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HEATING BRIDGE DECKS BY ELECTRICAL RESISTANCE

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HEATING BRIDGE DECKS BY ELECTRICAL RESISTANCE

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The 9th-Street interchange was designed and constructed with an automated electrical heating system for snow and ice removal. This report describes the heating system, its construction, and initial operation. The heating system was capable of keeping the interchange free of ice and snow accumulation. The average daily slab temperature fell below 0°C (32°F) on only one occasion. The average cost of electrical power for heating the interchange was $1,075 per day.

Design Requirements

The presence of snow or ice on highways, especially at bridges and interchanges, often results in hazardous driving conditions. Conventional snow and ice removal may prove inadequate due to the time lag between ice and snow accumulation and plowing and(or) salting operations. Also, deterioration of concrete in bridge decks is often attributed to the use of deicing chemicals. A number of non-chemical methods of preventing freezing have been investigated. One solution for the control of such conditions is a heating system for bridge decks and pavements capable of melting any snow or ice that might accumulate on the roadway. Various systems of heating pavements using embedded pipes or embedded electrical elements have been tried in the United States, Canada, and Europe. Analyses of these systems have confirmed their ability to remove and prevent the accumulation of snow and ice on bridge decks and pavements *(1)*. However, the installation and operation of these systems is very expensive as compared to the cost of conventional snow removal.

The 9th-Street interchange in Louisville, Kentucky, is subject to extreme conditions due to the use of maximum interstate grades and superelevations, the height of the ramps, and the location near the Ohio River. The major portions of the ramps are elevated, exposing both the top and bottom surfaces of the ramps to wind currents. Conventional snow and ice removal would be undesirable due to potential traffic congestion. Therefore, an automated heating system, with manual override switches, was deemed necessary for this location.

The 9th-Street interchange was first conceived in 1959 *(2)*. Preliminary design began in the early 1960's, and design began in 1964. Hazelet and Erdal of Louisville were the principal consultants. They engaged Bosch and Latour of Cincinnati, Ohio, to design the electrical heating system, controls, and monitors. Design criteria established by the Department are summarized as follows:

1. three independent, parallel 20-watt circuits with variable controlled inputs to provide a total heating capacity of 645.8 watts per m^2 (60 watts per square foot),
2. embedded mineral-insulated cables interrupted at joints and otherwise sectionalized,
3. prevent icing and clogging of deck drains and downpipes,
4. provide building to house controls and monitors,
5. provide TV monitoring throughout,
6. provide ice detectors at strategic points,
7. provide remote-reading temperature sensors and recorders,
8. provide meters and indicators of circuit operation, and
9. provide operating and maintenance manuals and operator training.

The contract for the 9th-Street interchange was awarded April 27, 1973, to the E. Randle Company and the R. R. Dawson Bridge Company. The electrical subcontractor was the Marine Electric Company. The Nelson Electric Company was contracted to manufacture the heating cables. Work began on the project May 17, 1973. The interchange was opened to traffic and the heating system became operational December 3, 1976. The final acceptance of the project by the Department was March 29, 1977. The final costs of the heating system are listed in Table 1.

TABLE 1. HEATING SYSTEM: FINAL COSTS

Electrical Distribution System	$715,345
Roadway Heating and Connectors	720,500
Control Building	204,275
Instrumentation System	168,500
TV System	69,550
Total	$1,878,170

The total project cost was $14,130,645.45.

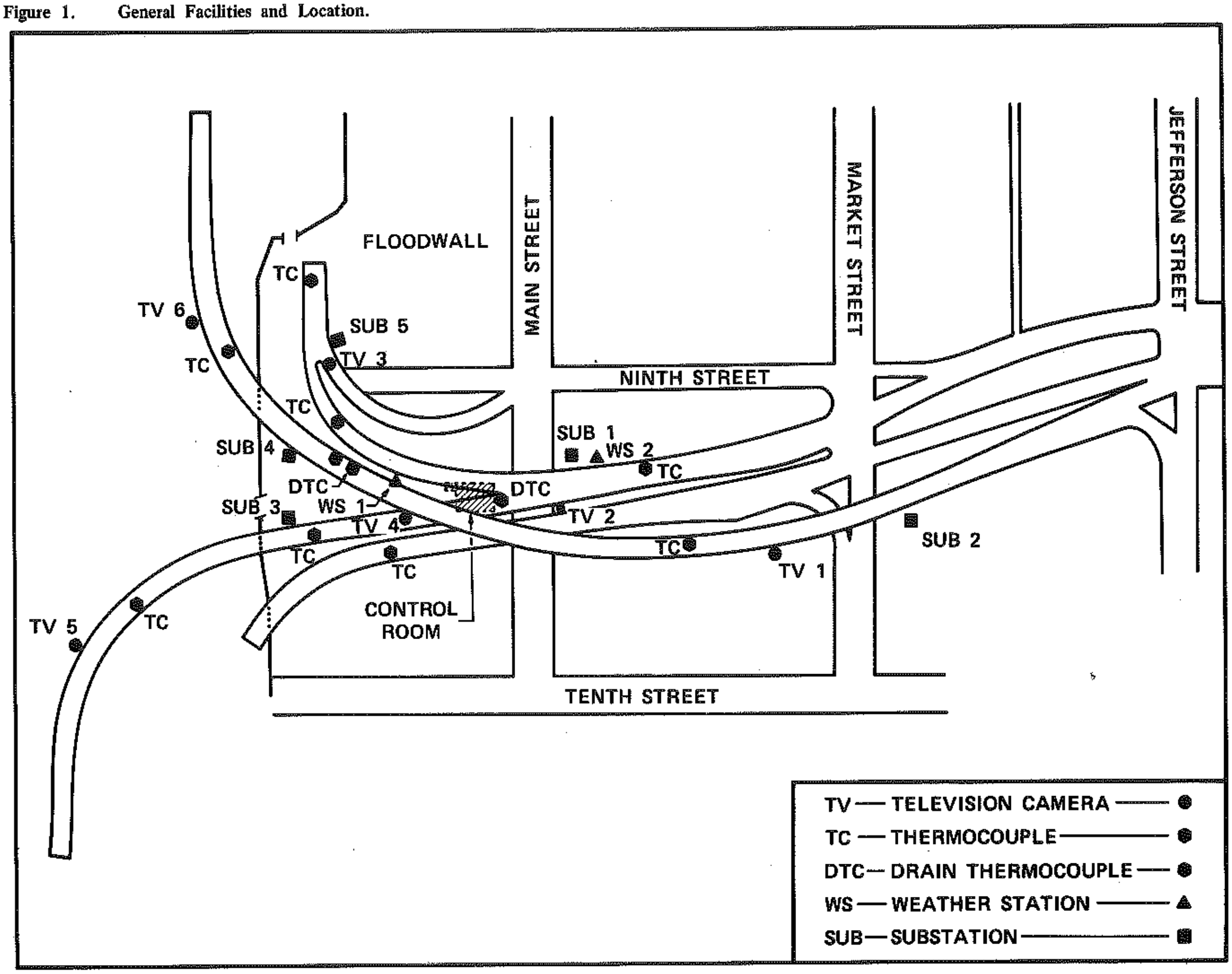
Description of System

The 9th-Street interchange (Figure 1) consists of 1.252.12 m (4,108.0 feet) of welded steel plate girder (continuous, composite) bridge ramps and 353.87 m (1,161 feet) of grade ramps for a total length of 1,605.99 m (5,269.0 feet). The width of the ramps ranges from 6.70 m (22.0 feet) to 15.85 m (52.0 feet). The decks are 229 mm (9 inches) thick while the pavements are 254 mm (10 inches) thick. Class AA concrete (368.1 kg/m^3 (6.6 bags per cubic yard)) was used in both bridge and ramp sections. The total area of heated pavement is 16,713.95 m^2 (174,095 square feet). The bridge ramps can be heated to a maximum of 645.83 watts per m^2 (60 watts per square foot), and the grade ramps can be heated to a maximum of 538.20 watts per m^2 (50 watts per square foot).

All power for the ramp heating system is supplied by a Louisville Gas and Electric (L. G. & E.) underground cable at 13,800 volts, three-phase, ungrounded. There is a 1,200-amp, 500-MVA air-type circuit breaker ahead of the L. G. & E. meter. The main switchgear located in the control building is supplied with 13,200 volts; the remaining power is for auxiliary purposes. The power level is controlled by a motorized, tap-changing-under-load voltage regulator having 32 steps and a range of 2,200 to 13,200 volts. The voltage regulator, positioned behind the control building, may be controlled manually or by automatic response to various sensing devices.

Power from the voltage regulator is distributed through underground electrical ducts to five substations where transformers reduce the adjusted high voltage to low voltage levels which can be utilized by the ramp-heating system. Each substation supplies approximately 2,500 kVA. The maximum secondary voltage at the substations is 480 volts phase to phase and 277

Figure 1. General Facilities and Location.



volts from neutral to ground. Each substation transformer is equipped with two main buses to feed two sections of pavement. Each bus has three panels, each having 12 three-pole, 100-amp breakers. Each panel is protected by a ground-fault interrupter. The secondaries are three-phase, ungrounded, wye-type; each phase returns to neutral. The maximum input to any heater circuit is 270 volts.

Distribution cables (No. 4 wire (5.95 mm)) from the substations extend in conduit (Figure 2) to steel wireway units, termed plinth boxes (Figure 3), on the bridge ramps or concrete hand holes (Figure 4) on the grade ramps. It is here the distribution cables from the substation connect to the cold section of the embedded roadway-heating cables.

Three types of plinth boxes are employed. The first is the plinth-feeder box, i.e., entrance box. The distribution cables connect to the cold sections of the heating cables in this unit. The second type is the plinth-expansion box. Connections are made in this type of box between cold leads of adjacent bridge sections so that a bypass may be made around the expansion joint (Figure 3). The third type is the plinth-termination box where the phase leads are joined together to complete the wye-neutral connection. The same type of arrangement is made in the concrete hand holes for the grade ramps. Both the steel plinth boxes and concrete hand holes are designed so that the cover may be removed for periodic inspection or repair of the various cables.

Cold-section cables leave the plinth boxes through ports and are embedded in the lower plinth and curbing concrete. The connection of the hot and cold sections of each cable is in the concrete below the curb and gutter. The entrance of the cable to the pavement and position of the cold joint prior to the placement of the concrete is shown in Figure 5. The hot sections of the cables extend various distances across the roadway from the entrance box, then turn to run longitudinally for the length of the ramp unit. At the end of the ramp, they turn and exit on the side opposite their entrance. This pattern continues through three or four ramp sections where the cables exit in the termination box and are joined to complete the neutral "wye" connection. At converging bridge or grade sections, the heating cable is joined to a cold section which passes through a sealed construction joint box (Figure 6) to the adjoining pavement and is rejoined to the heating cables.

Cable spacing varies to accommodate the reinforcing rod pattern in the respective units. However, cables are arranged so that each cable is essentially the same length and has the same current for a prevailing voltage, thus assuring uniform heating in the respective units. In addition, phase leads from the three-pole breakers are alternated so that, in the event of a breaker tripout, three separate, 152-mm (6-inch) unheated widths alternating with 305-mm (12-inch) heated widths would occur rather than one 457-mm (18-inch) unheated area.

The heating cables consist of a single copper (No. 16 wire (1.6-mm)) conductor with magnesium oxide (MgO) insulation in a copper sheath. The cold section, 1.83 m (6 feet) at each end of the heating cable, is No. 6 (5.2-mm) copper wire in a copper sheath.

The system is equipped with closed-circuit television so that the effectiveness of the heating system can be monitored visually. Six pan-and-tilt zoom-lense TV cameras are mounted on standards above the plinth. The housings for the cameras are weatherproof and equipped with window wipers. Shielded transmission cable extends from each camera to the control room where the six TV monitors are located.

Two weather stations are also mounted on standards above the plinth. Each is capable of measuring wind speed and direction, outdoor temperature, and humidity; and each is equipped with sunshine, rain, and snow detectors.

The system has eleven thermocouple stations. At each station there are either six or twelve thermocouples. Where six are employed, they are in the drain; where twelve are employed, six are in the gutter area and six are in the centerline of the deck (Figure 7). One of two surface temperature detectors (Figure 8) can be used for modulation of the voltage

Figure 2. Distribution Cables in Conduit.

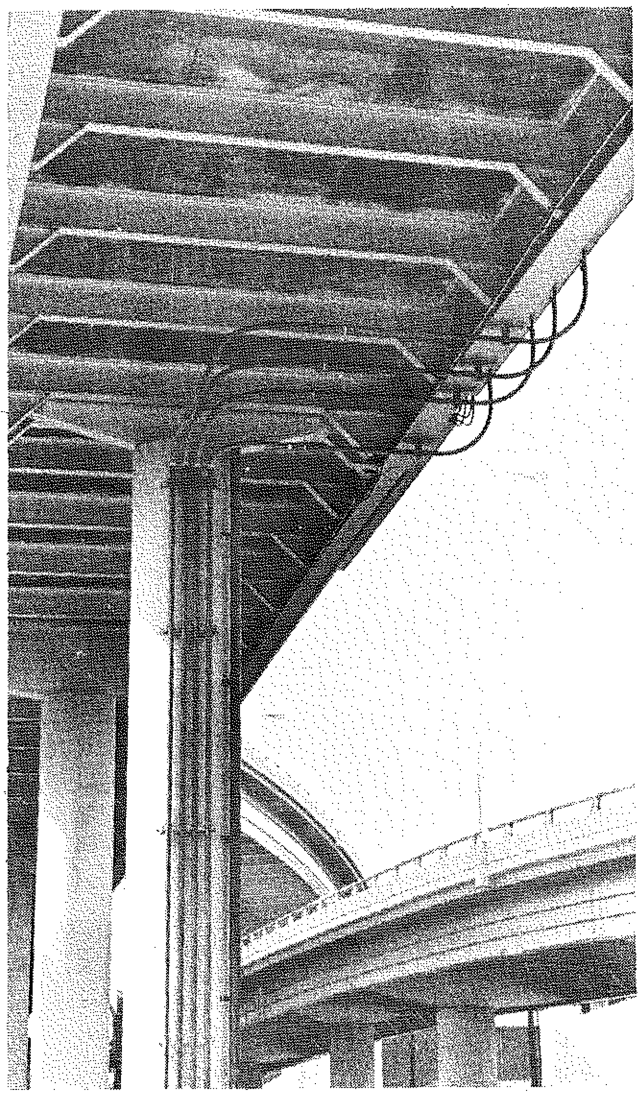


Figure 3. Typical Plinth Box and Expansion Loop at Expansion Joint.

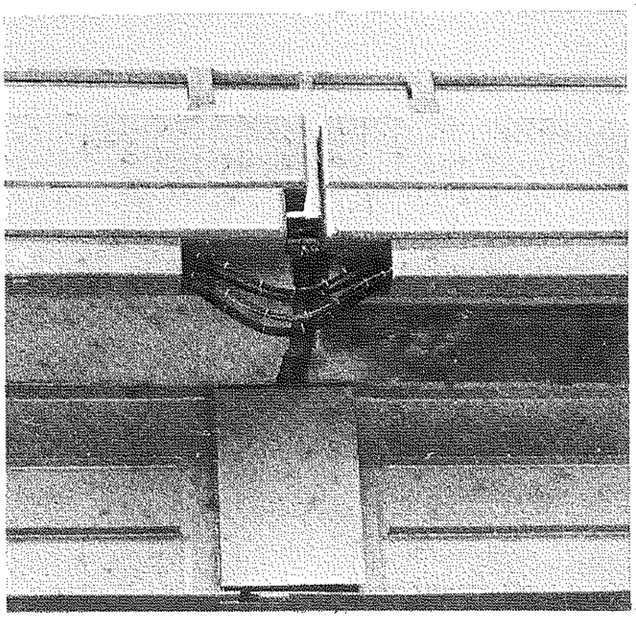


Figure 4. Concrete Hand Holes in Pavement Section.

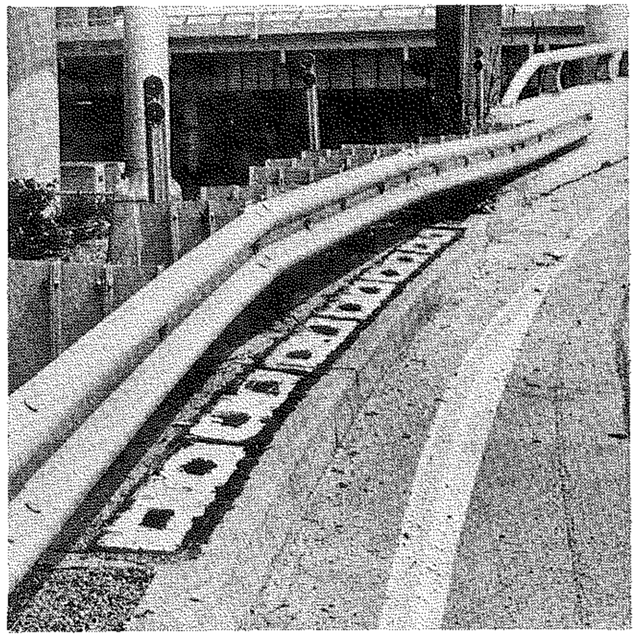
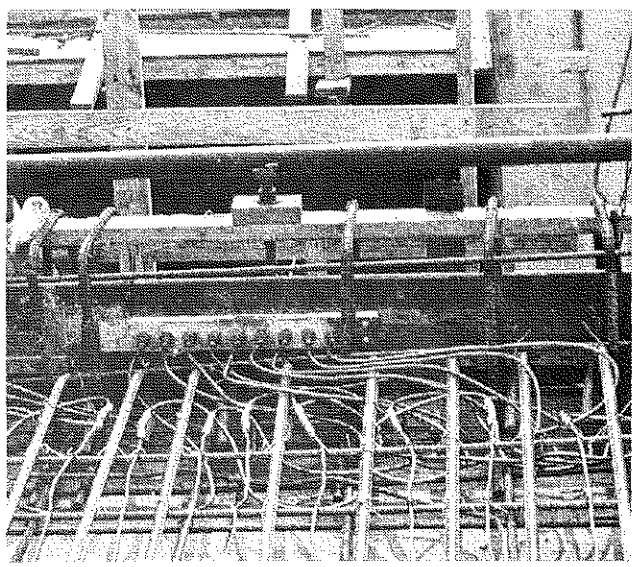


Figure 5. Position of Cold-Section Junction.



regulator.

All drainage troughs and drain pipes are insulated to prevent icing and clogging. The drain troughs are insulated with 16-mm (5/8-inch) foamed plastic and covered with 2-mm (0.08-inch) galvanized steel. The drain pipes are insulated with 25.4-mm (1-inch) fiber glass and covered with a 0.2-mm (0.01-inch) stainless steel jacket.

The control building is located on Main Street under the converging sections of Ramps 1 and 2. It houses the main switchgear, TV monitors, power and weather meters, and the master controller.

The L. G. & E. 13.8-kV service enters in the switchgear room. The power is fed through the main circuit breaker, the main switchgear, and on to the voltage regulator and then runs underground to the various substations. An uninterruptable power supply is also located in the main switchgear room. This 20-unit battery system provides storage of energy for resetting the voltage regulator and the main circuit breaker in the event of a power failure.

The control room houses the six television monitors and various instruments for monitoring the weather and power levels and for adjusting the heating system. The TV monitors, power meters, weather indicators,

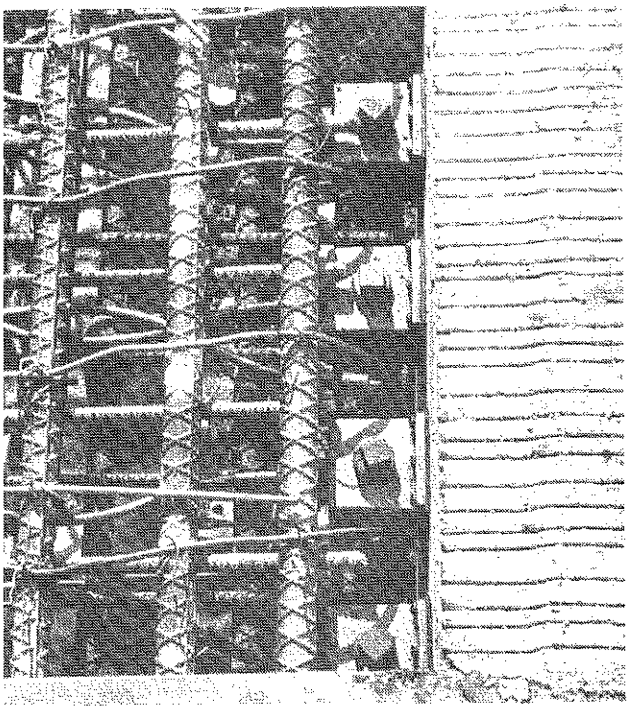


Figure 6. Junction Box at Construction Joint.

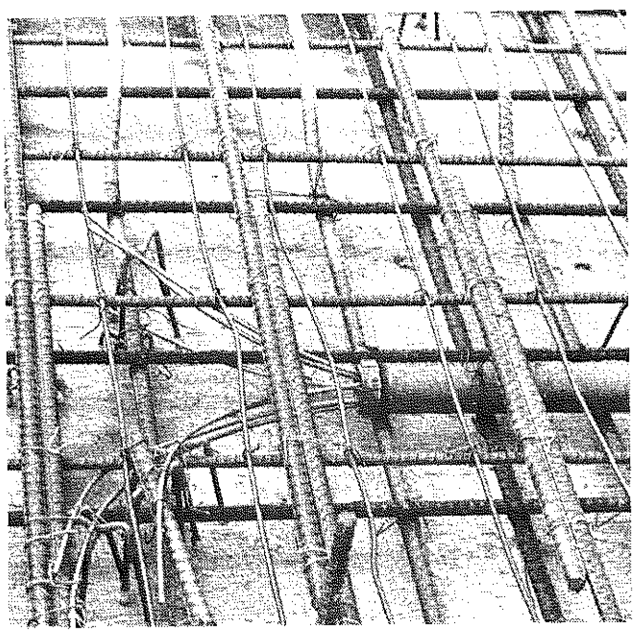


Figure 7. Typical Thermocouple Installation at Centerline of Deck.

and thermocouple monitors allow the operator to stay abreast of current road, weather, and power conditions at the interchange. The annunciator display panel will immediately indicate the location of any problem in the electrical system. Two failsafe systems protect the electrical heating system from overheating. One lowers the voltage regulator when the controlling slab temperature exceeds the set point. The other failsafe trips the main circuit breaker when the outdoor temperature is -8°C (18°F) and the voltage regulator is on Step 33 or when the outdoor temperature is 24°C (75°F) and the voltage regulator is on Step 1.

The master controller is provided to obtain as full an automatic control as possible. The basic concept is to operate the heating system at a low level of heat when the slab temperature goes above a certain set point. As the temperature drops, slab temperature sensors cause the voltage regulator

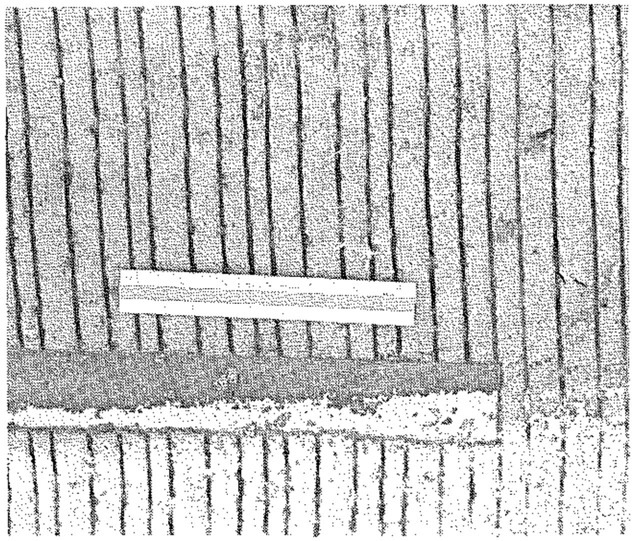


Figure 8. Surface Sensor.

to increase the voltage into the system. As the temperature increases, the voltage level is reduced. However, various weather parameters, such as barometric pressure, rain, snow, humidity, and others, are programmed into the system so that the system actually operates on the probability of snow and ice rather than the detection of snow or ice. An illustration is given in Figure 9. The slab temperature establishes a base-line condition. As the temperature drops, more heat input goes into the slab. The basic straight-line situation is then changed by the weather factor signal modifiers, represented by the cross-hatched areas between the curves. If weather conditions remain ideal, even though the temperature goes very low, a minimum of heating would be required, as shown by the lower portion of the cross-hatched area. If weather conditions are unfavorable, more heat would be required as shown by the upper portion of the cross-hatched area.

There are 11 signal modifiers affecting the modified slab temperature. Eight digital timers on the weather instrumentation console are used by the master controller for timing weather condition changes and duration of

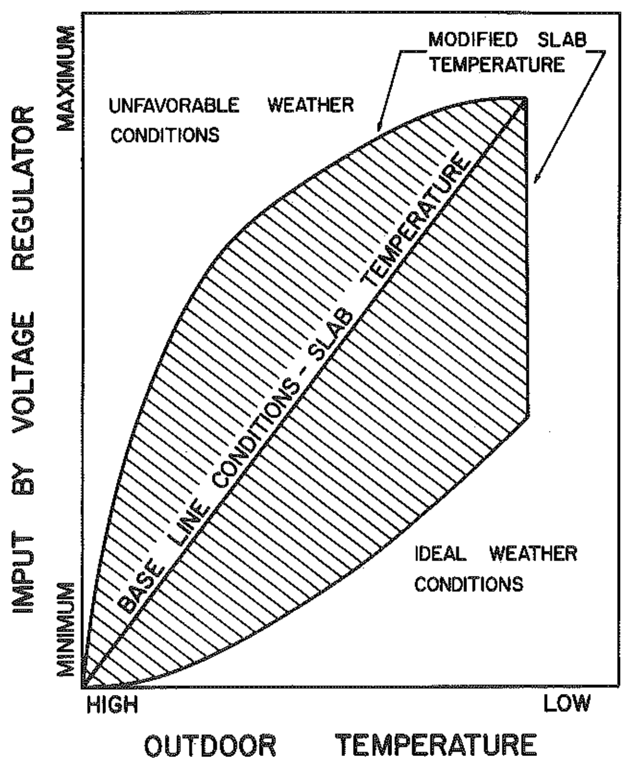


Figure 9. Modified Slab Temperature Conditions.

heating at the various steps. Output of these timers is incorporated into the logic of the master controller to automatically establish the amount of power to be delivered to the heating system.

Signal modifiers and slab set point can be set manually on the system control console. The slab set point is a predetermined slab temperature used by the master controller. If the modified slab temperature as computed by the master controller falls below this set point, the master controller calls for more heat; if the modified slab temperature goes above the set point, the controller reduces the amount of heat to the slab. The console is also equipped with two recorders. The weather factor signal recorder indicates which signal modifiers have been activated by the prevailing weather conditions. The slab temperature for control and composite weather factor signal recorder indicates the actual slab temperature used for control and the modified slab temperature, as computed by the signal modifiers.

Construction

Original design of the heating cables called for the outer sheath to be stainless steel and of a thickness not less than 0.56 mm (22 mils). Cables in the decks were to be tied at 0.91-m (3-foot) intervals with No. 16 (1.6-mm) stainless steel wire. Cables in the pavements were to be clipped to stainless steel mounting strips which were 3.05 m (10 feet) by 25 mm (1 inch). The mounting strips were on 0.91-m (3-foot) intervals, and the clips on the strips were on 140-mm (5 1/2-inch) centers. Due to manufacturing difficulties in drawing the stainless steel covering, a decision was made to use copper-sheathed mineral-insulated cable with a minimum sheath thickness of 0.61 mm (24 mils). This necessitated a means of relieving galvanic action between the copper sheath and the reinforcing steel. To insulate between the copper sheath and the reinforcing steel, the top mat of steel, including the truss bars, in the decks and the entire reinforcing mats in the pavements were epoxy-coated. Copper tie wire replaced the stainless steel tie wire. The stainless steel mounting strips were replaced by 6.4-mm (1/4-inch) solid copper rods on 0.61-m (2-foot) intervals. All chair or bar supports were to be epoxy-coated or of a rustproof material.

Mineral-insulated cable is very rugged, and its use is widespread. It can be hammered almost flat without destroying its operating characteristics; however, it still must be handled and installed with great care. A small cut in the sheath would permit moisture to enter and destroy the electrical insulating properties of the magnesium oxide.

Heating cables were delivered to the job site in pre-cut lengths and with the cold sections attached at the factory. The cables were coiled and packaged in individual cardboard boxes.

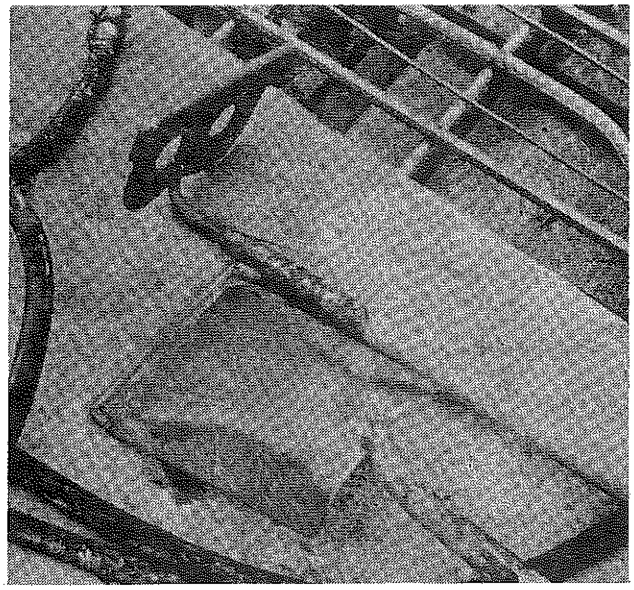
All work, except the concreting, was completed on the decks before cable installation began. Prior to being positioned on the decks, the cables were lubricated with a Dow Corning silicone compound. The lubricant was used to prevent the adherence of the concrete to the surface of the cable. Individual cables were played out from reels and stretched the length of the deck for proper positioning. Heating cables were to be no closer than 38 mm (1 1/2 inches) horizontally to any longitudinal reinforcing bar or no closer than 102 mm (4 inches) to another heating cable or at a distance not greater than 152 mm (6 inches) apart. However, some deviations in this spacing occurred due to variations in cable length as received from the manufacturer. After positioning the cables on the deck, the cables were tied with copper tie wire at 0.91-m (3-foot) intervals. All electrical connections were made according to conventional wiring codes. Plywood walkways were provided for construction workers, preventing damage to the cables prior to the placing of concrete.

Concrete was placed with a crane and bucket. The finishing machine used was a self-propelled, rail-mounted Bidwell finishing machine with a rotating drum, front-mounted auger, and drag-type plate. Concrete was dumped ahead of the finishing machine from approximately 0.46 m (1 1/2 feet) above the heating cables. No apparent damage or displacement of the heating cables occurred as a result of dropping the concrete from this height. The concrete was partially leveled with specially modified shovels and rakes (Figure 10). Tubing was welded to the sharp edges of these tools to prevent damage to the cables. The concrete was vibrated by hand-held portable vibrators. Workmen stood on plywood walkways which were continually backed away as the concreting operation progressed. The concrete was cured in a normal manner.

Each cable assembly was tested for continuity and insulation resistance before, during, and after concreting operations. Each cable assembly was required to measure not less than 200 megohms. Of the 1,800 cables in the system, only one failed during concreting operations.

After 9.14 m (30 feet) of concrete had been placed in Ramp 3, resistance in a cable at the gutterline dropped below the required 200

Figure 10. Specially Modified Shovels and Rakes.



megohms. As concreting continued, the damaged cable was removed from the fresh concrete and a replacement cable was installed in its place. The replacement cable was tied at irregular intervals with copper wire. The concrete was replaced around the new cable and floated by hand. No revibration of the concrete occurred. The completed interchange is shown in two aerial photos taken December 2, 1977 (Figures 11 and 12).

Upon completion of the interchange, the electrical heating system underwent a full-load test to determine the integrity of the system. At a time when the outdoor temperature was predicted to be below -7°C (20°F) for a period of 24 hours or longer, the system was advanced to full load (Step 33) at regular intervals. The system was required to maintain a stabilized condition at this load with all heating cables, power, weather, and recording instruments functioning properly.

Discussion

The 9th-Street interchange was opened to traffic December 3, 1976. The initial operating season extended through April 16, 1977. The heating system was in operation at various levels throughout this period.

Monthly weather summaries are listed in Table 2. Figures 13 and 14 compare the average daily slab temperature to the average daily air temperature as recorded at the 9th-Street interchange. The position of the thermocouple used in determining the average slab temperature was at the surface of one of the bridge ramps. On only one occasion, January 10, 1977, during the period December 30, 1976, to April 16, 1977, did the average slab temperature fall below 0°C (32°F). This was the date of the greatest snowfall (198 mm (7.8 inches)) of the winter season. Visual observations throughout this period indicated that both deck and pavement sections were kept free of snow and ice accumulation. Figures 15 and 16 show the transition between heated and non-heated pavements during a period of snow accumulation. Both pictures were taken of the same snowfall. The official ground cover for this day was 127 mm (5 inches) of snow. In Figure 15, note the accumulation of snow on the plinth and curb and patches of snow directly above the roadway drains in the gutterline. These are non-heated areas. Figure 17 is an aerial view of the entire interchange taken on February 2, 1978. The photo clearly shows the difference between heated and non-heated sections during severe cold and snow accumulation.

On January 10, 1977, a short circuit in a plinth box caused a portion of one bridge ramp to be without heat for four days (January 10 through January 13). The largest snowfall of the winter season occurred during this period. However, a combination of adjoining heated pavement and traffic was able to keep this section of pavement clear of ice in the wheel tracks. Inspection of the plinth boxes on this bridge ramp revealed the cause of the short circuit. An apparent buildup of heat within the plinth box had melted the insulation on the cables, thus allowing bare wires to come in contact. The damaged wires (No. 6 (5.2 mm)) were replaced with No. 4 (6.0-mm) wires, and heat was restored to the bridge section. An inspection of all plinth boxes followed, and a decision was made to ventilate all plinth

Figure 11. 9th-Street Interchange, Looking toward River.

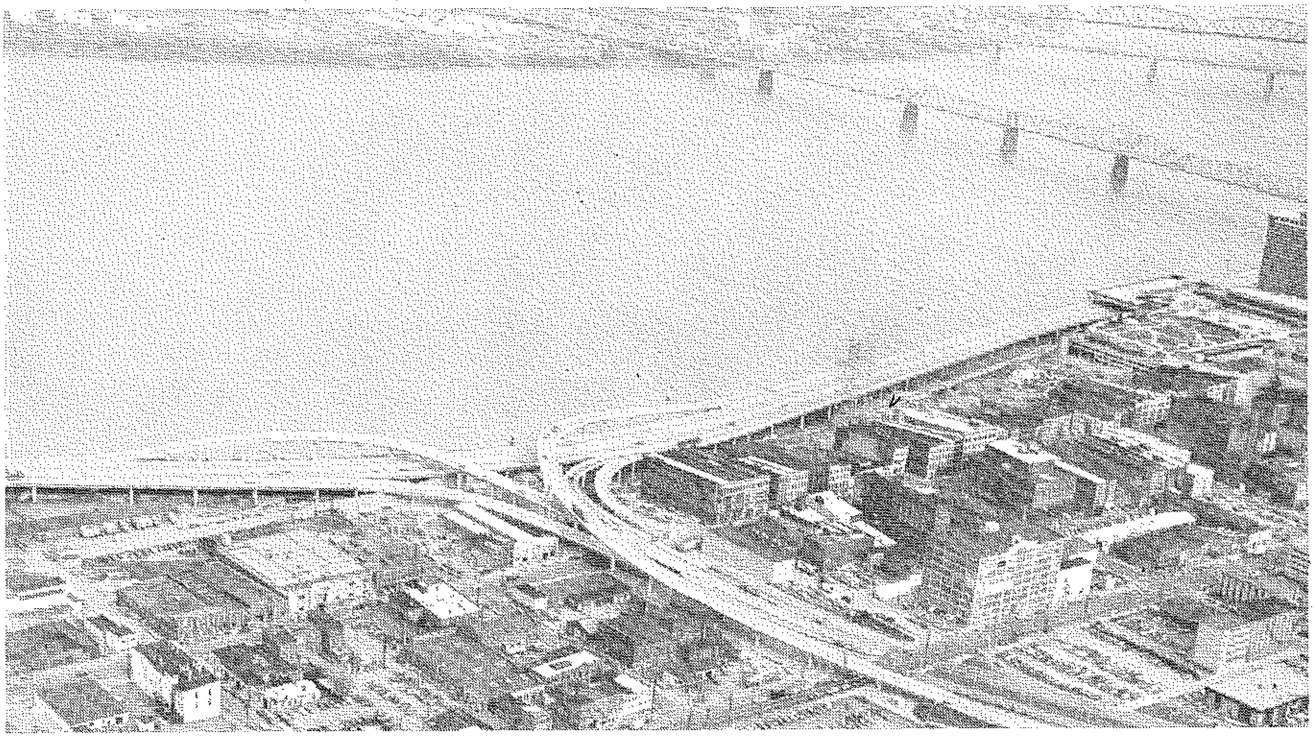
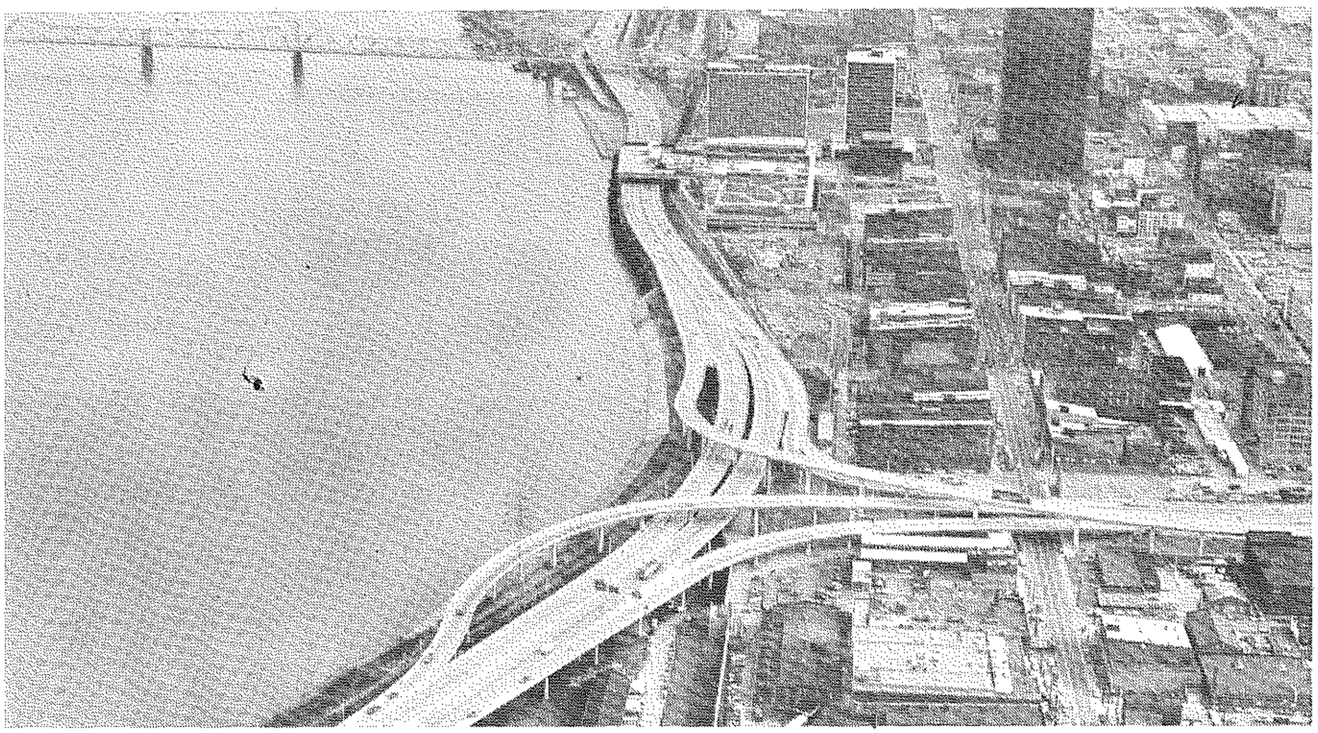


Figure 12. 9th-Street Interchange, Looking Upstream.



boxes and separate the cables within the boxes to prevent further damage to the cables from excessive heat. All plinth boxes were opened and have remained open since that date with no further damage occurring. The cost to the Department for repair of the cables was approximately $5,000.

Heating the 9th-Street interchange on the probability of snow appears to be an advantage over other roadway heating systems. Such an approach does not require "catch-up" time after a snowfall to clear a pavement but rather keeps the interchange clear as the snow falls. Figures 18 and 19 show the actual slab temperature compared to the modified slab temperature as computed by the master controller for the period January 1, 1977, to April 16, 1977. The average modified slab temperature is slightly lower than the average actual slab temperature throughout this period because the heating system is based on the probability rather than the actual occurrence of bad weather. In Figures 18 and 19, any average modified slab temperature above 10°C (50°F) is recorded as 13°C (55°F).

A slab set point of 3°C (38°F) was adjudged to be the temperature at which, under normal conditions, the master controller should call for more heat. This allows for a time lag in which the slab may begin to heat as snow and ice conditions approach. The set point was adjusted to as high as 5°C (41°F) by the operator when threatening conditions prevailed.

TABLE 2. MONTHLY WEATHER SUMMARIES

	DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL
High Temperature	18° C	6° C	24° C	28° C	30° C
Low Temperature	-17° C	-25° C	-15° C	-6° C	1° C
Average Temperature	1° C	-7° C	3° C	11° C	16° C
Largest Snowfall/Date	23 mm/12-29-76	198 mm/1-9, 10-77	10 mm/2-19, 20-77	3 mm/3-22-77	20 mm/4-5, 6-77
Greatest Accumulation/Date	25 mm/12-29-76	229 mm/1-11-77	51 mm/2-3-77	Trace/3-22-77	Trace/4-6-77
Total Snowfall	28 mm	498 mm	20 mm	3 mm	20 mm

Note: 1 in. = 25.4 mm; $T_C = (T_F - 32)/1.8$.

Figure 13. Average Temperature Versus Time (January and February).

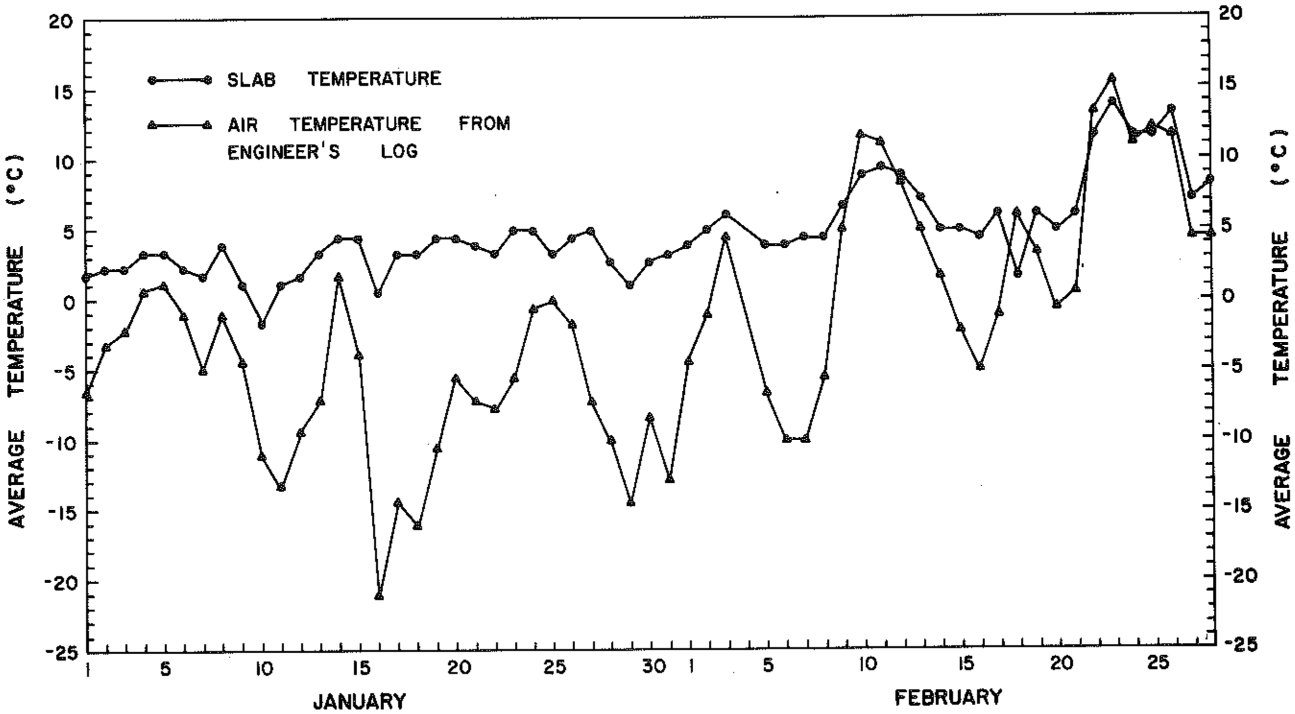


Figure 14. Average Temperature Versus Time (March and April).

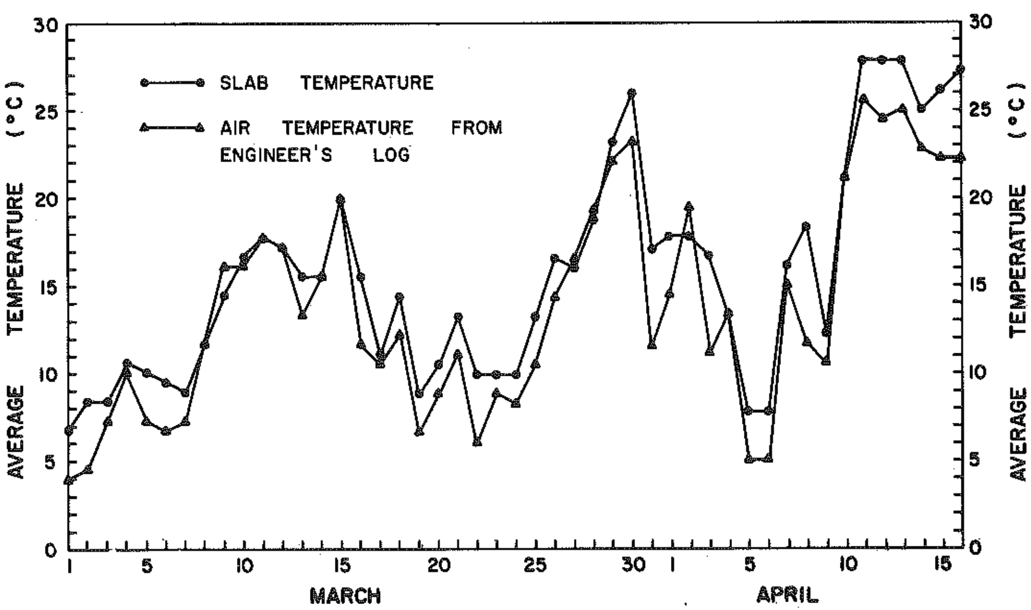


Figure 15. Heated Pavement (January 14, 1977).

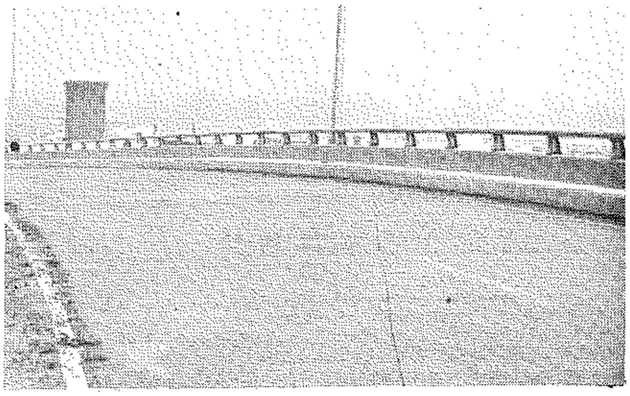
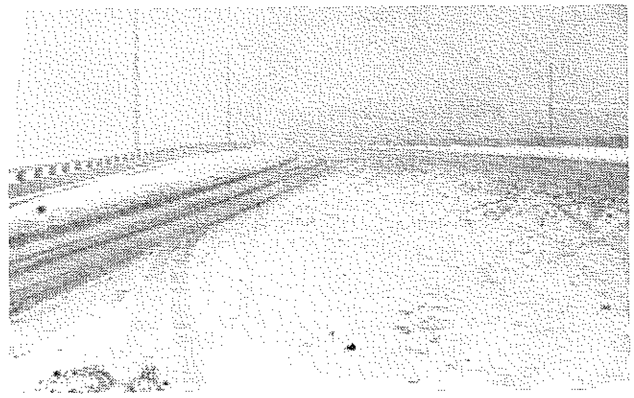


Figure 16. Non-Heated Pavement (January 14, 1977).



Although compensation is made by the signal modifiers for rapidly changing weather conditions, the voltage-raise timer must also be adjusted as is the slab set point. Care was exercised in adjusting both the slab set point and the voltage-raise timer as a sudden increase in the voltage could damage the cables or thermally shock the concrete.

It must be noted that the above conditions apply to "automatic operation". The operator may adjust the voltage regulator manually as he deems necessary.

The power usage and costs for the heating system are listed in Table 3. The cost for heating the interchange from December 9, 1976, through April 16, 1977, was $8.50 per m^2 ($0.79 per square foot) or $1,075 per day. These costs do not include labor charges for operators who monitor the interchange 24 hours a day throughout the season. An agreement with the electrical subcontractor for maintenance of the system has been estimated to be $50,000 per year.

The cost of operating the heating system is dependent on several factors. The weather greatly determines the power required to heat the pavement. January of 1977 had the lowest average temperature for any month dating back to 1872. The 498 mm (19.6 inches) of snow made it the snowiest January since 1918 for the Louisville area. Manual settings of the signal modifiers and the slab set point may also affect the amount of heat input to the slab. The voltage-raise timers affect the power demand by controlling the time allowed the voltage regulator for increasing or decreasing the heat input to the slab. The opinion of the operator, in judging weather conditions and the probability of snow or ice, determines the settings for these instruments.

Some time after April 16, 1977, a longitudinal crack approximately 94 m (310 feet) in length was noted in Ramp 1. Some transverse cracking in this ramp and in Ramp 3 was noted in the fall of 1977. The cracking appears to have had no effect on the integrity of the heating system to the present time.

On October 12, 1977, the heating system was turned on because of the forecast of cold temperatures and snow. It was shut off October 16, 1977. Resistance readings of the heating cables taken October 27-30, 1977,

Figure 17. Aerial View of the 9th-Street Interchange on February 2, 1978, Showing the Distinct Difference between Heated and Non-Heated Sections.

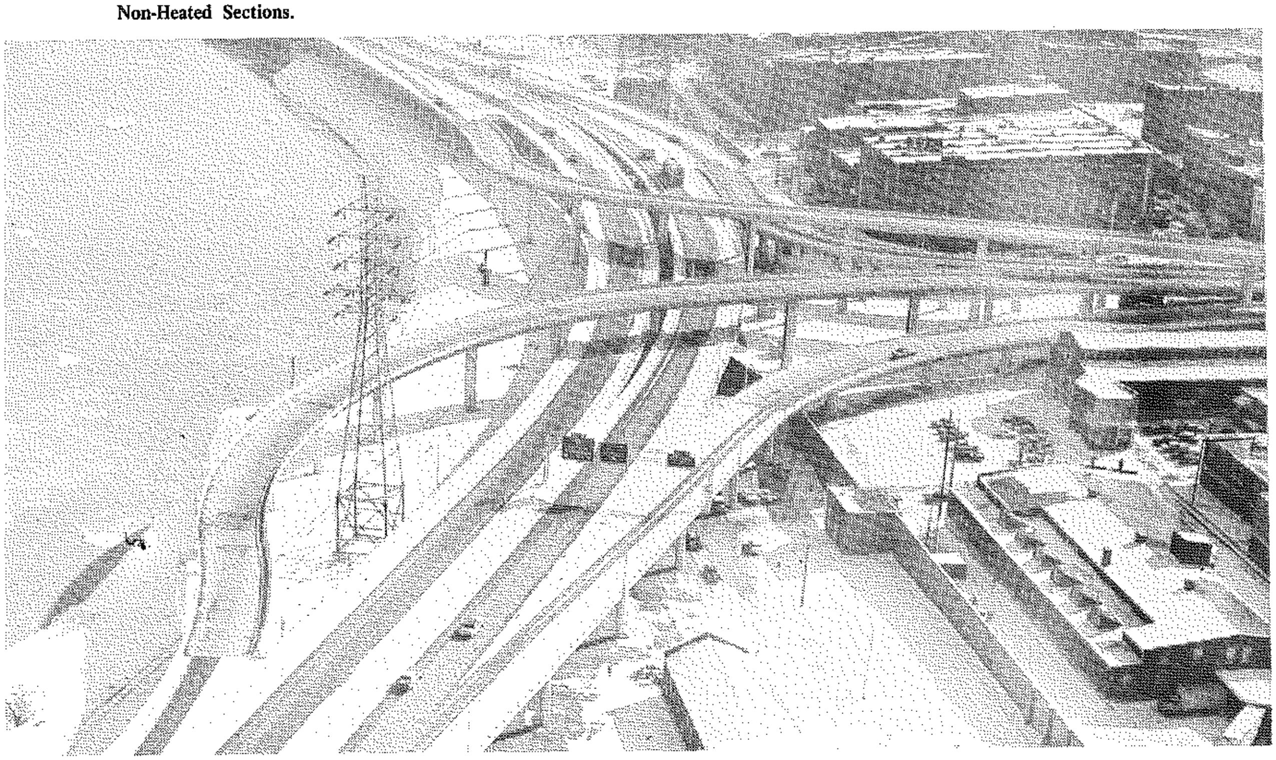


Figure 18. Average Temperature Versus Time (January and February).

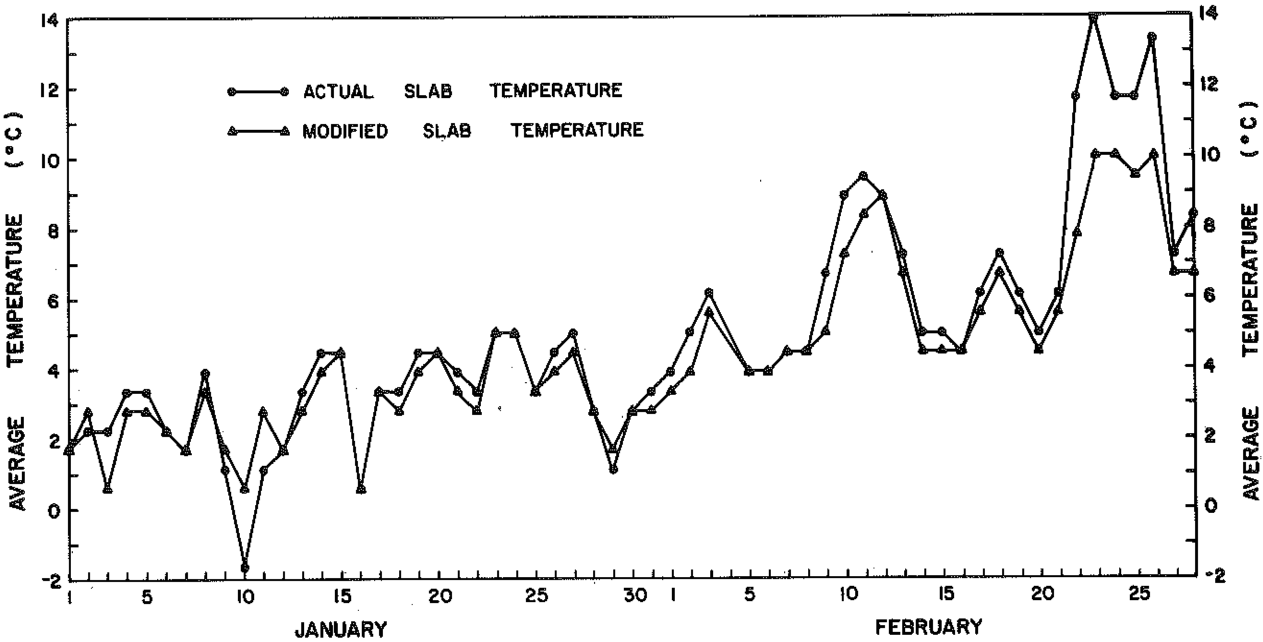


Figure 19. Average Temperature Versus Time (March and April).

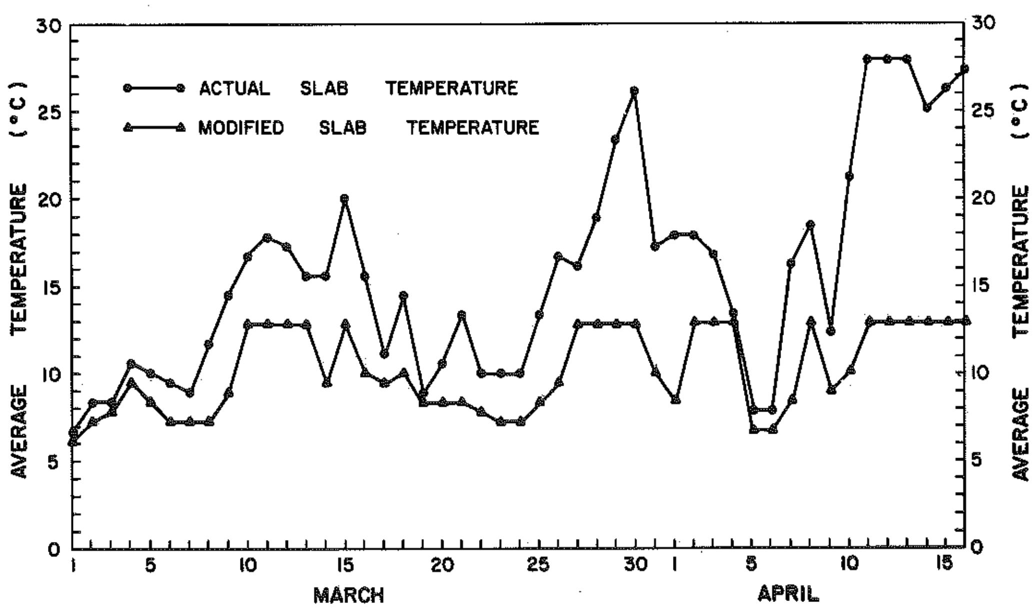


TABLE 3. POWER USAGE AND COSTS

PERIOD	NUMBER OF DAYS	KWH	AVERAGE KWH/DAY	COST	AVERAGE COST/DAY
12-9-76 - 1-10-77	32	2,011,200	62,850	$50,765.62	$1,586.43
1-11-77 - 2-8-77	29	2,505,600	86,400	63,484.30	2,189.11
2-9-77 - 3-10-77	30	648,000	21,600	16,618.09	553.94
3-11-77 - 4-8-77	29	230,400	7,945	5,952.84	205.27
4-9-77 - 5-10-77[a]	8	28,800	3,600	797.36	99.67
12-9-76 - 4-16-77	128	5,424,000	42,375	137,618.21	1,075.14

[a]Heating system turned off 4-16-77; billing cycle through 5-10-77.

showed a decrease, in some instances, attributed to the presence of moisture. On November 1, 1977, the system was turned on to dry the cables; this was earlier than anticipated. The system was kept on thereafter.

On November 25, 1977, Loadcenter 1-A was tripped by the ground-fault interrupter. To restore power, four breakers in three panels of Loadcenter 1-A had to be opened. Upon checking the records, these circuits were found to have low resistances. The cables in these circuits are in the pavement section of Ramp 1. Although the cables from these breakers are adjacent to each other in sections of the pavement, neighboring cables have kept the pavement clear of any snow or ice accumulation (102 mm (4 inches) recorded November 27, 1977) during the first snowstorms of the winter season.

The heating system at the 9th-Street interchange has proven functional; but no economic justification has been attempted. There are no data pertaining to conventional snow removal costs in the Louisville area or to actual maintenance costs of the heating system. Future research efforts will include the monitoring of deck temperatures at various depths and the establishment of definite operational settings for the logic system of master controller.

References

1. Roy Jorgensen and Associates, *Non-Chemical Methods of Snow and Ice Control on Highway Structures,* National Cooperative Highway Research Program, Report 4, Highway Research Board, 1964.
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