossible to detect any difference in conductance. An explanation of this is suggested by the observation that, as saline water freezes, the dissolved salt is displaced to the surface where a supersaturated film of microscopic thickness is formed. This film has the same conductance as the unfrozen saline water.

Investigation of several other ice detection systems revealed that some have operating characteristics apparently based on the assumption that water freezes at 32 F (0 C). This is not always true on highway bridge decks, since the presence of dissolved salts often makes the freezing point indeterminate. Investigation in Iowa revealed that, after the first application of salt to a bridge deck, frost seldom formed above 22 F (-5.5 C).

The investigation of commercially available frost and ice detection systems eventually led to consideration of the most desirable operating characteristics for a dependable system and to a study of the theory and design features necessary to produce such a system.

OPERATION OF IOWA SYSTEM

The operation of the Iowa system for detection of frost and ice on bridge decks is based on detection of the heat of fusion of ice. The sensing surfaces are heated periodically at a carefully controlled rate so that melting of any frost, ice, or snow on the surface can be obtained. If the sensing surface is dry or wet, the relationship between the rate of temperature change and time will follow characteristic patterns. Water in a frozen form produces a definite change in the rate of temperature rise in the sensor at that point in time when the heat of fusion occurs.

The sensing element is a thin, stainless steel plate $^{5}/_{16}$ in. (7.9 mm) wide and 2 in. (5 cm) long. A Chromel-Alumel thermocouple is attached to the underside of the plate. The element is mounted in a nonconducting holder that is cylindrical and that has a diameter of 4 in. (10.2 cm) and a thickness of 1 in. (2.5 cm). The element and holder are inserted in a hole drilled in the bridge deck between the wheel paths. The surface of the sensor is flush with the surface of the bridge. Each installation consists of three sensors that are placed about 8 in. (20.3 cm) apart.

When the presence of frost or ice or snow is tested for, one of the three detectors is activated each 30 min. During the sampling period, the stainless steel plate is heated at a definite rate. The resulting change in temperature is detached by the themocouple. Since there is a 90-min interval between successive heat applications to an individual sensor, there is adequate time for possible frost or ice formation.

The electronics package for each installation contains the necessary circuits to provide a programmed heating rate and detection of the resulting temperature change by the thermocouple. The temperature change with reference to time is electronically double differentiated. The signal then is fed to a detector circuit that is capable of distinguishing a signal that is indicative of frost, ice, or snow melting on the surface of the sensor.

TESTING OF IOWA SYSTEM

There are several methods whereby frost and ice detection equipment may be coupled with warning devices to alert motorists of dangerous bridge deck surfaces. Perhaps the most common method is use of an illuminated sign at some approach distance from the end of the bridge.

During the Iowa investigation, it was concluded that it would be impractical to equip many highway bridges with frost and ice detectors and that it would be preferable for the highway agency to take some positive action to alleviate the condition rather than to merely warn the motorist that the danger exists. When frost and ice form, the Iowa system is to be used to alter local maintenance personnel, who will immediately apply salt and abrasives as required.

Arrangements were made with maintenance department personnel to evaluate the operation of five detectors during the 1971-72 winter. Special forms were completed each time an alarm was received and each time maintenance personnel observed an icy condition that did not produce an alarm. All alarm conditions were verified by actual observations.

Each unit was tied into the radio system operated by the Iowa State Highway Commission. All alarms generated by the frost and ice detectors were relayed by the radio system as a distinctive beeping tone obtained by modulation of the transmitter. Receivers were installed in the homes of the maintenance foremen responsible for the test locations. During normal working hours, frost or ice alarms were monitored at the maintenance garages and in local maintenance vehicles equipped with two-way radios. Alarms were sounded by the unit in the maintenance foreman's home at all other times.

Data from the five installations for a 4-month period are as follows:

Condition	Genuine Alarms	Alarm Failures
Snow	30	3
Ice	19	3
Frost	8	1
Total	57	7

Nine false alarms were received during the 4-month period.

Attempts were made to immediately identify the causes of alarm failures and of false alarms. These investigations resulted in a few minor adjustments in the electronic systems. For example, the reliability of two of the units was improved by a slight modification of the heating circuit. The effect of these minor adjustments was evident during the testing.

An important purpose of the frost and ice detecting system is to provide a warning of frost or ice on a bridge deck at times when adjacent pavement may be free of frost or ice. Because of this, it was deemed necessary to achieve a high degree of sensitivity in the detecting system. Unfortunately, this sensitivity is such that the sensors may be overpowered by rapidly forming deposits of wet snow or freezing rain and sleet. It was determined that three of the seven alarm failures occurred under such conditions.

CONCLUSIONS

The Iowa frost and ice detection system will reliably report thin layers of frozen water; therefore, its reliability is best for frost, fresh snow, and light freezing rain. Packed snow and rain mixed with snow are not detected with the same degree of reliability. Frost is detected when it is barely discernible on the pavement surface.

The five units that were in operation during the winter of 1971-72 had a total reliability of 78 percent [(57×100)/(57+9+7)]. Analysis of the failures and false alarms of the individual units suggests that reliability is greatly influenced by the quality of the electronic components. The most dependable unit contains high-grade components throughout. These, alone, cost about $900. Modification had been made in the electronic design of the other four units to permit a cost reduction of about $500 per unit. Development efforts are currently being directed to obtaining both operational reliability and economical design.

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

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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.

	Class 1[a]		Class 2[b]		Class 3[c]		
Area	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.

[b] Commercial.

[c] Critical.

[d] ASHRAE calculations are not available; no information on class of installation.

[e] Calculated; includes adjustment for loss of ground heat.

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:

$$\frac{dQ}{dt} = h_c A \Delta T \tag{1}$$

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 Δ T 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.

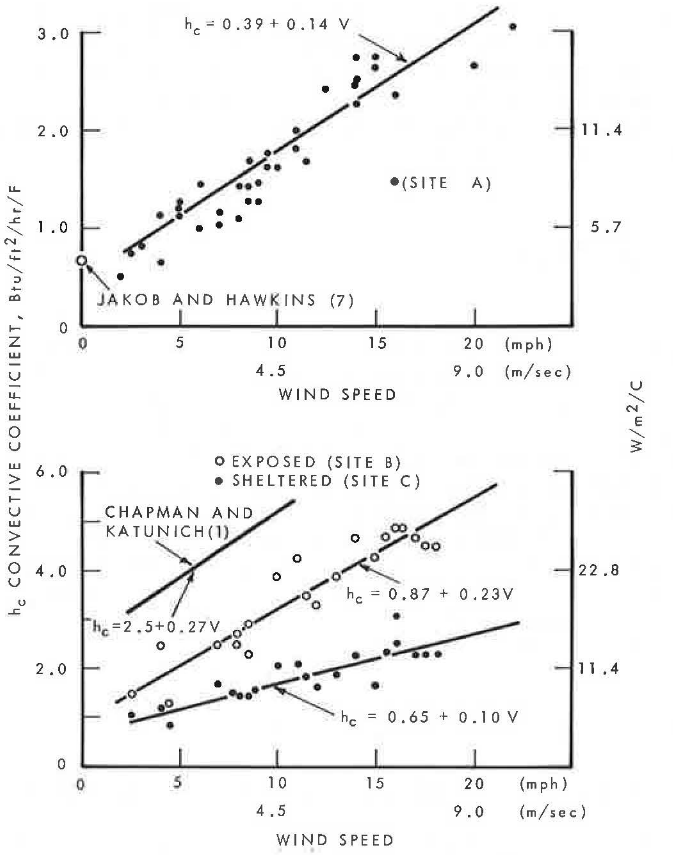


Figure 3. Long-wave radiative coefficient versus change in temperature.

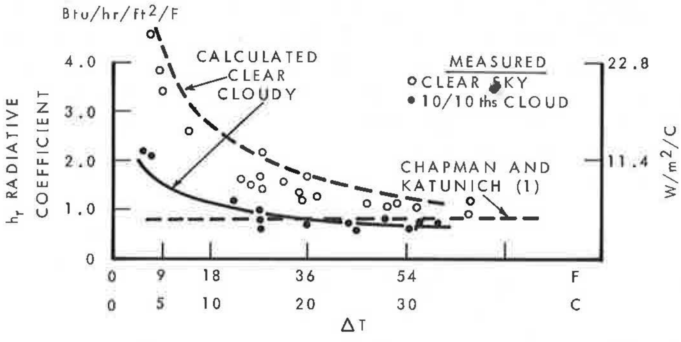
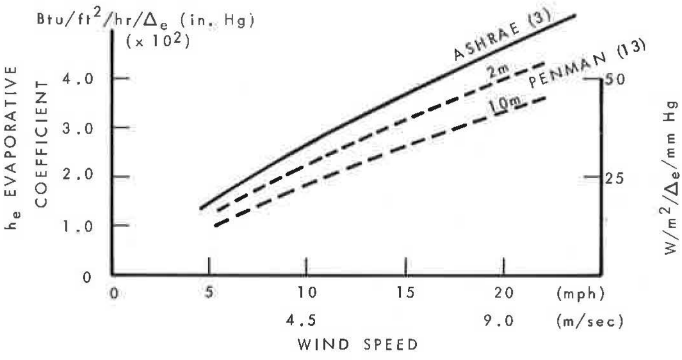


Figure 4. Evaporative coefficient versus wind speed.



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.,

$$\frac{Q_c}{Q_e} = R\,\frac{\Delta T}{\Delta e} \tag{6}$$

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.

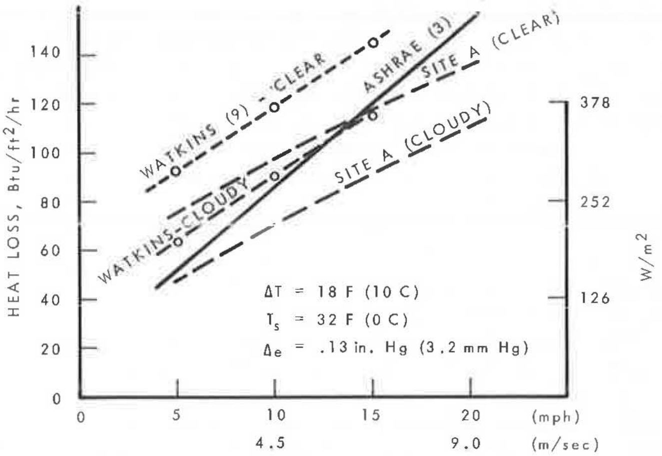
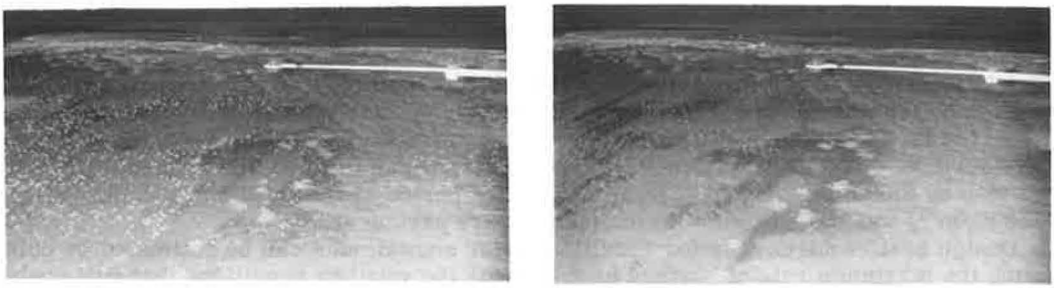


Figure 6. Conditions after snowstorm.

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.

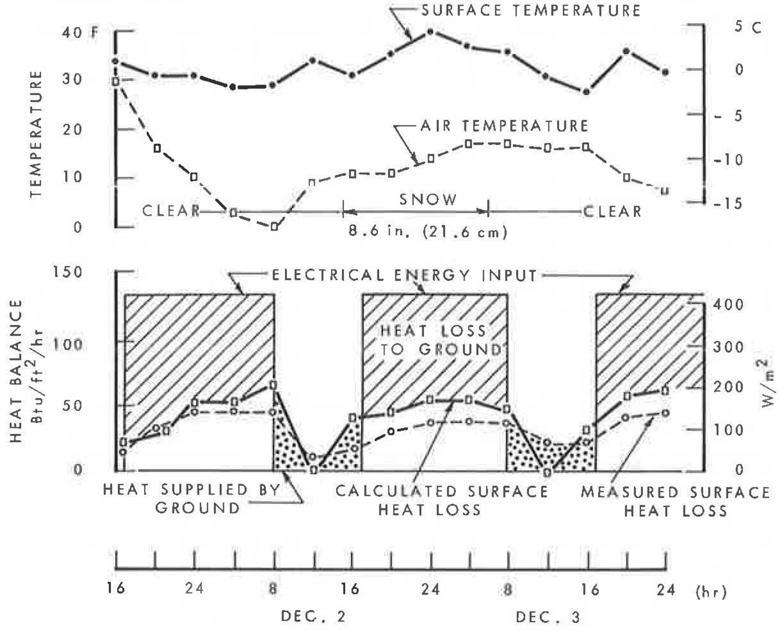
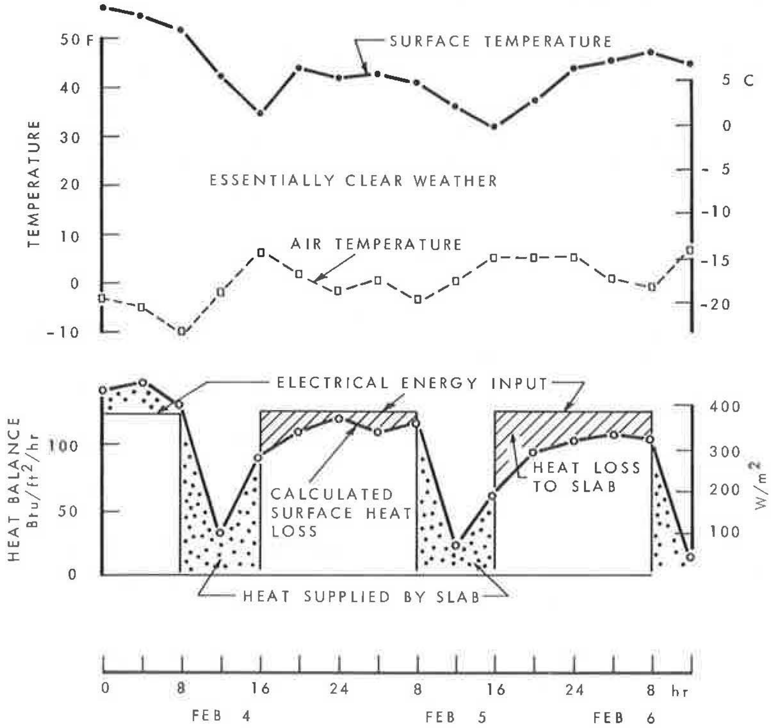


Figure 8. Estimated ground heat loss for insulated snow-melting system, site A.



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.

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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.

BEHAVIOR OF FERROCYANIDE AND CYANIDE IN RELATION TO DEICING SALT RUNOFF

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ABRIDGMENT

•IN RUNOFF from highway deicing salt, sodium ferrocyanide is partially decomposed by sunlight, and cyanide ion is liberated. Sunlight causes partial decomposition of sodium ferrocyanide, in runoff from highway deicing salt, and the liberation of cyanide ion. Rate of ferrocyanide breakdown depends on incident solar energy, ferrocyanide concentration, and water depth and clarity. In shallow solutions exposed to direct sunlight, ferrocyanide breakdown is rapid, but cyanide escape from solution is also accelerated; in deeper solutions, ferrocyanide breakdown to release cyanide is slowed by light reflection and by water turbidity. When generated, cyanide is transferred into the atmosphere as hydrogen cyanide gas at a rate accelerated by wind, water turbulence, and higher water temperature. Present levels of ferrocyanide treatment of highway deicing salt do not appear to present imminent dangers of fish mortality or of atmospheric pollution.

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