# Bridge Heating Using Ground-Source Heat Pipes

**RON C. LEE, JOHN T. SACKOS, JOHN E. NYDAHL, and KYNRIC M. PELL**

ABSTRACT

An experimental bridge deck heating system has been constructed and monitored that uses field-assembled heat pipes to transfer energy from 100-ft vertical evaporators in the ground. Measurements indicate that the heated surface was from 2° to 14°C warmer than the unheated portion of the bridge during heating events. This heating was sufficient to prevent the preferential freezing of the bridge deck surface relative to the adjacent road and provided some snow melting. A computer model that simulates the performance of ground heat pipe systems has been developed and verified by using data from two experimental facilities. This model is being used in conjunction with experimental results to prepare a general design procedure for these types of systems.

Pavement heating systems to control snow and ice accumulation on bridges and ramps have been incorporated at certain critical locations as an alternative to the more traditional methods of plowing or using deicing chemicals. These systems have typically been either embedded electrical resistive heaters or pipes circulating a fluid. The circulating fluid systems generally use fossil fuel energy sources, although several low-grade renewable thermal energy sources such as geothermal water (1) and the warm ground below the frost line (2) have also been tested. The efficiency with which low-grade energy can be transported to the road surface is an area where improvement can be made.

The use of gravity-operated heat pipes to transport thermal energy to a road surface was investigated and developed during the 1970s (3-8). The gravity-operated heat pipe consists of a sealed enclosure that contains a fluid in the liquid-vapor state over its operating temperature range. The lower end of the pipe is the evaporator section, whereas the upper portion is the condenser section. When the evaporator section is warmer than the condenser section, a portion of the liquid vaporizes and travels to the condenser section, where it condenses with the release of its latent heat of vaporization. The evaporation and condensation process creates the driving potential to transport the vapor upward, while gravity returns the condensate to the evaporator. This makes the gravity-operated heat pipe an attractive heat exchanger because it is a completely passive system that does not require any mechanical or electrical parts. Ammonia has been used as the working fluid in these heat pipes, which has the advantage over water-based systems in that it is not susceptible to freezing.

Because the thermal energy is transported in the form of latent heat of vaporization, the heat pipe can transport large amounts of energy over relatively long distances (∿55 m at two installations) with only a small temperature difference. For this reason, low-grade thermal energy sources that might otherwise be totally inadequate for the heating of road surfaces may be feasible energy sources in some situations. The ground heat pipe concept is particularly attractive because of the availability of its renewable energy source.

The average ground temperature several meters below the surface is typically a few degrees greater than the yearly average air temperature. This means that a large media at a temperature on the order of 10°C is theoretically available for use at most U.S. locations. However, the extraction rate of this ground energy is limited by the surface area of the heat pipe, the thermal conductivity of the deck and the ground, and the heat capacitance of the ground. The cost of the ground heat pipe system is obviously also directly related to its surface area, especially the length of the evaporator pipes. Approximately 40 percent of the cost of the ground heat pipe systems that have been installed has been directly attributable to drilling and grouting the evaporator holes. These costs are extremely site specific and are therefore a significant design consideration.

## EARLY GROUND HEAT PIPE SYSTEM RESEARCH

Experimental testing of ground heat pipes was initiated in 1970 at the FHWA Fairbanks Highway Research Station (4). The tests, which were conducted by the Dynatherm Corporation, successfully demonstrated the concept as well as pointing out necessary construction precautions. It confirmed, for example, that proper internal cleaning of the heat pipe was extremely important to prevent the generation of noncondensable gases that subsequently block the condenser. The results of this experiment were sufficiently promising to justify the heating of a highway ramp (5) in Oak Hill, West Virginia, by heat pipes. This system was constructed in 1975 and uses 1,213 ground heat pipes extending 60 ft (18.3 m) into the ground. This system was generally successful in preventing snow and ice accumulation, except when snow drifting occurred. The far-field ground temperature in this case averaged around 13°C.

To further develop ground heat pipe technology, the University of Wyoming, under the sponsorship of the Wyoming Highway Department and FHWA, has designed and operated two experimental facilities in southeastern Wyoming. The goals of these projects have been to experimentally investigate the performance of ground heat pipe systems for bridge decks as well as to develop the analytical framework to extend these experimental results into a general design procedure. A schematic of the ground heat exchangers used at these two facilities is shown in Figure 1.

The Sybille Canyon facility (6) was constructed in 1976. A small section of this bridge was heated by 15 heat pipes with ground evaporator lengths that averaged around 40 ft (12.2 m). This experimental site was heavily instrumented to monitor the thermal response at various locations in the deck and roadway and the environmental conditions. At the conclusion of the study, 22 months of essentially continuous data had been collected at 10-min intervals.

The heat pipe system proved to be capable of eliminating any preferential freezing of the heated bridge relative to the adjacent road. The reductions in some of the other freezing parameters that can be

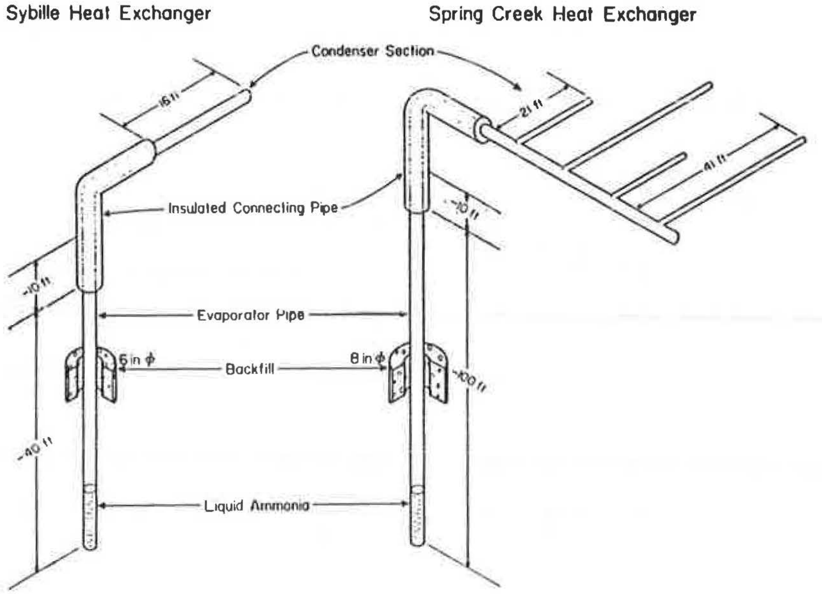

FIGURE 1 Schematic illustration of Sybille Canyon and Spring Creek heat exchangers.

used to characterize the performance of the system are as follows:

| | Percent Reduction | |
|---|---|---|
| Heated Surface Parameters | 1977-1978 | 1978-1979 |
| Snow cover time | 48 | 37 |
| Time frozen | 72 | 57 |
| Integrated temperature below freezing (°C days) | 90 | 79 |

The time-temperature below freezing is the area under the freeze line (0°C) on a surface temperature versus time plot. This parameter provides a measure of the severity of a freeze period.

This was a fairly impressive performance, considering that this was a bridge exposed to the severe Wyoming climate (the second winter being unusually severe), whereas the West Virginia test was performed on a ramp at grade. The far-field ground temperature at Sybille Canyon averaged around 10°C.

## SPRING CREEK EXPERIMENTAL FACILITY

The Spring Creek facility (7) was constructed in 1981 in Laramie, Wyoming. An overview of this site is shown in Figure 2. The entire bridge deck, except for a small control section, is heated with 60 evaporator pipes using the manifold ground heat exchanger design shown in Figure 1. In addition, the bottom surface of the heated deck was insulated.

The evaporator sections were constructed from 2-in. (5.08-cm) schedule 80 steel pipe. The sections extend 100 ft (30.5 m) into the ground on 10-ft (3.05-m) centers. A high thermal conductivity grout was backfilled around the evaporator pipes to improve their thermal contact with the ground. Each evaporator pipe supplies four condenser pipes embedded in the deck on 6-in. (0.152-m) spacing through a manifold. The condenser pipes were constructed from 1-in. (2.54-cm) schedule 40 pipe. The pipes were alternatively 21 and 41 ft (16.4 and 12.5 m) long.

The construction of this heat pipe system was obviously much more complex than the previous systems, which consisted of a single tube that was totally assembled in the factory, except for a single field bend. The assembly of the large Spring Creek heat pipes each involved several welds, leak tests, and charging that had to be performed in the field without contaminating the system.

This experimental site was also heavily instrumented to record environmental conditions and system performance. Data acquisition was initiated on January 1, 1982.

The following reductions in heated surface freezing parameters relative to the unheated deck surface (nontraffic lanes) is again used to quantify the system performance:

| | Percent Reduction | |
|---|---|---|
| Heated Surface Parameters | 1/82-5/82 | 10/82-5/83 |
| Snow cover time | 46 | 47 |
| Time frozen | 46 | 34 |
| Integrated temperature below freezing (°C days) | 72 | 68 |

These results are not as impressive as those obtained at Sybille Canyon, but the far-field ground temperature at Laramie is only 8°C, which represents a 20 percent drop in ground temperature relative to freezing as compared to the Sybille Canyon site.

Figure 3 presents a plot of weekly averaged temperatures on the top surfaces of the heated and control sections, as well as the remote ground temperature at the 60-ft (18.3-m) depth. Because heating events are of present interest, only events where the heated surface temperature was below that of the remote ground were considered. The remote ground temperature represents the maximum temperature that the heated surface can approach during such events, whereas the difference between the heated and control temperatures corresponds to the amount of heating that actually occurred. Maximum temperature increases on the order of 10°C were achieved during the coldest periods.

Although the remote ground temperature represents the theoretical temperature potential of the system, the local temperature surrounding the evaporator pipes is depressed because of energy extraction. This depression can degrade the performance of the system with time, and it is a complicated function

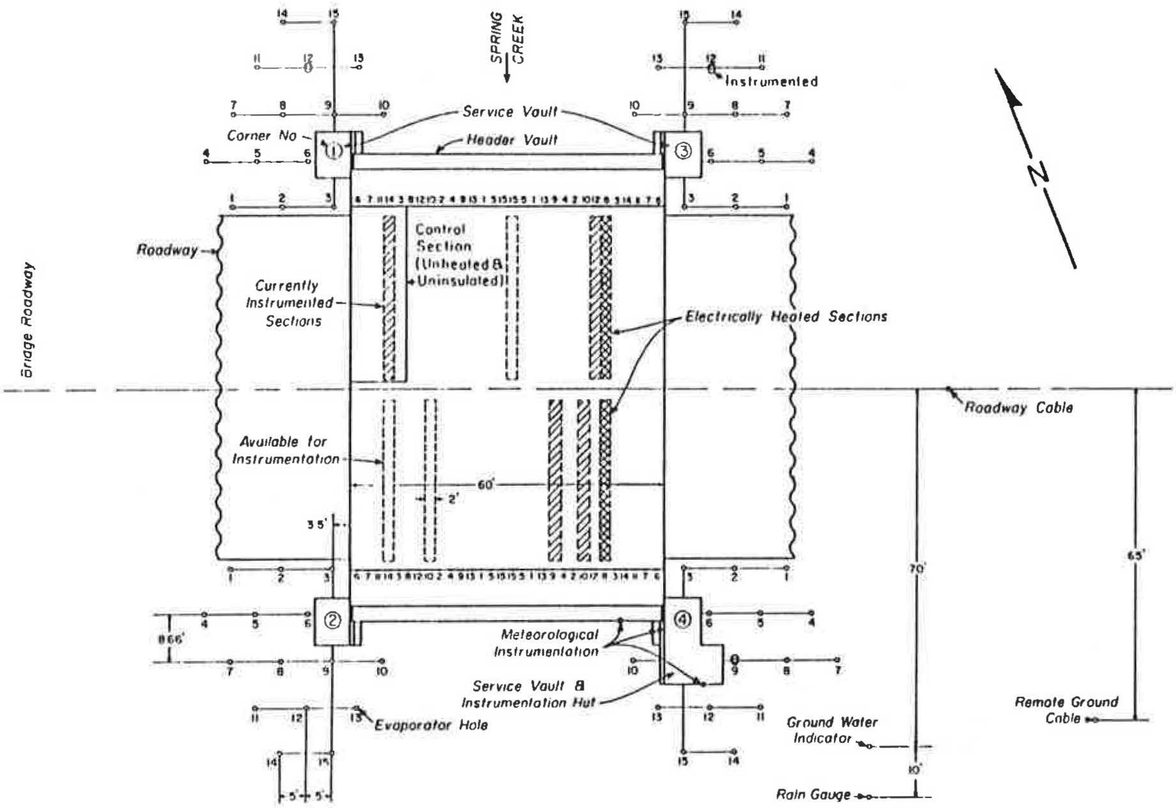

FIGURE 2 Schematic of the Spring Creek facility.

of the amount and rate of energy extraction as well as the thermal recovery of the evaporator field over the summer. The evaporator pipe and remote ground temperature histories are shown in Figure 4. The data in this figure indicate that the temperature of the ground in proximity to an evaporator was depressed by as much as 10°C, with recovery after the first two heating seasons being within 1°C of the far-field ground temperature. The system is to be monitored for 2 more years (until September 1985), which should provide sufficient experimental evidence concerning whether there will be any progres-

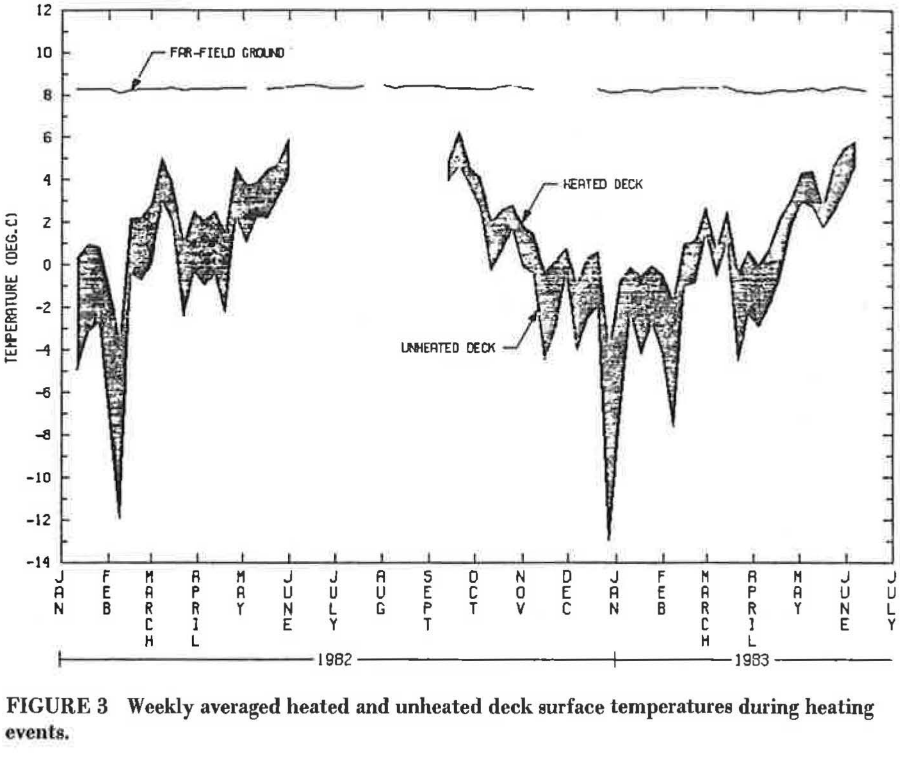

FIGURE 3 Weekly averaged heated and unheated deck surface temperatures during heating events.

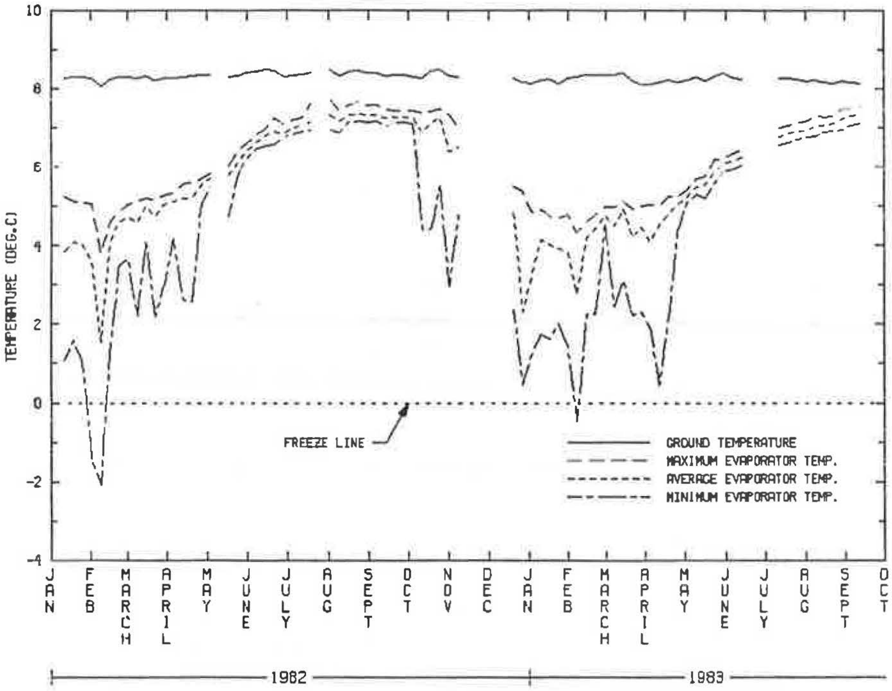

FIGURE 4 Weekly averaged evaporator pipe and far-field ground temperatures at 60 ft (18.3 m).

sive thermal depression of the ground surrounding the evaporator pipes.

The results of the Spring Creek and Sybille Canyon systems were sufficiently successful and provided the necessary expertise to encourage the incorporation of 177 ground heat pipes in the design of an overpass in Cheyenne, Wyoming (8).

## ANALYTICAL MODELING

The results of the Spring Creek project, as well as those of the Sybille Canyon facility, provided valuable quantitative performance data for ground heat pipe systems. However, to extend these results into a general design procedure, it was necessary to construct a model that is capable of accurately predicting system performance. A schematic of the heat transfer system that formed the basis of this model is shown in Figure 5.

The model accounts for time-dependent heat transfer in the ground and bridge deck, and the necessary coupling to the environment. Snow melting was not included in the model because only the long-term system performance was of major concern in the design model. There are three types of bottom sur-

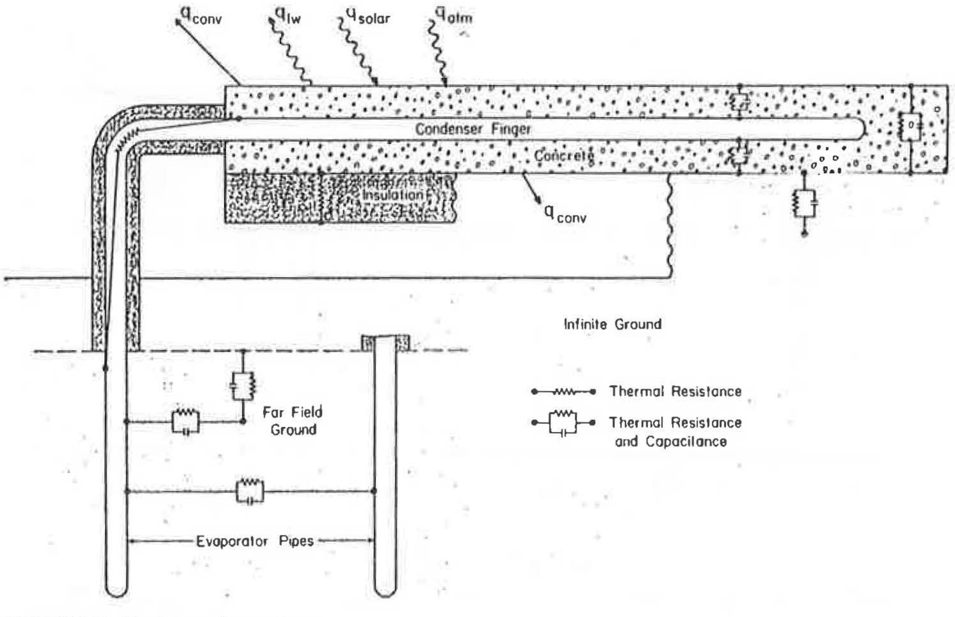

FIGURE 5 Heat transfer system.

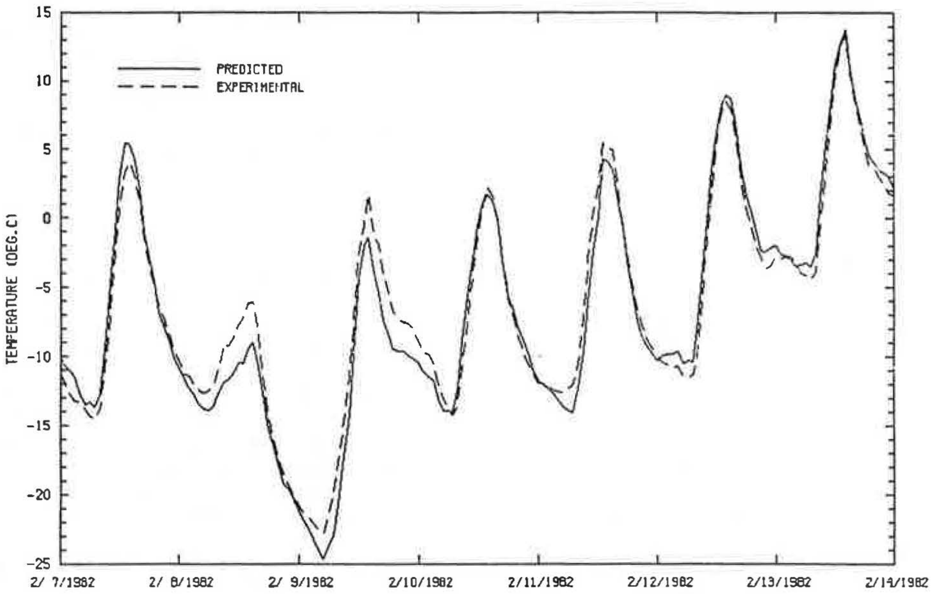

FIGURE 6 Top surface temperatures of unheated deck.

face conditions that can be accounted for: insulated, uninsulated, and ground coupled. Even though standard hourly weather tapes are used as part of the input data base, multiyear simulations can be performed with little computer time because the heat transfer equations are formulated in terms of response functions. The details of the heat transfer model are presented elsewhere (8,9).

To test the validity of the model, a comparison between the predicted and measured performance of the Spring Creek system was performed. The results from 1 week (February 7-14, 1982) of this simulation for the top surface of the unheated and heated decks are presented in Figures 6 and 7. This time period was chosen as being representative of a period of significant deck heating. Figure 6 shows that there is consistent agreement between experimental and predicted unheated top surface temperatures. The corresponding results for the heated top surface (Figure 7) also indicate satisfactory agreement, with minimum temperatures being as much as 14°C higher than the control surface. Similar results were obtained for the remainder of the Spring Creek data base and also for the Sybille Canyon system. The accurate simulations of these two different systems indicate that the analytical model can be used with some confidence as a design tool.

A preliminary parametric study has been undertaken by using the model to predict the performance of the Spring Creek system as a function of certain significant thermal and geometric parameters. The measure of performance that was chosen was the total energy extracted by the heat pipe system over one heating season (September 1982-May 1983). Figure 8 presents the results of this parametric study, where the percent of base heat extraction is plotted as a function of percent change of a system parameter. Energy extraction is seen to be a reasonably strong

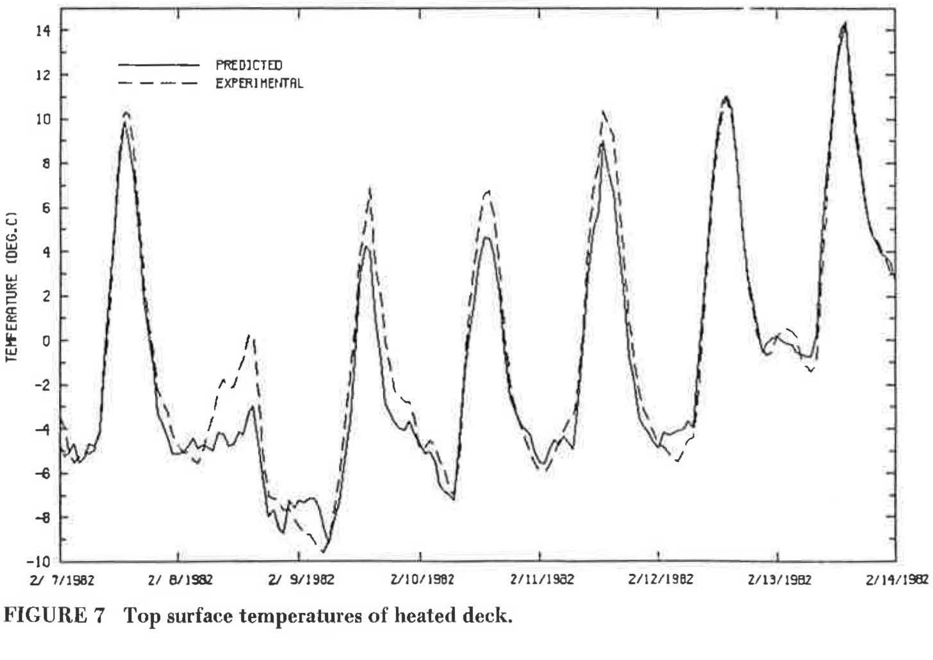

FIGURE 7 Top surface temperatures of heated deck.

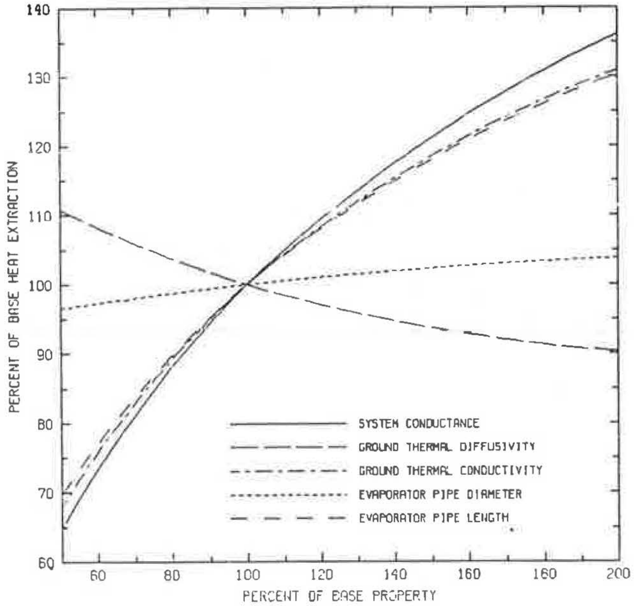

**FIGURE 8 Percent change of base energy extraction at Spring Creek as a function of various parameters.**

function of the length of the evaporator pipe, the thermal conductivity of the ground, and the thermal conductance of the system from the heat pipe to the air. A somewhat weaker dependence on the thermal diffusivity of the ground is exhibited, and it was found that there is essentially no dependence on the diameter of the evaporator pipe.

## CONCLUSIONS

The experimental results for the two bridge heat pipe systems that have been recorded to date indicate that these systems have prevented preferential icing conditions on the bridges as well as providing a significant amount of snow- and ice-melting capability. Further monitoring of the Spring Creek facility will address the long-term characteristics of the system.

The experimental data bases generated at the Sybille Canyon and Spring Creek facilities have been used to verify an analytical model that predicts the transient performance of ground heat pipe systems. This model, in conjunction with experimental results, is being used to prepare a general design procedure for ground heat pipe systems.

## REFERENCES

1. M. Sekioka et al. Thermal Considerations on Snow Melting System with Natural Thermal Water at Jozankei Spa, Sapporo, Japan. Journal of Japan Geothermal Energy Association, Vol. 16, No. 2, 1979.
2. F. Winters and S.R. Sasor. Pavement Heating--Executive Summary. Report 77-003a-7722. New Jersey Department of Transportation, Trenton, 1977.
3. J. Nydahl et al. Data Collection and Analysis for Geothermal Research. Final Report. Colorado Department of Highways, Denver, 1981.
4. W.B. Bienert et al. Snow and Ice Removal from Pavements Using Stored Earth Energy. Report FHWA-RD-75-6. FHWA, U.S. Department of Transportation, 1974.
5. D.C. Long and J.S. Baldwin. Snow and Ice Removal from Pavement Using Stored Earth Energy. Report FHWA-TS-80-227. FHWA, U.S. Department of Transportation, 1980.
6. V.A. Cundy. Transmission of Earth Energy by Heat Pipes for Thermal Control of Bridge Decks. Ph.D. dissertation. University of Wyoming, Laramie, 1979.
7. J.T. Sackos. Bridge Deck Heating Using Earth Coupled Heat Pipes. Thesis. University of Wyoming, Laramie, 1983.
8. J. Nydahl et al. Thermal Design of the Earth Heat Pipe System for the U.P. Railroad Overpass. SETA Corporation, Laramie, Wyo., 1981.
9. R.C. Lee. Heat Transfer Analysis of Geothermally Heated Road Structures. Thesis. University of Wyoming, Laramie, 1983.

---

Publication of this paper sponsored by Committee on Winter Maintenance.