

Effect of Bridge Deck Insulation on Icing Conditions

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The effectiveness of urethane foam sprayed on the underside of bridge decks as insulation to reduce icing was evaluated. A tri-level interchange in Rochester, N. Y., was selected for the experimental installation. Surface temperatures of the upper and lower decks and the approach pavements were measured continuously before and after application of the urethane foam. Supplementary information included precipitation records, visual observations of icing, traffic studies, and an examination of a previously insulated bridge.

The uninsulated decks were only slightly more susceptible to icing than the approaches. Moreover, the temperature-stabilizing effect of the urethane increased the potential for icing during most of the winter. Evidence that the insulation had trapped water suggested that the concrete deck and structural steel could be adversely affected. The only benefit derived from the insulation was a significant reduction of freeze-thaw cycles. This is considered to be secondary, compared to the effect on the potential for icing. Further use of insulation should be discontinued and the insulation should be removed from the experimental bridges.

•DURING THE WINTER, the decks of highway bridges sometimes become coated with ice quicker and more often than their approach pavements. This can be explained by the fundamental principles of heat exchange. Since a bridge deck is a relatively thin body with exposed surfaces, it gives up heat readily when the temperature of the surrounding air declines. In contrast, an approach slab is usually supported by an earth embankment which can supply large quantities of heat. During a given interval of time, therefore, a decline in air temperature has less effect on lowering the temperature of the approach pavement. In some instances, the air completes a freezing cycle so rapidly that the deck freezes and then thaws while the approach slab remains wet.

Icing of bridge decks creates several problems, the most serious of which is the safety hazard which the unsuspecting motorist faces when driving from a wet approach pavement to an icy bridge surface. Another consideration is the deterioration of concrete bridge decks resulting from repeated cycles of freezing and thawing. Although these undesirable conditions cannot be eliminated, it seems reasonable to expect a marked improvement by creating more nearly the same temperature environment in bridge decks that exist in approach pavements.

BACKGROUND AND SCOPE

Various methods have been attempted to alleviate icing of bridge decks and its attendant problems. Some states, notably Texas and New Jersey, have experimented with electrically heated cables embedded in the deck. However, the high operating cost of such installations prohibits their use on a large scale. A more recent method

makes use of electrical snow and ice detecting sensors which are mounted in the surface of the pavement and activate warning signs. The success of this system depends on how closely the anticipated temperature, humidity, and salt concentration, which must be preset on automatic switching devices, agree with actual conditions corresponding to the formation of ice.

A unique approach to the problem was suggested to the New York State Department of Public Works in 1960 by Allied Chemical Corp. The use of a synthetic resin on the underside of a bridge deck was suggested as a means of creating the same insulating effect that exists beneath approach pavements. Accordingly, a thermosetting resin, commonly known as urethane foam, was sprayed on portions of the underside of a grade separation on I-81 in Watertown, N. Y. Short-term temperature measurements and periodic observations made by the Department's Bridge Subdivision during the winter of 1960 indicated that icing was significantly reduced by the insulation.

Encouraged by the results of this limited experiment, which was not sufficiently elaborate to detect subtle temperature differences, the Department scheduled a contract in the spring of 1962 for insulating two bridge decks of a tri-level interchange in Rochester, N. Y. The Bureau of Physical Research was requested to assist the Bridge Subdivision with the investigation. The details of the installation and evaluation of the urethane foam are the subject of this report.

Essentially, the investigation consisted of measuring temperatures in the decks and approach pavements of the test bridges with and without insulation. Thermocouples connected to an automatic recorder provided continuous temperature measurements throughout a 2-year testing period. These data were augmented by periodic observations of icing conditions, traffic counts, and information on winter maintenance practices regarding the use of deicing salts.

INVESTIGATION

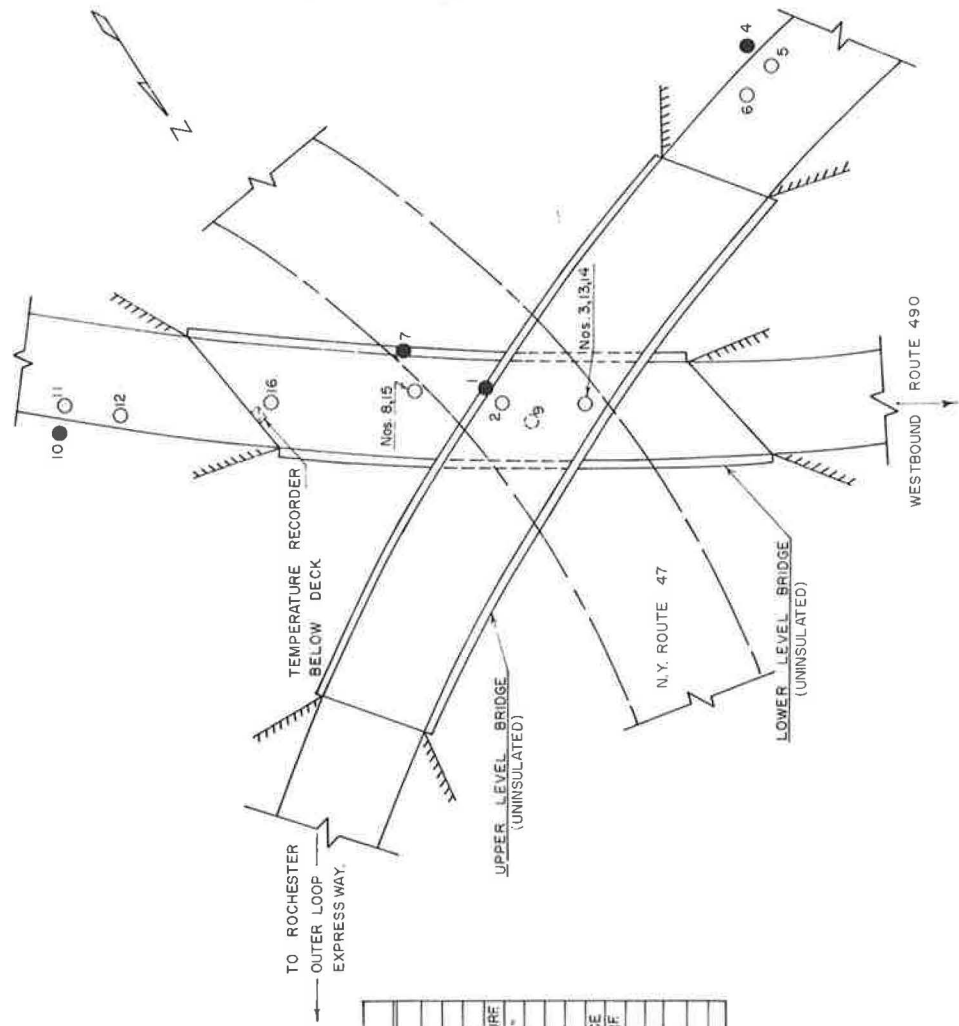
Project Description

The experimental bridges are situated in the southeastern section of Rochester near the city line. The two structures form part of a three-level interchange at the intersection of the Outer Loop Expressway, I-490, and N. Y. 47 (Figs. 1 and 3). An adjacent railroad overpass (Fig. 2) was used as a control structure after the test bridges were insulated.

During the winter, the daily average temperature of the Rochester area varies between the narrow limits of 15 and 45 F, primarily because of nearby Lake Ontario. This temperature range is conducive to repeated cycles of freezing and thawing. Another effect of the lake is to create cloudiness and precipitation, especially during cold weather, in the form of light but frequent snowfalls. These conditions necessitate a well-organized winter maintenance program for highways and bridges, including frequent applications of deicing chemicals.

Instrumentation

Sixteen thermocouples were installed on the uninsulated test bridges and at other locations shown on Figure 1. Later, when the decks were insulated, three of the thermocouples were removed and placed in the adjacent uninsulated railroad overpass (Fig. 2). The thermocouples consisted of 24-gage nylon-coated copper-constantan wire installed in $\frac{1}{2}$ -in. diameter holes in the decks and approach pavements. The holes were drilled completely through the decks, and the thermocouples were inserted from the underside (Fig. 4). This facilitated filling the annular space with an epoxy grout. (Laboratory tests of the epoxy grout and ordinary cement mortar showed no significant difference in heat transfer characteristics.) The leads were conducted along the underside of the decks and secured to the concrete with metal fasteners. The only exception to this procedure was the installation of the thermocouple for the uninsulated control deck. Because of the railroad's restrictions concerning the suspension of wire over the tracks, this thermocouple was installed through the top of the deck. Holes were drilled to a depth of 1 in. in the approach pavements and deck, and the thermocouples were installed from the top. The leads were conducted to the pavement's edge in saw



THERMOCOUPLES

LOCATION	
N.O.	
1	AIR TEMP. AT HANDRAIL OF UPPER BRIDGE
2	CONCRETE TEMP AT 1-INCH BELOW UPPER DECK SURFACE
3	" " " " " " " " " " " "
4	AIR TEMP AT 4 FEET ABOVE UPPER APPROACH SURFACE
5	CONCRETE TEMP AT 1-INCH BELOW UPPER APPROACH SURF
6	" " " " " " " " " " " "
7	AIR TEMP AT HANDRAIL OF LOWER BRIDGE
8	CONCRETE TEMP AT 1-INCH BELOW LOWER DECK SURFACE
9	" " " " " " " " " " " "
10	AIR TEMP AT 4 FEET ABOVE LOWER APPROACH SURFACE
11	CONCRETE TEMP AT 1-INCH BELOW LOWER APPROACH SURF
12	" " " " " " " " " " " "
13	CONCRETE TEMP AT MIDDLE OF UPPER DECK
14	AIR TEMP 1-INCH BELOW UPPER DECK
15	AIR TEMP 1-INCH BELOW LOWER DECK
16	TEMPERATURE AT RECORDER

Figure 1. Location of thermocouples (1961-1962).

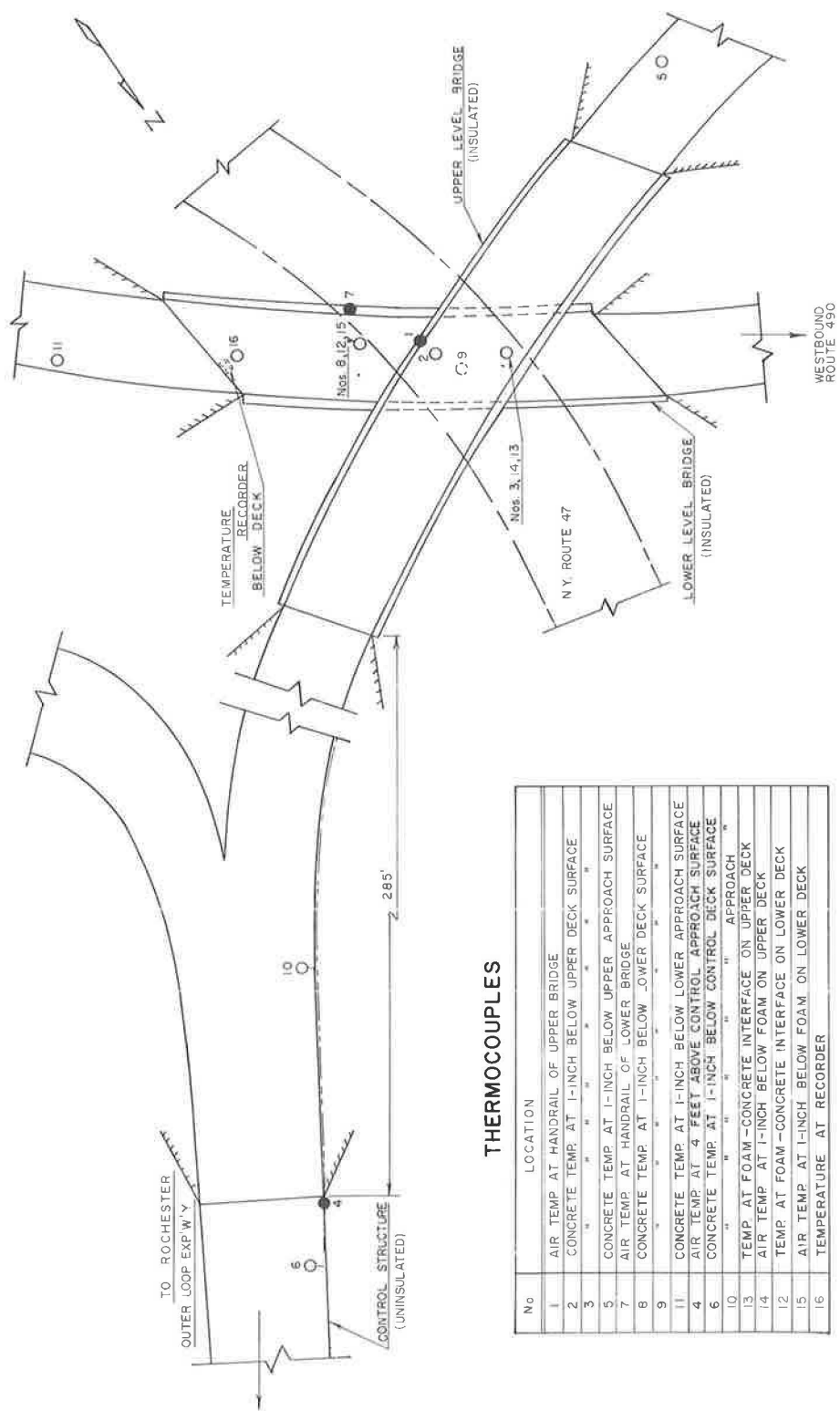


Figure 2. Location of thermocouples (1962-1963).



Figure 3. Experimental bridges (uninsulated), looking north, May 1962.

cuts, $\frac{1}{2}$ in. deep by $\frac{1}{8}$ in. wide, which were later filled with epoxy grout. Pipe conduits were employed to protect all portions of the leads carried underground. Thermocouples for measuring ambient air temperatures were located about 4 ft above the pavements on pipe supports in the approach shoulders and on the guide rails along the decks.

A 16-channel automatic recorder completed a full cycle of temperature measurements every 16 min (one channel a minute) and printed the results on a roll of calibrated graph paper. The recorder was protected by an insulated plywood housing mounted on the east abutment headwall of the lower bridge (Fig. 1). The housing was equipped with an electric baseboard heater, thermostat, and electric light.

Urethane Foam Insulation

Materials. --Urethane foam is a thermosetting plastic produced by the reaction of two organic materials, an isocyanate and a polyol. The isocyanate (usually toluene diisocyanate) supplies the extremely reactive radical $[N=C=O]$ which is characteristic

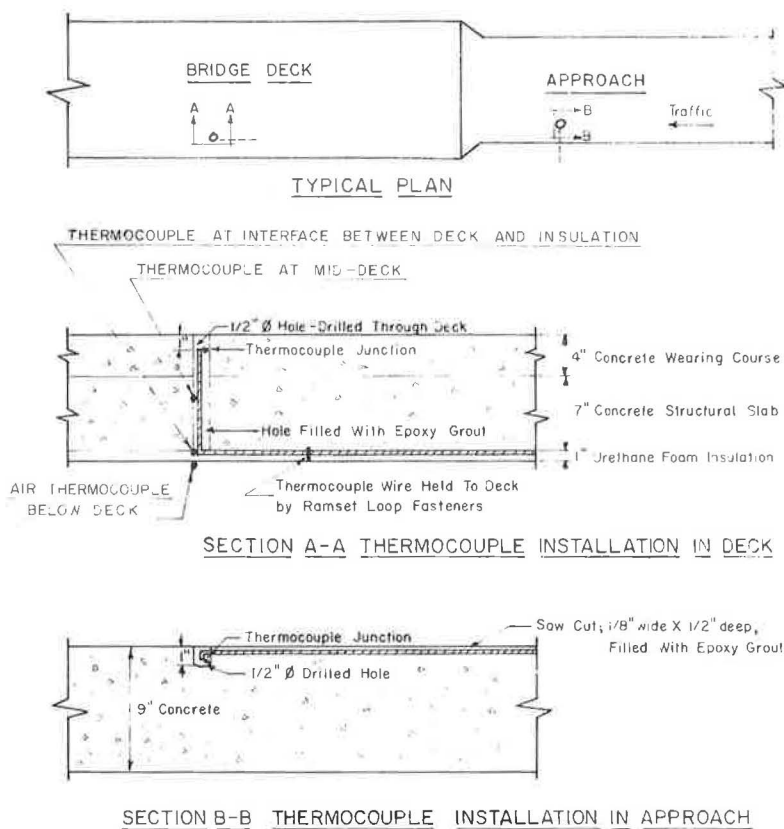


Figure 4. Typical thermocouple installations.



Figure 5. Mobile unit for preparing and applying urethane foam.



Figure 6. Underside of upper bridge deck, partially insulated (light areas).

of a urethane plastic. The polyol, for example a polyester or polyglycol, contributes the [OH] radical necessary to complete the molecular structure of urethane.

The reaction of these components is assisted by the addition of a premix which contains a catalyst, liquid foaming agent, filler, plasticizer, fire retardant and colorant as required. The heat generated by the chemical reaction transforms the foaming agent into a gas which expands and creates a cellular structure. For the most part, the cells consist of disconnected voids which retain the gas indefinitely, thus accounting for the low thermal conductivity of urethane foam. The stiffness of the solidified material can be varied between wide limits (flexible to rigid) by controlling the amounts and types of the primary constituents.

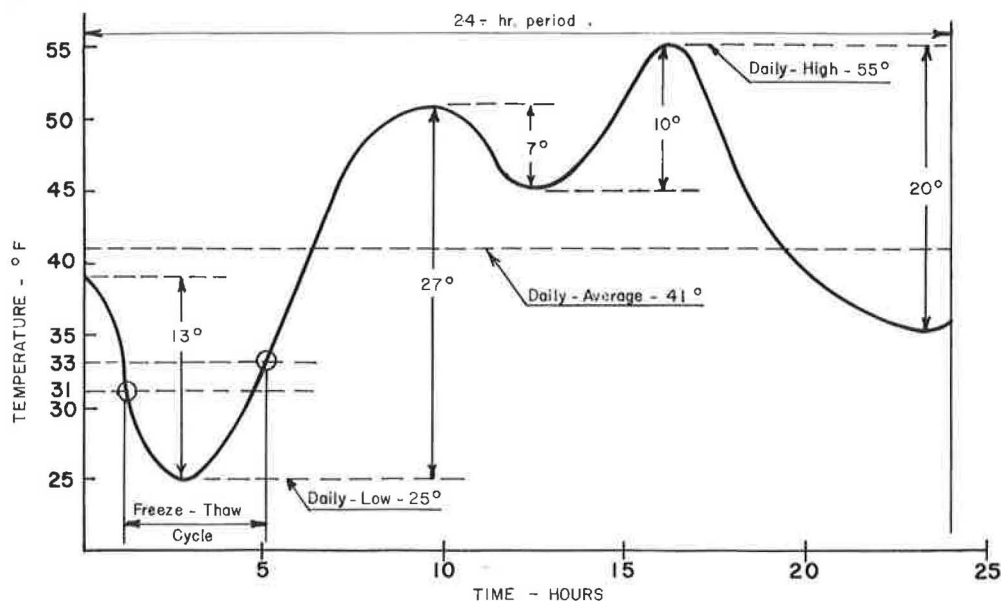
The urethane foam used in this investigation was developed by Allied Chemical Corp. specifically for bridge deck insulation. The formulation consisted of an isocyanate known commercially as Nacconate 4040, and a polyester resin type of polyol. Genetron was used as the foaming agent, which, together with a fire retardant and other ingredients in the premix, produced a rigid type of foam having the following properties:

1. Low density, approximately 2 pcf;
2. Low thermal conductivity, a maximum of 0.16 BTU-ft/hr-sq ft-°F;
3. Excellent adhesion to concrete and steel;
4. Essentially impervious to water; and
5. Resistant to deicing salts and other chemicals.

Application. — Urethane foam was applied to the underside of both bridge decks of the interchange. Operations commenced on May 17, 1962, but were not completed until July 17, 1962, because of malfunctioning of equipment, inclement weather, and delays in material shipments. The insulation was sprayed from a hydraulically operated lift mounted on a truck outfitted with an AC motor generator, air compressor, mixer, and other equipment necessary to precondition and apply the materials (Fig. 5).

When the materials reached the mixing chamber of the spray gun through separate electrically heated hoses, they were combined in the ratio of one part by weight isocyanate at 100 F to 1.33 parts polyester resin at 75 F, and atomized. Concrete and steel surface temperatures at the time of treatment varied from about 51 to 89 F, with an average of 70 F. Initially, the hardened foam was white, but later the surface oxidized to light brown.

The specified thickness of insulation was $\frac{3}{4}$ in. for all exposed concrete and the top flange of steel stringers, tapering to $\frac{1}{4}$ in. at about the midpoint of the web. It was further specified that the foam be applied in three separate layers of $\frac{1}{4}$ in. each.



Notes -

(a) Total temperature change for 24 hrs. = $13 + 27 + 7 + 10 + 20 = 77^{\circ}$.

(b) Daily average temperature is based on hourly readings.

Figure 7. Illustrative temperature pattern.

However, since the contractor had experienced difficulties with this method on a previous installation, the foam was applied in one operation. Moreover, to insure maximum continuity from concrete to steel, the contractor elected to coat the entire web of all beams (Fig. 6). The final thickness of insulation was nearer $1\frac{1}{4}$ in. than $\frac{3}{4}$ in.

The insulation at several locations failed to adhere properly when initially applied to the steel and concrete. This was very likely due to surface moisture which reacted with the unsolidified foam and created a gas which prevented a satisfactory bond. Another possible cause was that the critical ratio of polyester resin to isocyanate was not maintained. All areas where the foam failed to adhere properly or was less than $\frac{3}{4}$ in. thick were stripped and resprayed. These areas totaled about 1,000 sq ft (3 percent of the area insulated).

A year after application, the insulation was found to be in excellent condition. A few small areas on the webs of the beams in the end spans of the upper bridge exhibited slight peeling within the insulation. However, in no case did it extend entirely through the foam to the steel.

RESULTS AND DISCUSSION

Winter of 1961-62 (Uninsulated Condition)

The uninsulated bridges were instrumented in December 1961, and a power line for the equipment was installed early in 1962. Temperatures were recorded from Feb. 2, 1962, to April 18, 1962, except for a brief time in March. During the testing period, the decks and approach pavements were often covered with snow because the interchange remained closed to traffic until the spring of 1962. Therefore, the data do not strictly represent temperatures in an uninsulated deck and approach pavements under usual winter conditions. However, the results are valid with regard to relative temperature

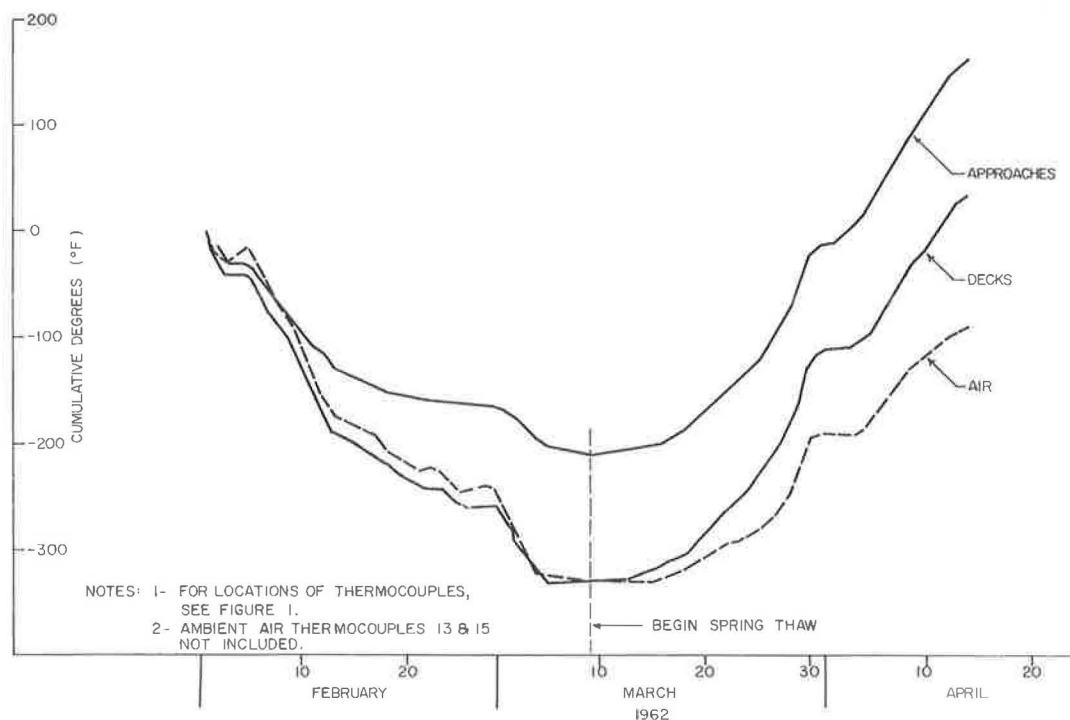


Figure 8. Cumulative degrees above and below 32 F, Feb. 2 through April 14, 1962, uninsulated condition.

differences and general temperature patterns. Unless otherwise noted, the information represents combined hourly averages of the thermocouples in each element, i. e., decks, approaches, and air. In this connection, all references to the lower deck are based on a single thermocouple, No. 8 in Figure 1. The results of thermocouple No. 9 were excluded since it was continually shaded by the upper deck and could not be compared with the exposed thermocouples.

At the outset, it was necessary to establish a reasonable method of interpreting the recorded data with regard to identifying freezing and thawing. Since the investigation mainly concerns icing conditions, criteria were selected which are based on the temperature of water at which freezing or thawing is incipient (32 F). Field observations indicated that a margin of ± 1 F would allow for temperature changes which occur during the transformation of water and ice. Accordingly, for this investigation, freezing or thawing is assumed to have occurred when the temperature has fallen below 31 F or risen above 33 F, respectively. These conditions are illustrated in Figure 7, together with other criteria which are discussed later.

Cumulative Temperature Changes.—The technique of analyzing temperature data by a cumulative process is useful for demonstrating overall trends. This concept has been used by the U. S. Corps of Engineers for many years to establish a quantitative measure of frost penetration. The difference between a reference temperature, usually 32 F, and the daily average temperature is computed for each day of the period studied. The difference is considered minus when the daily temperature is below 32 F and plus when the temperature is above. By plotting the algebraic cumulative differences for an entire winter, a characteristic sine curve is created having a maximum positive value at the beginning of the period and a maximum negative value at the end. The difference between these peak values is used as an index of freezing.

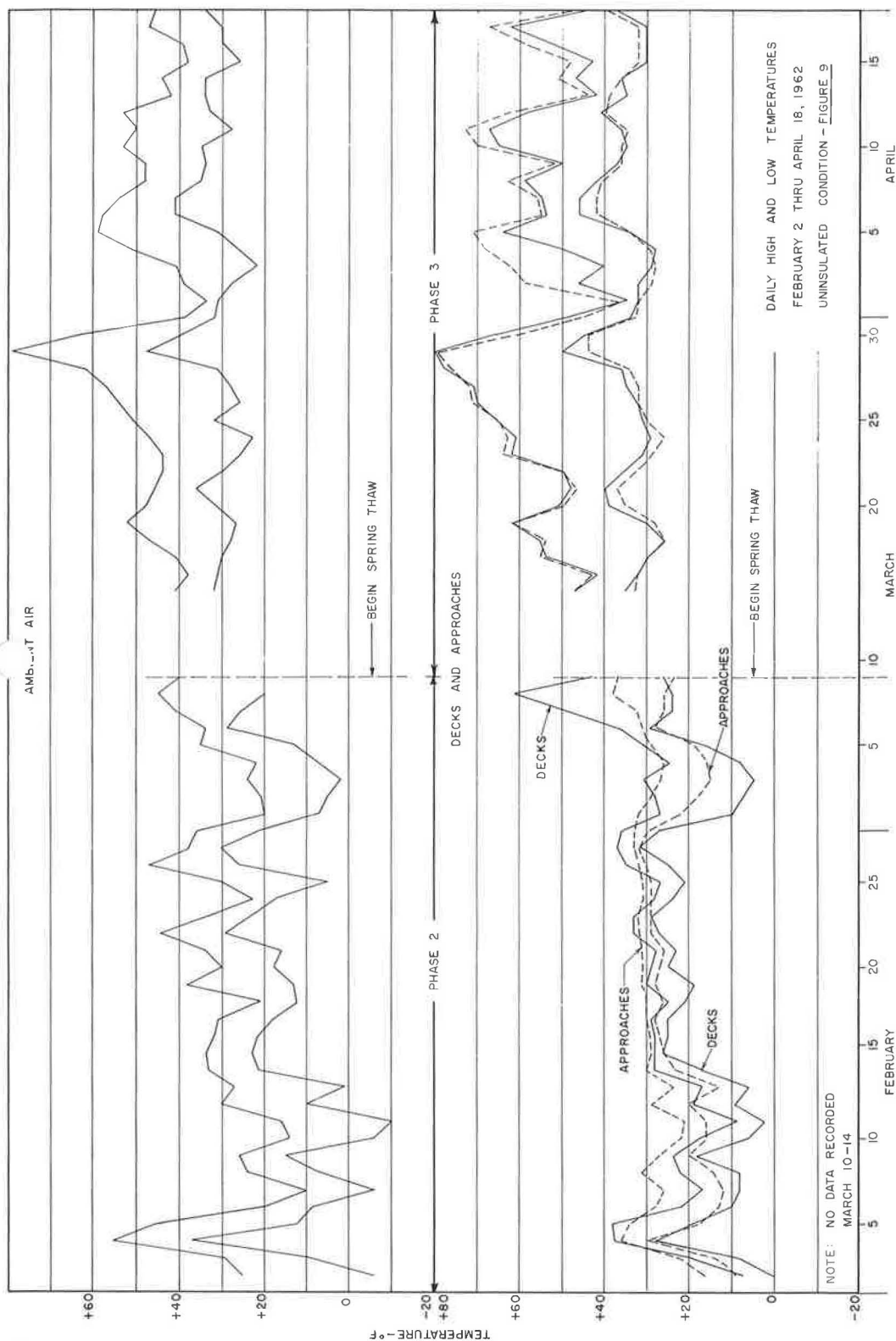


Figure 9. Daily high and low temperatures, Feb. 2 through April 18, 1962, uninsulated condition.

A similar approach was used in the present study. Figure 8 shows the resulting graphs for the uninsulated decks, approach pavements, and ambient air. In this case, the recording period began when average temperatures were generally below 32 F (Feb. 2, 1962). Consequently, the curves exhibit an initial downward trend which continues until maximum negative values are reached corresponding to the beginning of the spring thaw on about March 9, 1962. Thereafter, they reverse their direction and climb steadily in response to above-freezing mean temperatures, completing the negative portion of the cycle. The fact that the positive half of the cycle is not included does not invalidate the results since any segment of the period can be studied in this manner.

The curves indicate that the uninsulated decks and the ambient air had essentially similar average daily temperatures until the beginning of the spring thaw. During this period, the approaches were consistently warmer, as evidenced by the increasing vertical distance between the curves. This demonstrates the moderating effect of the embankment on pavement temperatures, in contrast to the uninsulated decks which mirrored the rises and falls of the air temperature. When the thaw began, however, the deck temperature rose to and then paralleled that of the approaches for the remainder of the recorded period. For this experimental installation, therefore, it is apparent that insulating the decks would have had no beneficial effect on equalizing average temperatures after the beginning of the thaw.

Although the cumulative average temperature curves effectively illustrate general temperature trends, they do not describe the various patterns which occur during the winter. Moreover, they mask the daily fluctuations associated with freeze-thaw cycles. These important considerations are discussed separately.

Temperature Patterns.—The two generalized periods are further distinguished by different temperature patterns. To establish continuity with the comparable conditions of the second winter (insulated condition), the periods represented are identified as Phases 2 and 3.

Phase 2 (Feb. 2 to March 9, 1962).—During this 36-day period, below-freezing temperatures prevailed. The structures were covered with several inches of snow most of the time, which moderated the effect of the sun on deck and approach temperatures. Consequently, a more stable temperature condition existed than would occur under traffic. This is illustrated in Figure 9 which depicts daily high and low temperatures for the entire recorded period.

The characteristics of the temperature patterns in the approaches, uninsulated decks, and ambient air typical of this phase are shown in Figure 10a for a 4-day period in February 1962. The greater uniformity and generally higher temperatures of the approaches, compared with the decks and the air, are clearly evident. Throughout the recorded period, the variations in deck temperatures were often sufficient to produce a complete freeze-thaw cycle while the approaches remained essentially frozen. As a result, the decks completed 12 freeze-thaw cycles, compared with 6 and 18 for the approaches and air, respectively. Other corroborating comparisons, such as average temperatures and cumulative daily temperature changes (Fig. 7), can be made. However, because of the effects of the snow cover, the numerical values have limited significance.

Phase 3 (March 10 to April 18, 1962).—This period represents the transition from winter to spring, with its characteristic mild days and cool nights. Early in the period, the snow cover was completely melted. Consequently, the results are more indicative of the performance of an uninsulated bridge deck. In contrast to the previous period, the approaches and decks exhibited considerably larger temperature fluctuations (Figs. 9 and 10b). In general, both attained higher daily high and low temperatures than the surrounding air because of absorption of heat from the sun. Characteristically, freeze-thaw cycles occurred at relatively short intervals.

Figure 10b illustrates several significant facts typical of this phase. In the absence of a snow cover, the approaches were as sensitive to ambient air temperature changes as the uninsulated decks. This is evidenced by almost identical temperature patterns. In fact, the approaches and decks developed the same average temperature for the period (44 F) and total number of freeze-thaw cycles (14). More important, however,

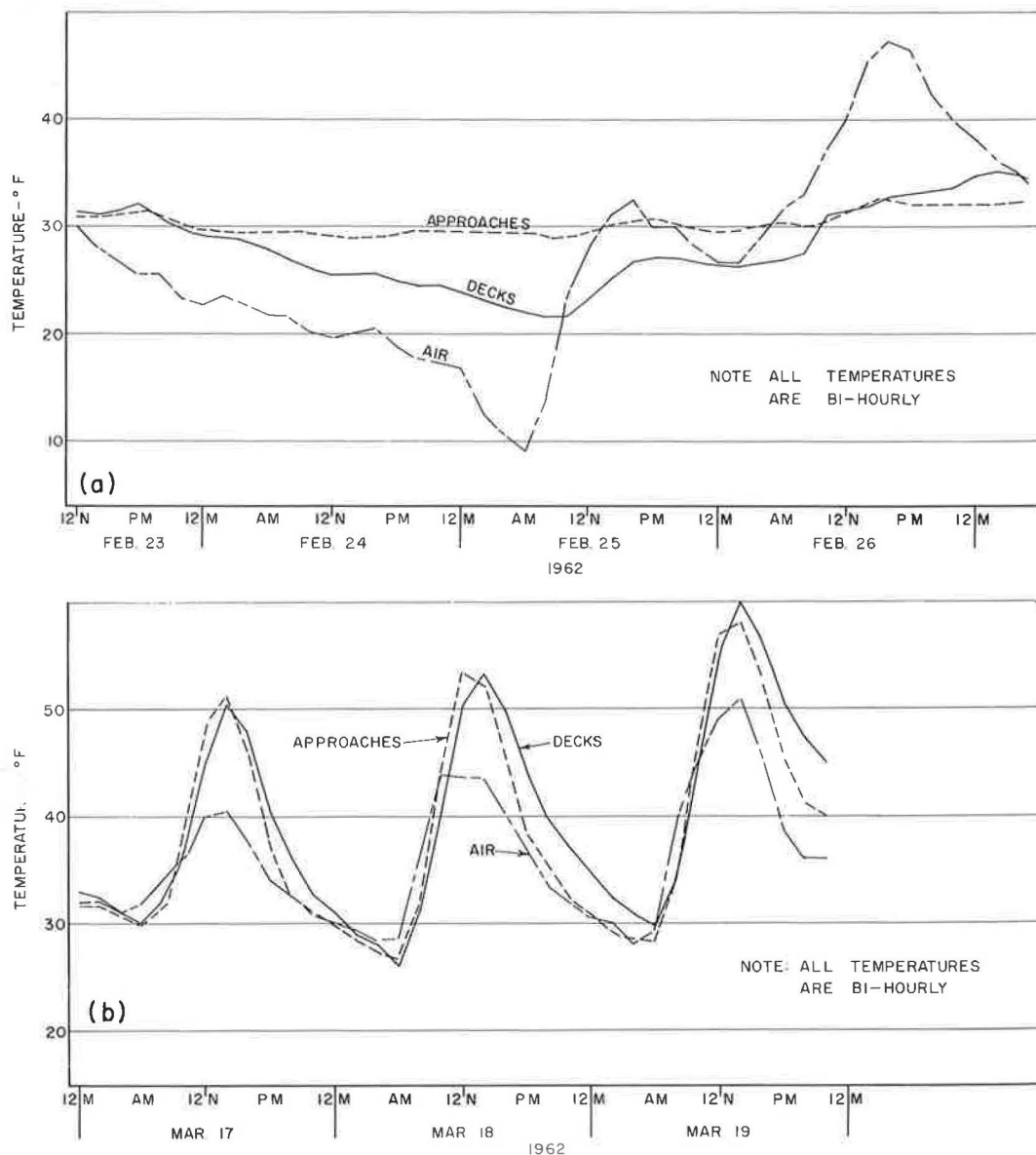


Figure 10. Typical temperature patterns (uninsulated condition): (a) Phase 2, and (b) Phase 3.

the approaches frequently attained below-freezing temperatures at the same time as the decks, or sooner. Therefore, when precipitation accompanied these freezing intervals, it is probable that ice frequently formed on the approaches before or at the same time as it formed on the decks. These findings are contrary to the premise that uninsulated decks always develop ice sooner and more frequently than their approach pavements.

Winter of 1962-63 (Insulated Condition)

Temperatures were recorded continuously from Sept. 13, 1962, to March 24, 1963, except for a brief inoperative period from Nov. 1 to 9, 1962. The thermocouple loca-

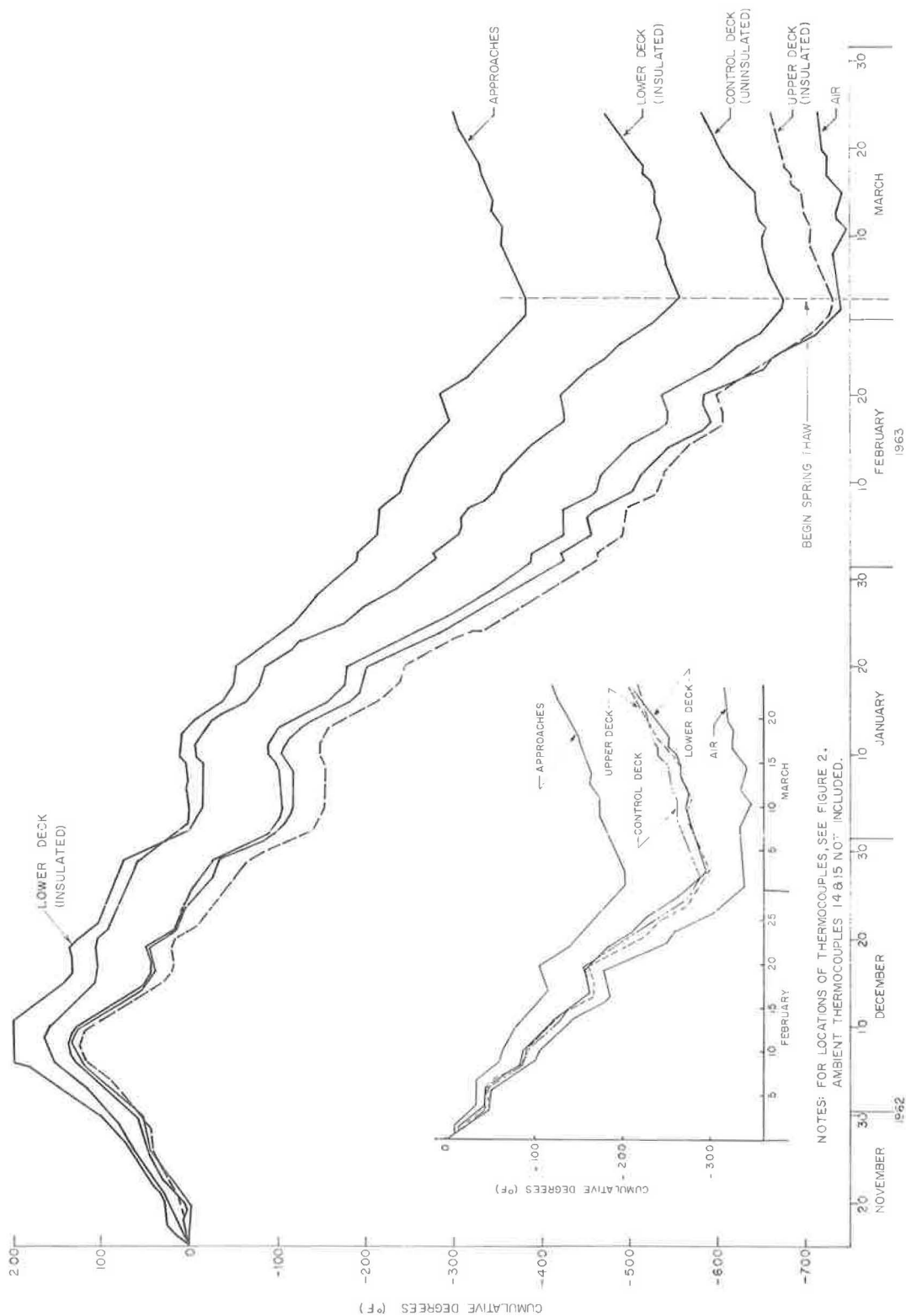
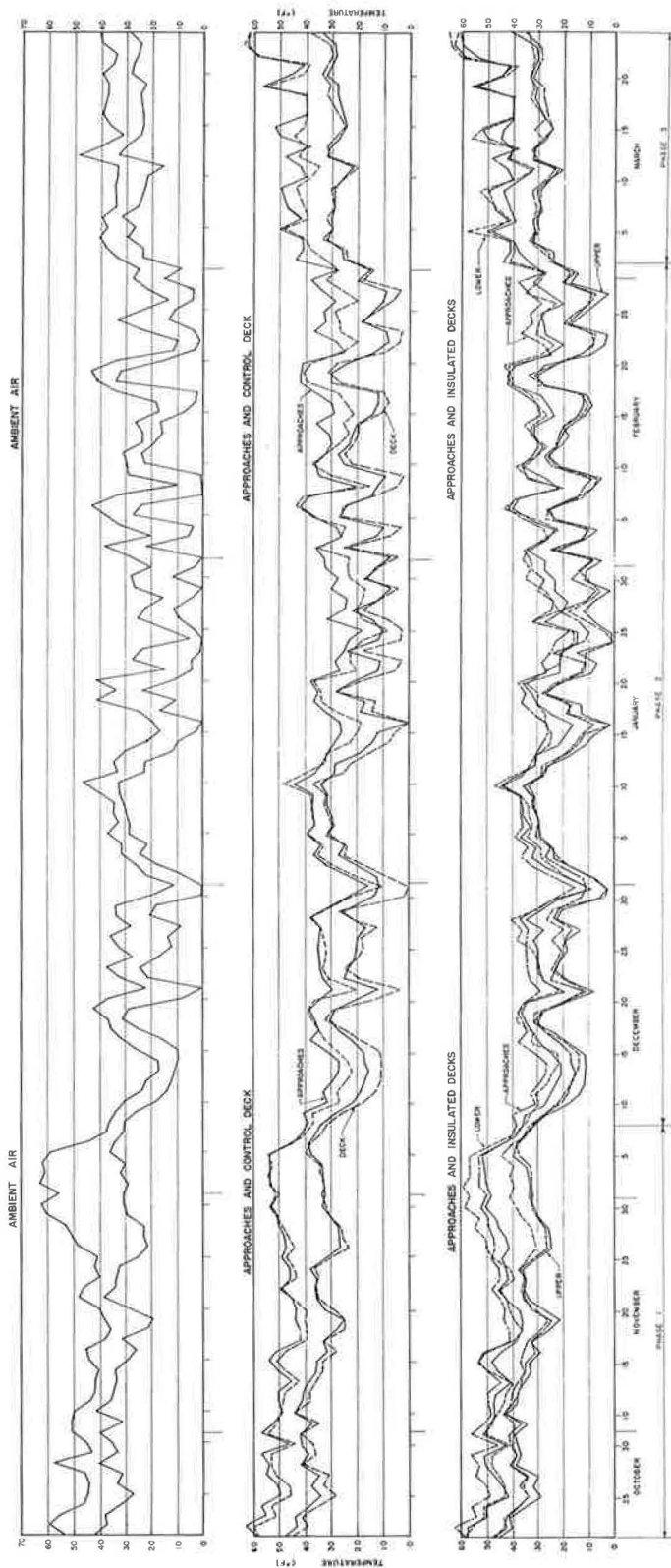


Figure 11. Cumulative degrees above and below 32 F, Nov. 15, 1962, through March 24, 1963 (insulated condition).



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Figure 12. Daily high and low temperatures, Oct. 21, 1962, through March 24, 1963 (insulated condition).

TABLE 1
SUMMARY OF RESULTS, 1962-63

No. of Days Snow & Sleet (Inches) Total Precipitation (Inches of Water)	PHASE 1 OCT. 21 - DEC. 8			PHASE 2 DEC. 9 - MAR. 2			PHASE 3 MAR. 3 - MAR. 24						ENTIRE PERIOD*							
	Upper		Low	Upper		Low	Upper		Low	Upper		Low	Upper		Low	Upper		Low		
	Air	Deck	Cont	Air	Deck	Cont	Air	Deck	Cont	Air	Deck	Cont	Air	Deck	Cont	Air	Deck	Cont		
41	39.3	39.1	41.7	40.1	41.6	21.5	21.8	22.9	22.5	26.1	33.3	36.0	37.4	36.3	37.0	28.2	28.8	30.3	29.5	32.0
6.8	2134	1131	930	1541	1508	2495	1860	1550	2124	2366	540	500	400	480	670	5169	3491	2880	4145	4354
3.66	84.1	86.5	96.2	87.7	92.4	12.4	9.7	11.3	13.4	14.4	60.5	72.6	75.0	69.8	70.6	39.6	40.5	44.5	42.6	44.6
	6.1	6.7	3.5	6.3	4.8	7.9	9.1	9.1	9.6	11.9	12.6	12.6	13.6	14.6	10.1	8.1	9.0	8.2	9.4	9.7
	9.8	6.8	0.3	6.0	2.8	79.7	81.2	79.6	77.0	73.7	26.9	14.8	11.4	15.6	18.3	52.3	50.5	47.3	47.9	45.6
	11	10	1	10	4	17	10	11	18	23	14	9	7	12	12	42	29	19	40	39
	Freeze-Thaw Cycles																			

* ALL Averages Are Weighted

tions are shown in Figure 2. Consideration had been given to maintaining half of the upper and lower decks uninsulated to serve as the control. However, the possibility of creating a hazardous differential icing condition made this arrangement inadvisable. Instead, the nearby uninsulated railroad overpass was instrumented.

Electronic data processing was used to analyze the large volume of data. This made it feasible to use all the temperature readings to compute average parameters. However, the results are plotted in the accompanying illustrations only for the periods discussed. It is noted again that all references to the lower insulated deck are based on a single thermocouple, No. 8 in Figure 2, since thermocouple No. 9 was shaded all of the time.

Cumulative Temperature Changes. — Figure 11 depicts cumulative temperatures of the insulated decks, uninsulated control deck, approaches, and ambient air for the entire winter and subsequent thaw. The characteristic sine curves described in connection with the previous season (Fig. 8) are clearly evident in this case. The downward trend signifying the start of winter began about Dec. 9, 1962 and ended with the spring thaw on March 2, 1963. With few exceptions, all the curves descend progressively farther below the approach curve, again demonstrating the moderating effect of the embankments.

From the relative positions of the bridge deck graphs, it appears that the upper insulated deck was consistently colder than the lower deck and control structure. This would conflict with the results of the previous season, for which the temperatures of the two uninsulated decks were so similar that they were averaged for Figure 8. To permit a direct comparison with the first winter, the corresponding period on Figure 11 has been reproduced in the inset. This shows that from the beginning of February, the three decks maintained essentially the same temperatures. Moreover, the temperature patterns for the two seasons are nearly similar, except for a slight displacement of the spring thaw. It is apparent, therefore, that the urethane foam has been unsuccessful in maintaining the temperature levels of the approach pavements during much of the winter.

A closer look at Figure 11 shows that

the similarity of the three decks extends back to early January 1963. Consequently, the divergence of the curves at the end of the recorded period in March reflects temperature differences which occurred before January, as evidenced by the gradually increasing vertical distances between the graphs of the three decks. This appears to be associated with the alignment and superelevation of the decks relative to the path of the sun which had more effect on temperatures during November and December 1962. This is discussed in more detail in the following section.

Temperature Patterns.—Details of the temperature variations similar to those discussed for the first season are given below for three successive periods representing the fall, winter, and spring of 1962-63.

Phase 1 (Oct. 21 to Dec. 8, 1962).—This 41-day period consisted mainly of mild days and cool nights. Every year, the latter part of this period is generally associated with early morning frost, as suggested by Figure 12 which shows that daily low temperatures frequently dipped below freezing after Nov. 15.

All concrete maintained essentially the same above-freezing average temperature for the period (Table 1). However, the corresponding daily temperatures exhibited measurable differences. For example, the control deck was almost always a few degrees colder than the approaches. As a result, the control structure experienced a total of ten freeze-thaw cycles compared to only four for the approaches. More significant is the fact that the surface of the control deck was below freezing (31 F) during 6.0 percent of the period, whereas the approaches were frozen only 2.8 percent of the time. These results indicate that during the fall, the uninsulated deck has a greater potential for icing than the approach pavements.

Another important comparison can be made between the control deck and the approaches. Figure 13 represents hourly average temperatures for a typical 48-hr period in Phase 1. On Nov. 18, at approximately 1:30 PM, the control deck and approaches were at essentially the same above-freezing temperature. By 6:00 PM, the ambient air and control deck temperatures had fallen below the 31 F reference temperature. However, the approaches did not freeze until 2 hr later. The following morning, when the approaches attained a thawed condition (33 F) at about 9:30 AM, the deck temperature was 26 F. The next cycle showed an even greater difference in temperature variations. The control deck cooled to a low of 28.5 F on the morning of Nov. 20, 1962, and then thawed in the afternoon. In contrast, the approaches never cooled below 32 F. For the structures under discussion, therefore, the evidence demonstrates that the uninsulated control deck generally reached a frozen condition quicker and more often than the approach pavements, that it maintained below freezing temperatures for longer periods of time, and that it thawed after the approaches. The consequence, in terms of icing, would depend on conditions of humidity and precipitation.

The insulated decks performed markedly differently from each other during most of this phase. In general, the lower insulated deck developed higher daily temperatures than the upper deck (Fig. 12). In fact, the daily low temperatures of the lower deck were very similar to those of the approaches, whereas the upper deck closely followed the control structure. This pattern was not as consistent with the corresponding high temperatures, although a parallel situation did occur occasionally. Significantly, the lower deck maintained virtually the same average temperature as the approaches for this phase, 41.7 F vs 41.6 F (Table 1); it was in a frozen state for less time (0.3 percent vs 2.8 percent); it underwent fewer freeze-thaw cycles (1 vs 4); and similar to the approaches, it froze after and thawed before the control deck (Fig. 13). On all counts, therefore, the lower insulated deck equaled or outperformed the approaches. This was not the case for the upper insulated deck, whose performance was almost identical to the control deck; i.e., average temperature, 39.1 F vs 40.1 F; portion of time below 31 F, 6.8 percent vs 6.0 percent; number of freeze-thaw cycles, 10 vs 10; and sometimes froze before the control deck (Fig. 13).

The differences in recorded temperatures between the two insulated decks deserve further consideration. Traffic counts conducted in January and March 1963 established that from 7 to 9 AM, the lower insulated bridge carried an average of eight times as many vehicles as the upper level and the control deck (3,200 vs 400 veh, approximately).

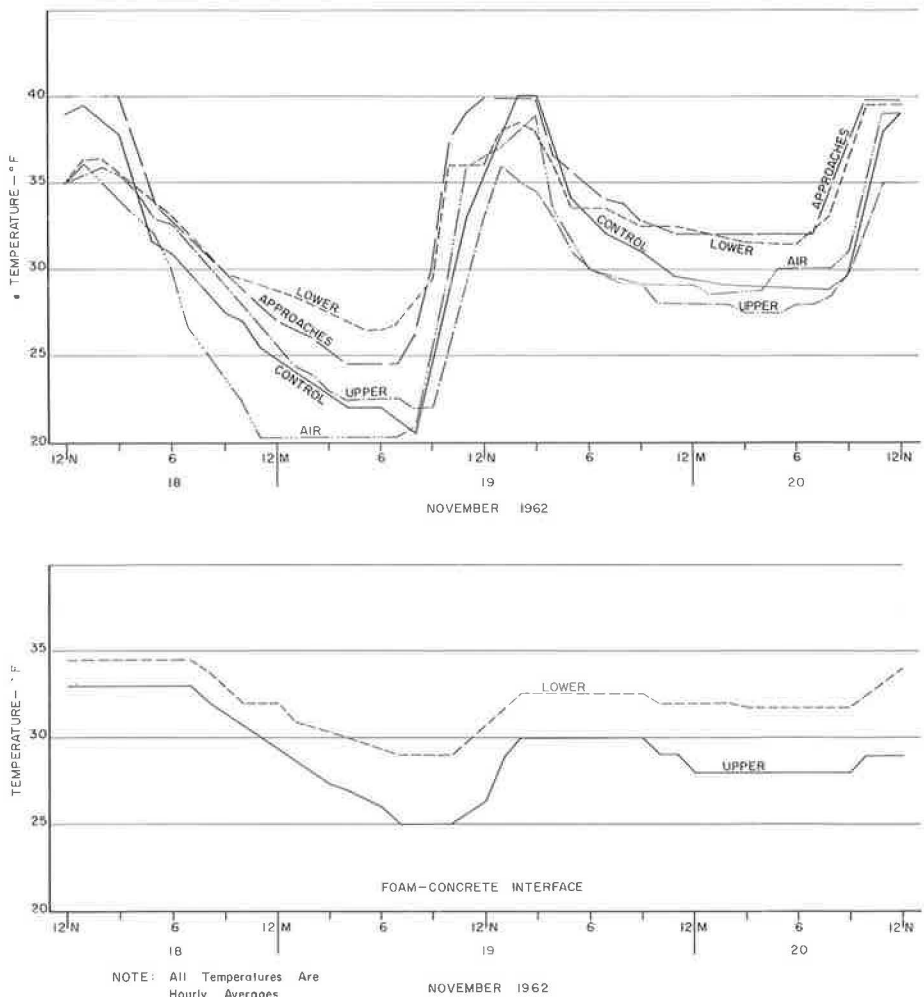


Figure 13. Typical temperature patterns, Phase 1, autumn freeze-thaw cycles (insulated condition).

Corresponding counts for the evening rush hours between 4 and 6 PM, and for 24 hr were 1,150 vs 1,650 and 10,800 vs 5,200, respectively. These data suggested that the generally greater volume of traffic on the lower deck might have raised the deck temperature. However, no correlation could be established. In fact, it was found that the upper deck occasionally attained higher temperatures than the lower level (for example, Nov. 11 and 12 and Jan. 2-9, Fig. 12).

The most logical explanation for the difference in temperatures between the insulated decks is the influence of the sun's radiation. Both decks are located on horizontal curves. The upper deck is superelevated approximately 3° toward the northwest, and the lower deck is superelevated about 5° toward the southwest. Consequently, the lower deck consistently received more solar radiation per unit of area than the upper deck, the amount varying with the time of year and the corresponding declination of the sun. It appears that the difference in the amount of heat absorbed by the two decks was sufficient to produce a measurable difference in deck temperatures. For example, the amount of sunshine, expressed as a percent of the maximum possible for each day, that was recorded at the Rochester airport from Nov. 13 to 21, 1962, inclusive, was 0, 56, 100, 72, 0, 10, 76, 21 and 0 percent, respectively. This agrees

remarkably well with the corresponding portions of the daily high temperature graphs of the insulated decks (Fig. 12) which indicate identical temperatures on Nov. 13, 18, and 21 and a maximum difference on Nov. 15, 16 and 19. Equally good agreement was established for many other similar periods, such as Nov. 25 to Dec. 8, Dec. 10 to 14, and Jan. 21 to Feb. 1, 1963. In every case, the recorded temperature differences were reasonably well verified by a theoretical analysis of the heat absorbed by each deck. Unfortunately, the few instances when the upper deck exceeded the temperature of the lower deck could not be explained. Evidently, other indeterminant factors, such as wind effects and topography, also influence temperature patterns. Nevertheless, this discussion serves to emphasize the fact that the performance of an insulated bridge deck is affected by a number of natural and physical factors which can vary over wide limits among bridge sites.

An interesting characteristic of the insulation is its effect on reducing temperature fluctuations. To represent this quantitatively, the concept of total temperature change was used. Successive peak-to-peak temperature differences which occur each day are added for the entire phase without considering algebraic signs, as illustrated in Figure 7 for a 24-hr period. The result is a cumulative total of the temperature differences, the magnitude of which is a measure of overall sensitivity to temperature variations. Table 1 indicates that the lower and upper insulated decks, with total temperature change values of 930 and 1131 F, respectively, had considerably greater stability than the approaches, control deck, and ambient air. This stabilizing effect of the insulation can produce adverse results during extended periods of below-freezing temperatures, as will be demonstrated in Phase 2.

Phase 2 (Dec. 9, 1962, to March 2, 1963).—Temperatures during this 84-day period were essentially below freezing. The relationship between the uninsulated control deck and the approach pavements which existed during Phase 1 continued throughout this phase; that is, the deck was usually colder than the approaches (Fig. 12). As a result, the average temperature of the deck was 3.6° lower than the approaches, and the deck maintained below-freezing temperatures 77.0 percent of the time, compared to 73.7 percent for the approaches. Because of the depressed temperatures, however, the deck experienced fewer freeze-thaw cycles (18 vs 23 for the approaches). As was the case in Phase 1, these data indicate that the control deck is generally more susceptible to icing than the approaches during the winter months.

With regard to rates of freezing, Figure 14 shows that the control deck attained a freezing temperature (31 F) before the approaches on Jan. 3, 1963, but did not freeze until several hours after the approaches in the following cycle. Similar alternating conditions occurred throughout this phase, some of which were witnessed by field inspectors during periods of precipitation. This behavior is evidently the result of the equalizing effect of the approach embankments, which tend to absorb heat from the approaches after cold periods and to release heat stored during warmer periods. The sequence of thawing was also found to be equally divided.

It will be recalled that significant differences in temperatures were recorded between the insulated structures during Phase 1. In contrast, the performance of both decks was very similar in Phase 2. From the standpoint of potential icing, neither structure performed as well as the control deck or the approaches. For example, the insulated decks were in a frozen state a greater percent of the time (Table 1) and they frequently remained below freezing while the control deck and approaches were thawing (Fig. 14). This is further demonstrated by the smaller values of total temperature change calculated for the upper and lower decks (1860 and 1550 F) compared to the control structure and approaches (2124 and 2366 F). During the winter months, therefore, the stabilizing effect of insulation created a potentially greater hazardous condition than existed on the uninsulated deck.

Phase 3 (March 3 to 24, 1963).—This period represents the annual spring thaw with its attendant rising temperatures (Fig. 12). The decks and pavements were generally unfrozen, although short freeze-thaw cycles associated with warm days and cold nights occurred frequently. It is interesting to note that the control deck and approaches performed essentially the same as the uninsulated structures and approaches during Phase 3 of 1962. Specifically, the control deck and approaches exhibited similar

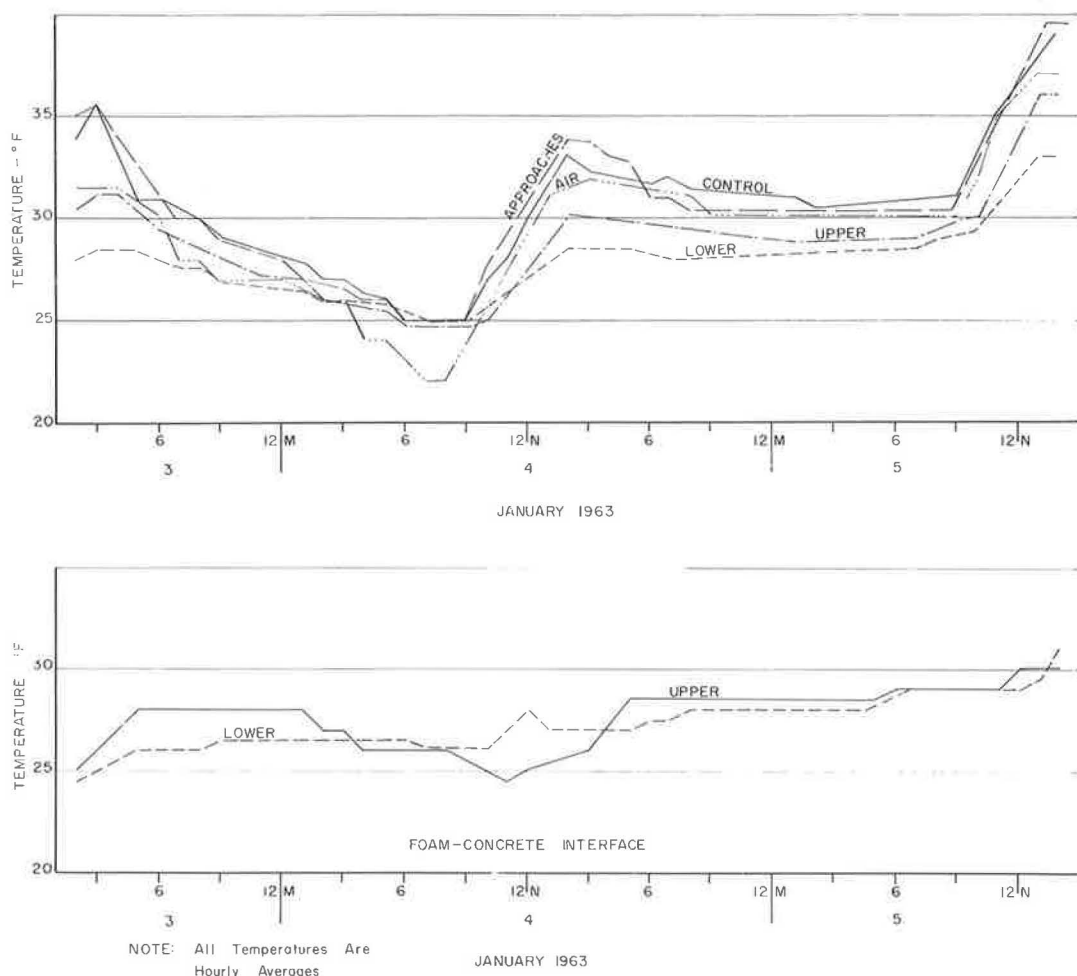


Figure 14. Typical temperature patterns, Phase 2, winter freeze-thaw cycles (insulated condition).

cyclical patterns (Figure 15), maintained almost the same average temperature, and underwent an identical number of freeze-thaw cycles (Table 1). As in the previous year, the approaches frequently attained a frozen condition before the control deck. Significantly, the approaches also maintained below-freezing temperatures a greater percent of the time (18.3 percent vs 15.6 percent for the control deck). These data further disprove the belief that uninsulated decks always develop ice quicker and more often than approach pavements. However, except for a few instances, the approaches attained above-freezing temperatures long before the control deck.

In most respects, the insulated decks performed more satisfactorily than the control deck and approaches during this phase. For example, they experienced fewer freeze-thaw cycles and maintained below-freezing temperatures a smaller percent of the time (Table 1). In addition, the insulated decks frequently attained the 31 F reference temperature after the approaches and the control deck, or not at all, and seldom were the first to freeze. Figure 15 illustrates each condition in successive cycles. However, the insulation has had very little influence on accelerating the rate of thawing, compared to the uninsulated structure.

Entire Period (Oct. 21, 1962 to March 24, 1963).—An evaluation of the insulated structures should consider overall performance based on average conditions. Accord-

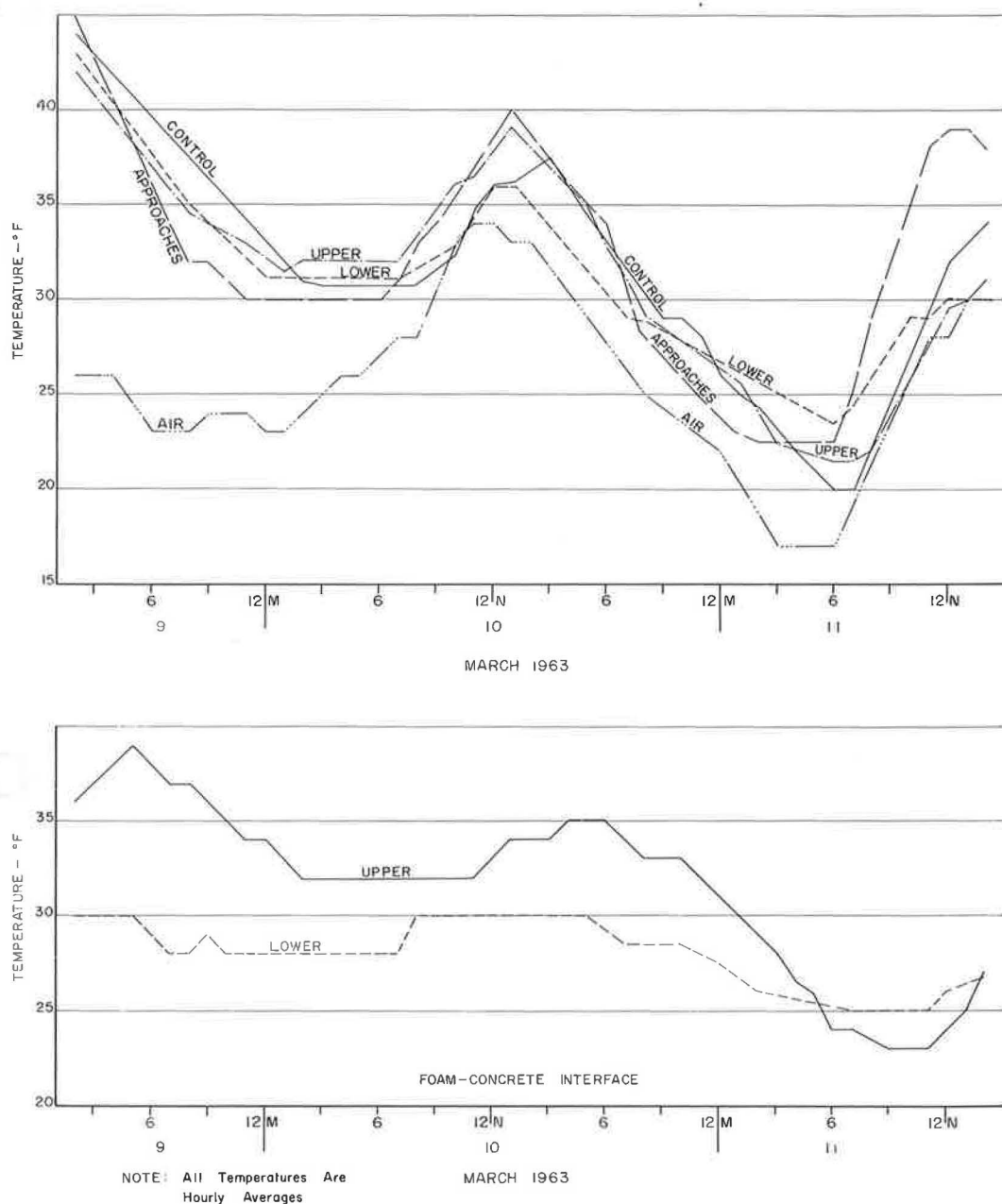


Figure 15. Typical temperature patterns, Phase 3, spring freeze-thaw cycles (insulated condition).

ingly, the results of all phases were combined and are included in Table 1 as totals and weighted averages. The average temperatures varied within narrow limits, between a maximum of 32.0 F for the approaches and a minimum of 28.8 F for the upper insulated deck. On the other hand, the cumulative temperature change, which is a measure of temperature fluctuations, was considerably higher for the approaches and control deck, with the lower insulated deck having the greatest stability. With regard to the maintenance of subfreezing temperatures, the upper insulated deck was the least

satisfactory, and the lower deck performed essentially the same as the control deck; neither performed as well as the approaches. Lastly, the control deck and approaches experienced an almost equal number of freeze-thaw cycles, whereas the insulated decks underwent considerably fewer, particularly the lower deck which received more radiation from the sun.

Precipitation

The previous discussions have concerned the potential for icing exhibited by the instrumented structures based on continuous temperature measurements. From a practical standpoint, it is also important to know the sequence of freezing and thawing when icing actually occurred. In this connection, an attempt was made to correlate the temperature data with hourly precipitation measurements recorded by the U. S. Weather Bureau at the Rochester Airport during the 1962-63 winter season.

A total of 98 days during the 147-day recording period were identified as having less than a "trace" of precipitation, or as being days when all concrete maintained above-freezing temperatures. It was also determined that because of prolonged below-freezing periods, all the structures were in a frozen state a total of 42 days. It was assumed that any precipitation which occurred on these days formed ice simultaneously on all structures. On this basis, only 7 days remained when the conditions for differential icing were fulfilled; namely, temperatures changed from freezing to thawing or vice-versa, accompanied by a measurable amount of precipitation. In three of these instances, the approaches froze first or thawed last. Consequently, only 4 days occurred when ice could have existed on the control deck and not on the approaches. Additionally, the insulated decks performed the same as the control structure on all but one of these occasions, indicating that the potential for differential icing was not significantly reduced. This analysis has not considered the many indeterminant factors which affect icing, such as the influence of different wind patterns on evaporation rates, variations in the concentration of deicing salt solutions, and occurrences of icing caused by drifting and melting snow adjacent to the roadways. However, it serves to emphasize that relatively few instances of differential icing occurred during the entire period and suggests that the insulation had limited value.

Visual Observations

Several attempts were made to observe icing at the site during the 1962-63 winter season. This approach did not prove entirely satisfactory because it was difficult to anticipate icing conditions sufficiently in advance to station inspectors at the site. Moreover, the structures were open to traffic throughout the winter and were included in the District's winter maintenance schedule. Deicing salts were applied to all decks and pavements at least once on each day that a measurable amount of precipitation occurred. It was generally impossible, therefore, to observe freezing and thawing.

On March 6, 1963, however, icing developed before the application of salt. During the late evening, falling temperatures were accompanied by intermittent snow flurries. Ice formed first on the approaches to the upper insulated deck. Within $\frac{1}{2}$ hr, all approaches and the uninsulated control deck were frozen. The insulated structures did not form ice until about 10 min after the control deck. Continuous visual observations also were made throughout most of the period from 3:00 PM on March 11 to 9:00 AM on March 15, 1963. During that time, three freezing cycles occurred, two of which were accompanied by precipitation. In one instance, the control deck developed ice before the approaches, whereas the reverse occurred in the second freezing cycle. In both cases, the insulated decks were the last to develop ice. These observations are in substantial agreement with the interpretations of the temperature measurements for Phase 3 of both seasons. Moreover, two of the three observed icing cycles were predicted by the temperature-precipitation correlation previously described. The icing which occurred on March 6, 1963, was excluded since the concrete temperatures did not fall below 31 F, the adopted criterion for icing.

Another aspect of the urethane insulation concerns its potentially harmful effect on the concrete deck and supporting structural steel framing. Ordinarily, a bridge deck

is exposed on top and bottom and has an opportunity to dry after each period of precipitation. It is very likely, however, that an insulated deck remains wet considerably longer since the urethane is impervious and effectively seals the underside of the deck. Water trapped by the insulation, together with accumulations of deicing salts, could attack the structural steel and contribute to the deterioration of the concrete deck. This possibility was verified recently on the first experimental bridge in Watertown, previously described. Because ice had been observed forming first on the insulated portions of this bridge on at least one occasion, the Department decided to remove the insulation completely. It was found that the interior surface of the urethane had pockets containing water and exposed areas of the structural steel were corroded. There was no evidence that the concrete was affected, but this may have been because the insulation was not left in place long enough.

INTERPRETATION OF RESULTS

The foregoing evaluation of concrete temperatures, precipitation records and visual observations of the experimental installations described in this report indicates the following:

1. The uninsulated decks exhibited a slightly greater potential for icing than the approach pavements.
2. Throughout most of the winter and the spring thaw, the uninsulated control deck and approaches frequently alternated their order of freezing and thawing. In the fall and early winter, however, the control deck consistently attained subfreezing temperatures first and thawed after the approaches.
3. The performance of the insulated structures varied. In the fall, temperatures were influenced daily by the amount of sunshine and the alignment and superelevation of the decks relative to the path of the sun. As a result, the lower deck mirrored the performance of the approaches and the upper deck closely duplicated the control structure. During the winter, the insulated structures maintained below-freezing temperatures significantly longer than the control deck and approaches, thereby increasing the possibility of icing during this relatively long period. This condition was reversed during the spring thaw, the only period when the insulation appears to have consistently reduced the potential for icing. Moreover, the insulated structures were generally the last to freeze during this phase.
4. Throughout the entire season, only 4 days were identified wherein the uninsulated control deck could have exhibited icing while the approaches were in a thawed state. The insulated structures performed the same as the control deck on three of these occasions, indicating that the insulation was ineffective in significantly reducing the occurrence of differential icing.
5. The insulated decks experienced considerably fewer freeze-thaw cycles than the approaches and control deck. However, this benefit is of secondary importance, compared to the effect on the potential for icing.
6. Urethane foam or any other impervious insulating medium applied to the underside of bridge decks impounds water and accumulations of deicing salts which may be injurious to the concrete deck and supporting structural steel.

CONCLUSIONS

This investigation has shown that the urethane foam did not significantly reduce occurrences of differential icing between the bridge decks and their approach pavements. In fact, the insulation increased the potential for differential icing during the winter months. Based on these results, it has been concluded that:

1. Urethane foam or any other impervious material should not be used to insulate the bottom of bridge decks; and
2. The insulation applied to the experimental bridge decks described herein should be completely removed.

ACKNOWLEDGMENTS

This investigation was conducted in cooperation with the U. S. Bureau of Public Roads under the State-Federal Physical Research Program. Personnel of Public Works District 4 installed the test equipment under the supervision of the Bureau of Physical Research and furnished pertinent information on the installation of the urethane foam, traffic densities, and winter maintenance operations. Temperatures were analyzed statistically by the Department's Bureau of Electronic Data Processing. The Bureau of Physical Research compiled the information, interpreted the data, and prepared this report.