A DEMONSTRATION PROJECT FOR DEICING OF BRIDGE DECKS

Charles H. Wilson, David H. Pope, Wyoming Highway Department
Vic A. Cundy, John E. Nydahl, and Kynric M. Pell, University of Wyoming

An experimental facility to study the use of gravity operated heat pipes to couple earth heat to a bridge deck for snow and ice control has been developed at a site in southeastern Wyoming. Fifteen heat pipes of three different designs were incorporated in the design and construction of a composite bridge deck. Nine standard heat pipes 24.4 m (80 ft.) long and 2.5 cm (1 in.) outside diameter were installed transverse to the direction of traffic flow 5 cm (2 in.) below the deck surface on 15 cm (6 in.) centers. These pipes extend from depths of 15 m (50 ft.) in the earth up through the earth surface and through the edge of the deck to the bridge centerline. The performance of the heat pipe system has been monitored and recorded continuously at one minute intervals for over one year using a variety of instrumentation transducers and a digital data acquisition system. In addition the surface conditions on the deck and the adjacent roadway were recorded photographically at five minute intervals during daylight hours. The results obtained demonstrate that heat pipes can be an effective means of snow and ice control on bridge decks.

Heat pipes are a relatively recent invention (1) and have proven extremely efficient for transferring thermal energy. They have been widely used for thermal control of spacecraft and are being incorporated in an increasing variety of earth bound applications. Bienert and Pravda, et al. (2) proposed that gravity operated heat pipes be used to transfer low grade energy from the earth below highway structures to the road surface for control of ice and snow. The concept was investigated experimentally using several concrete slabs incorporating heat pipes in a study conducted at the Fairbank Highway Research Station (3,4). Results of this study were used in the design of a heat pipe system installed in a 366 m (1200 ft.) long interchange ramp in Oak Hill, WV (5). This system has operated successfully for the past two years. The use of heat pipes for control of preferential icing of bridge decks was investigated by Ferrara and Yenetchi in a study undertaken in 1975 (6). Somewhat earlier, work had been initiated at the University of Wyoming on modification of a heat transfer simulation for highway structures (7) to treat the case of heat transfer from the ground to a bridge deck via heat pipes (8). The simulation was used to investigate the performance of a heat pipe system at a site located in southeastern Wyoming. It was shown that heat pipes could be effective for the control of preferential icing; however, uncertainties in the thermal modeling of the coupling between the heat pipes and the earth imposed a requirement for field testing prior to incorporation of heat pipes in a major structure located in a severe environment. In the Spring of 1976, the Wyoming Highway Department and the University of Wyoming entered into an agreement to conduct a rather extensive research program on the thermal control of bridge decks using gravity operated heat pipes. In particular, a limited number of heat pipes and requisite instrumentation were to be incorporated in the construction of a new bridge. The overall objective of the research program was to generate an empirical data base on the insitu performance of gravity operated heat pipes. Specific goals of the program included:

1. Measurement of the power and energy delivered to the deck by a heat pipe.
2. Characterization of the thermal coupling between the earth, the heat pipe and the bridge deck.
3. Investigation of the thermal recovery of the earth surrounding the heat pipe during periods when the heat pipes were not functioning.
4. Characterization of the relative surface condition of the unheated portion of the bridge deck, the heated section of the deck and the adjacent roadway during an entire winter season.
5. A variety of minor studies, such as, the use of unconventional heat pipes.

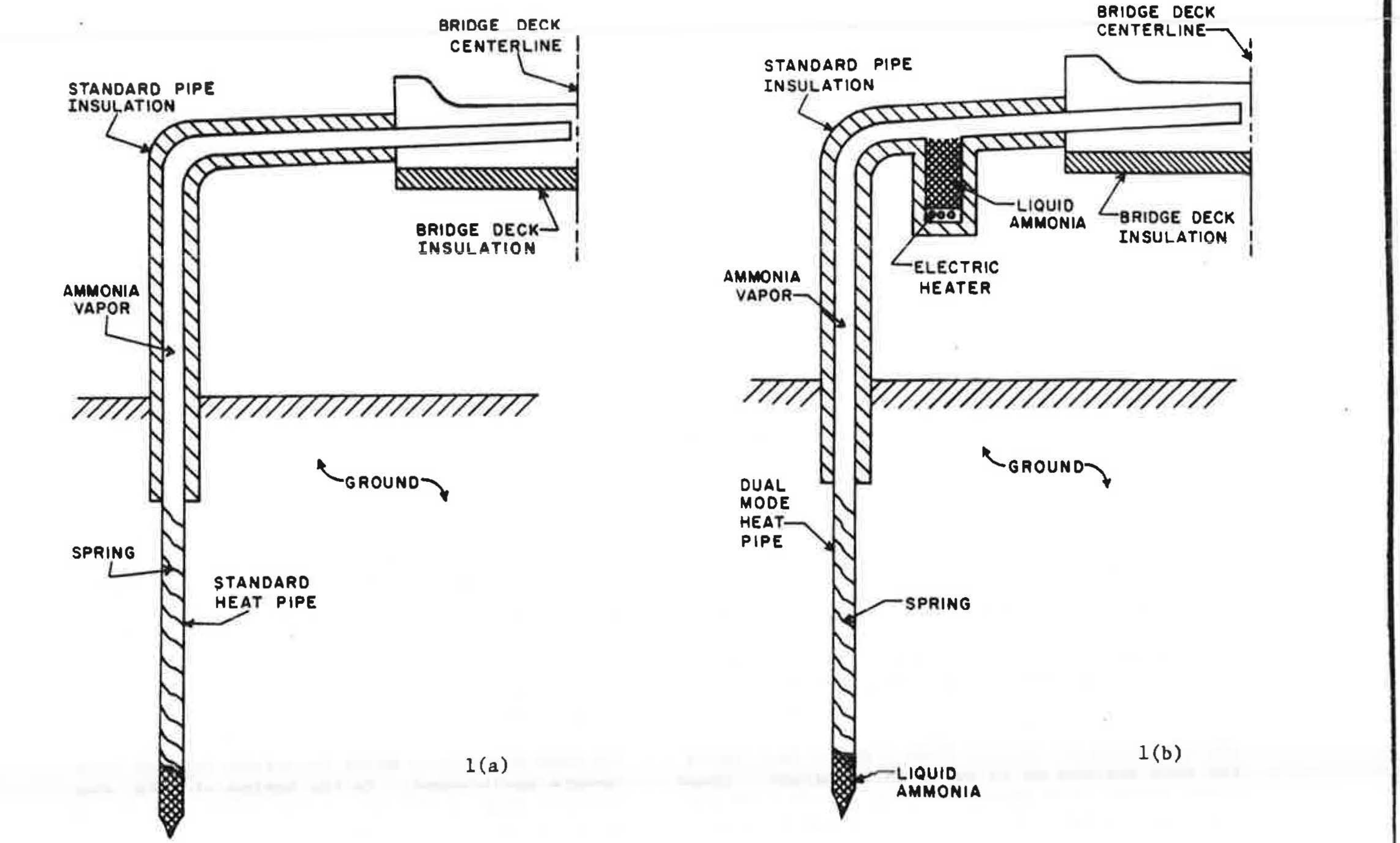
This paper describes the design, fabrication and installation of the heat pipes and instrumentation at the experimental site which is located at a bridge over Sybille Creek on State Highway No. 34 in southeastern Wyoming.

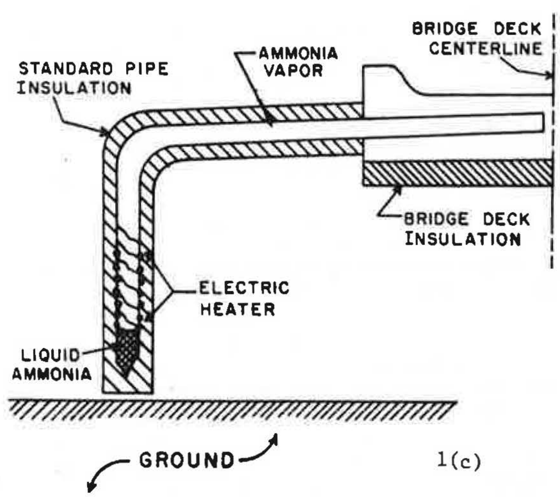
Heat Pipes

Conventional Heat Pipes

A conventional gravity operated heat pipe is a closed chamber, generally constructed of metal, containing a volatile working fluid. Figure 1(a)

Figure 1. Configurations of three types of heat pipes.





illustrates the standard heat pipes used in this study. The heat pipes were fabricated from seamless, cold rolled, low carbon steel tubing with an outside diameter of 2.5 cm (1 in.) and a 0.3 cm (1/8 in.) wall thickness into 24.4 m (80 ft.) lenghts. These tubes were evacuated and filled with 0.2 kg (0.45 lbm) of ammonia which was also the condensable fluid that was used in the other two demonstration projects. Over the temperature range that a heat pipe was exposed to, part of the ammonia resided as a liquid in a pool at the bottom of the tube while the remaining ammonia was in the vapor phase filling the rest of the tube. Anytime the deck temperature fell below the temperature of the ground in contact with a heat pipe, the vapor in the deck section condensed and flowed towards the bottom of the tube. At the same time, energy was conducted from the ground to the colder heat pipe where it evaporated part of the liquid ammonia. The spring in the evaporator section was used to increase the area that was wetted by returning condensate. The heat pipe is essentially an isothermal device since the energy is transferred in the form of latent heat of evaporation instead of sensible heat. It was therefore ideally suited for this application where low grade energy was extracted from the ground. Besides its apparent constructional simplicity, this device is self-regulating, should have a long lifetime, and could possibly be incorporated as part of the rebar structure.

Dual Mode Heat Pipes

Three experimental heat pipes were also used in the project. Their design termed here, dual mode, is illustrated schematically in Figure 1(b). As the name implies this heat pipe has two means of energy input. In addition to the standard evaporator in the ground there was an additional evaporator provided at a convenient location above ground. The purpose of this design was to allow additional energy to be transferred to the bridge surface when necessary by heating the secondary evaporator with an alternate energy source. Electrical resistance heaters were mounted in good thermal contact with the bottom of the secondary evaporator. These heat pipes operated as conventional heat-pipes when the secondary evaporator was full of liquid ammonia and no power was applied to the heaters. When additional

power was required and the heaters were activated some of the ammonia vapor from the secondary reservoir condensed in the lower part of the pipe as well as in the condenser and eventually the liquid ammonia in the secondary evaporator was depleted. The secondary evaporator was then recharged through a period of operation as a conventional heat pipe.

Electric Heat Pipes

Figure 1(c) is typical of three electrically operated heat pipes which were installed at the site. The evaporator sections of these pipes protruded from the side of the deck and were equipped with external heaters to provide the energy input. These pipes were included for two reasons. First, they could be heated using a controller to provide an accurate measurement of the power being provided by the standard heat pipes. Secondly, this design appears to be a viable approach to coupling renewable energy sources such as wind energy to a bridge deck and therefore merits further study.

Fabrication and Installation of Heat Pipes

Fabrication

Fabrication of the heat pipes involved the following seven steps regardless of the particular type of pipe being fabricated:

1. Cleaning of the tubing.
2. Installation of the springs.
3. Welding of the tubing sections.
4. Evacuation of the pipe.
5. Loading of the ammonia.
6. Crimping and welding of the fill nipple.
7. Testing.

Cleaning of the tubing was initiated with a solvent rinse using unleaded gasoline which was followed with a mechanical abrasive cleaning using SOS pads and alcohol. Following an acetone rinse, a clean dry rag was pulled through the tubes.

The inside wall of each of the evaporator sections was lined with a spring to cause the condensate to spiral down the pipe rather than run down one side in the form of a rivulet. This wets the wall more effectively allowing more efficient and uniform vaporization. There was a mechanical problem due to the fact that the springs must be tight against the inside wall of the pipe. Piano wire was wound on a mandrel in a lathe and placed inside the heat pipe where it was released to uncoil against the inside of the pipe.

Welding of the 6 m (20 ft.) lengths of seamless tubing to form the 24 m (80 ft.) heat pipes was accomplished using a TIG arc welder and an end cap was welded on one end and a workable steel nipple was welded to the opposite end. The pipes were evacuated using conventional vacuum techniques and then filled with 0.2 kg (0.5 lb) of ammonia. Finally, the nipples were crimped and welded. Testing of the pipes included resistive heating of the evaporators to cause the heat pipes to operate for a period of one month. The pipes were situated on an incline of approximately 5° for this test. Each weld was also tested chemically using a technique developed by NASA to insure that the leak rate was less than 3.3×10^{-7} std cc sec^{-1} (9). Fabrication of the dual mode and electrically operated heat pipes was similar to the conventional heat pipes.

Installation

After all of the footings had been poured at the bridge site, but prior to construction of any above ground formwork, a drilling crew from the geology division of the state highway department drilled 12 holes 15 cm (6 in.) in diameter and 18.3 m (60 ft.) deep at the locations indicated in Figure 2. The holes were cased with 10 cm (4 in.) PVC. Three men assisted in guiding each pipe into its particular hole and all twelve pipes were installed, using a crane, in two hours. In order to make the heat pipes as unobtrusive as possible during the subsequent construction, they were left standing vertical and the 6 m (20 ft.) to 9 m (30 ft.) of pipe extending beyond the surface of the ground was guyed off as shown in Figure 3. The pipes were installed in late October 1976 and remained in the vertical position until early in December when they were bent into position on top of the rebar. The bending operation may be seen in Figure 4. and the position of the pipes in the deck is shown in Figure 5. A manual tubing bender commonly used by electricians was used to bend the pipes. All of the heat pipes were tied to the rebar at a depth of 5 cm (2 in.) below the surface on 15 cm (6 in.) centers. The 2 percent slope from the centerline to the curb was adequate to insure that the condensate would flow back to the evaporator.

Wooden dowels were attached to the formwork under and in the vicinity of the heat pipes as shown in Figure 5. After the deck was poured, the PVC casing was removed from the holes surrounding the heat pipes with the exception of a 3 m (10 ft.) long section which was left extending from the surface down into the earth. The holes were backfilled with bentonite up to the PVC and then the region where the casing remained was insulated with strips of rigid, closed cell, insulation. The exposed portion of the pipe between the earth and the bridge deck was insulated with standard fiberglass pipe sections which were in turn wrapped with a thin plastic cover.

Instrumentation

Temperature Sensors

Previous investigations involving measurement of temperature in bridge decks and the earth have shown that thermistors can be a cost effective approach to temperature measurement; however, care must be taken to protect the small leads from vibration and to protect the thermistor and its associated circuitry from moisture (10). The technique used to instrument the deck involved attaching a thermistor and its precision resistor to each of ten pairs of shielded, twisted, conductors in an eleven pair cable. A single precision resistor was connected across the eleventh pair of conductors in the cable. The termistors and resistors were then potted in high thermal conductivity epoxy in one of the configurations shown in Figure 6.

The approach used on fabrication of the ground sensors was somewhat different and was intended to provide more assurance that moisture would not penetrate the cable or sensor. A short section of the outer jacket of the cable was peeled back and a single twisted pair of conductors was cut to install the thermistor and associated resistor. A cylindrical mold incorporating a reduced diameter on each end was used to cast an epoxy housing for the sensor. The cylinder was concentric with the cable. Silicone rubber sealant was then applied to the exposed shielded conductors and the shoulder of the epoxy

Figure 2. Schematic arrangement of experimental site.

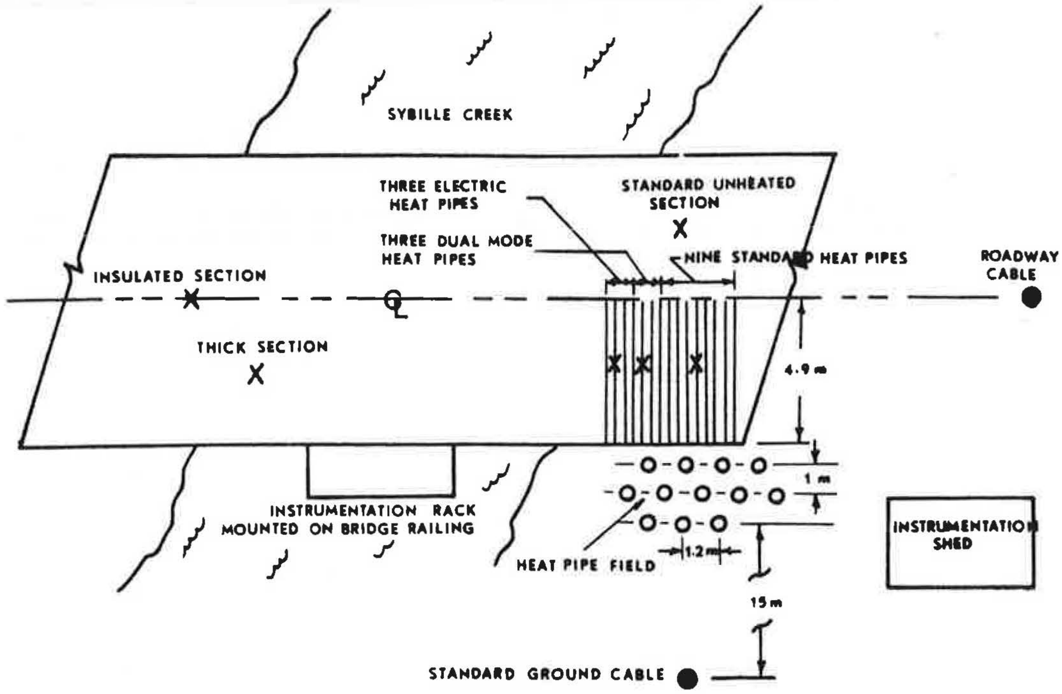


Figure 3. Heat pipes installed in the ground.

Figure 4. Heat pipes bent into the bridge deck.

Figure 5. Heat pipes and instrumentation dowels in the bridge deck.

step. The outer jacket of the cable was pulled over the shoulder of the epoxy and a fine wire was used to clamp the outer jacket to the epoxy. A small amount of silicon rubber sealant was applied to the outside of the cable jacket at the epoxy interface. A second mold was used to form a complete epoxy cylinder by filling in the region of the step. This sequence is illustrated photographically in Figure 7.

The technique used to instrument the heat pipes in the ground was similar to those described previously; however, each cable included only a single pair of conductors. An epoxy cylinder housing the thermistor and its resistor was cast concentrically on the heat pipe at various axial locations. The cylinders were 4.5 cm (1.7 in.) in diameter and 2.5 cm (1 in.) in length.

The wooden dowels installed prior to pouring the deck were drilled out to allow installation of the temperature sensors from the bottom of the deck as shown in Figure 8. Sensors were installed to mea-

Figure 6. Typical temperature sensor design and placement.

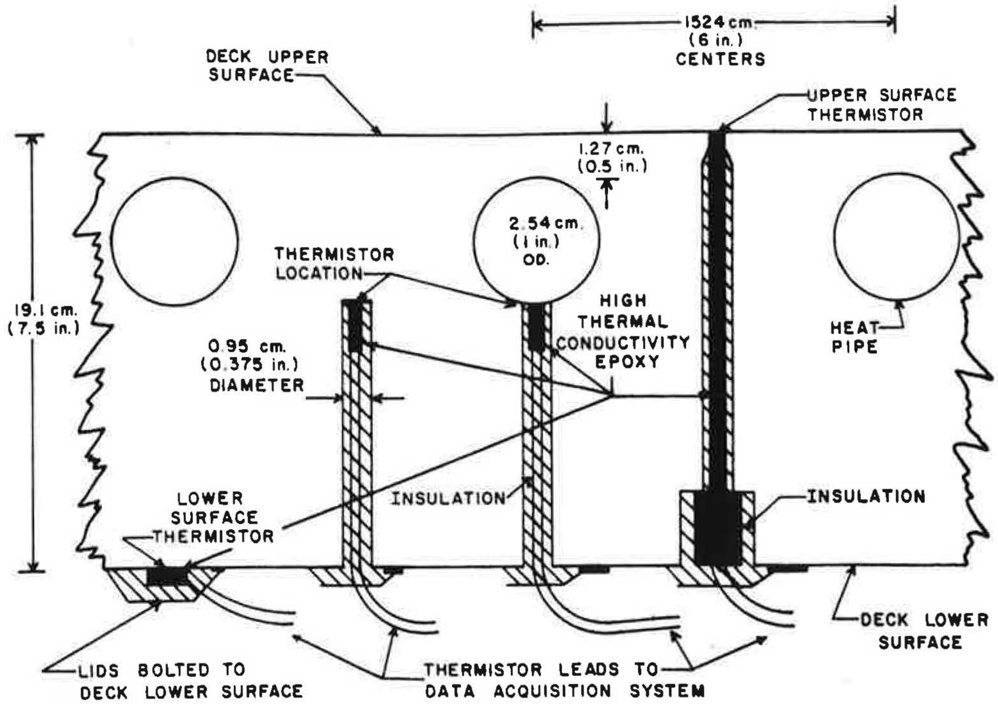


Figure 7. Sequence of fabrication steps for temperature sensors.

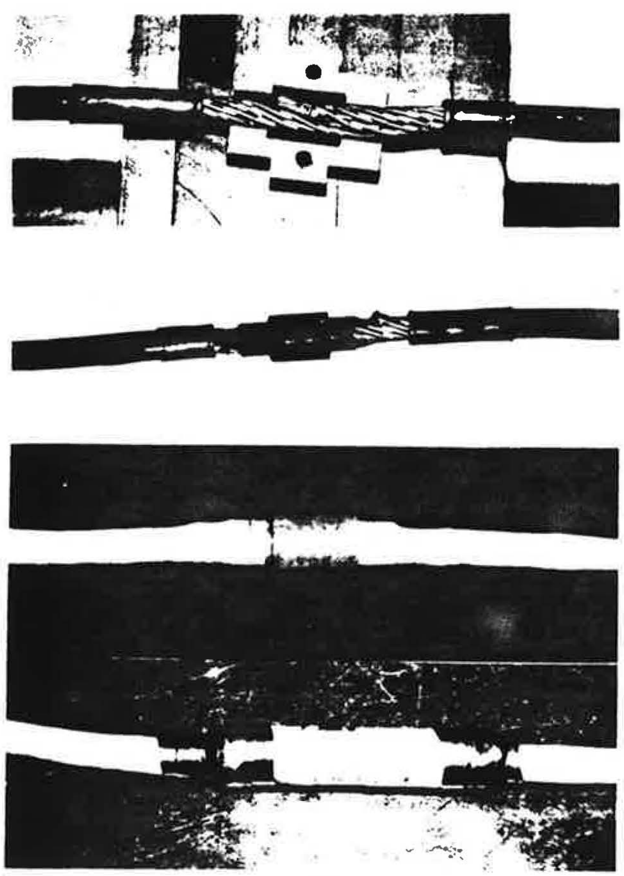
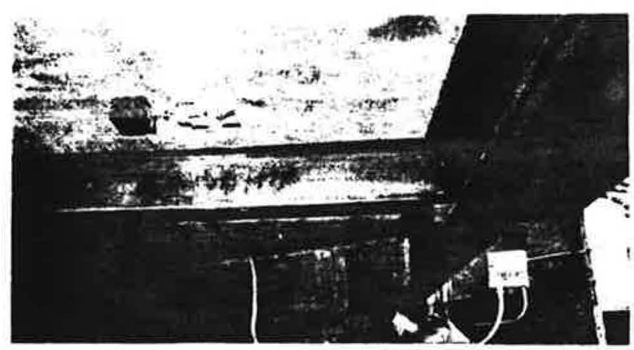


Figure 8. Instrumentation as viewed from the bottom of the bridge deck.



sure vertical temperature distributions in the deck at the locations indicated in Figure 2. In addition, one of each of the different heat pipes was instrumented with a symmetrical array of temperature sensors approximately at the midpoint of the condenser. Temperature sensors were also located on the surface of each heat pipe approximately 0.6 m (2 ft.) from the centerline of the bridge. The dual mode heat pipes each had a thermistor on the secondary reservoir approximately 2.5 cm (1 in.) above the bottom and an additional thermistor about 0.3 m (1 ft.) from the secondary evaporator on the surface of the condenser.

Two ground temperature instrumentation cables were fabricated with temperature sensors located at 1.5 m (5 ft.) intervals over a distance of 12 m (40 ft.). These cables were installed in 15 cm (6 in.) diameter holes indicated in Figure 2. which were then back filled with sand.

Table 1. Meteorological Instrumentation.

Parameter	Sensor	Sensor Range	Sensor Accuracy	System Accuracy
Relative Humidity	General Eastern Model 400-C	0-100%	±0.5%	±0.5% Humidity
Solar Radiation	Eppley Labs Model 8-48	0-2 $cal.cm^{-2}min^{-1}$	±1%	±.02$cal.cm^{-2}min^{-1}$
Reflected Radiation	Eppley Labs Model 8-48	0-2$cal.cm^{-2}min^{-1}$	±1%	±.02$cal.cm^{-2}min^{-1}$
Wind Speed	Electric Speed Indicator Model 420CR	0-100 Knots	±1%	±1 Knot
Wind Direction	Electric Speed Indicator Model 420CR	0-360 Degrees	±1%	±4 Degrees
Barometric Pressure	H.E. Sostman Co. 2014	19.2-25.7" Hg	±0.1%	±0.065" Hg
Precipitation	Science Associates Model 598-2	Yes-No	----	----------------
Temperature	Yellow Springs Inst. Thermilinear Thermistors	-50°C→+150°C	±0.15%	±0.32°C

Meteorological Sensors and Data System

The meteorological sensors and the data acquisition system were moved from the site of a previous experimental program and installed at the Sybille Canyon project after refurbishment and calibration in the laboratory. A list of the transducers installed at the site is provided in Table I. The data acquisition system is housed in the concrete shed illustrated in Figure 2. This system was designed and fabricated at the University of Wyoming and is capable of sequentially sampling, digitizing, and recording 100 channels of analog input in less than four seconds. The entire system consisting of a line voltage regulator, digital system and digital recorder is mounted in one instrumentation rack. The digital system includes an electronic multiplexer, amplifier, A/D converter, digital clock, and a logic module. These components are mounted in functional arrays on printed circuit boards. A rack mounting unit with appropriate card guides and terminal strips houses the complete digital system. In order to isolate the data acquisition system from transients introduced by the various heaters and the air conditioner in the instrumentation shed, a separate power line, operating off its own step down transformer, was provided.

Precipitation data was obtained from the Wyoming Game and Fish Commission Sybille Canyon Experiment Station, which is 0.8 km (0.5 mi.) west of the bridge site.

Other Instrumentation and Cabling

Surface conditions on the bridge deck and the adjacent roadway were monitored using a time lapse camera which was mounted on the instrumentation rack. The camera is a modified super eight movie camera which can be driven electronically by a variable timer which was set to provide a photograph every 5 minutes during daylight hours.

Power delivered by the standard heat pipes was measured indirectly by heating the electric heat pipes so that their condenser temperature matched the condenser temperature of the standard heat pipes and recording the amount of power delivered to the electric heat pipes. A simple binary controller was found to be suitable for maintaining the temperature of the electric heat pipes within 1 C° (1.8 F°) of the standard pipes.

Two 10 cm (4 in.) diameter PVC conduit were run underground from the shed to the bridge. All of the data cables installed on the bridge were run in steel conduit to a box at the bridge end of the PVC conduit and then through the PVC back to the instrumentation shed. The AC power lines for the various heaters and a utility outlet installed under the bridge were routed through the other PVC conduit in an attempt to isolate noise from the data lines. Cabling for the heat pipe instrumentation installed in the ground was gathered in a metal box located just below the earth surface in the heat pipe field and run through an underground conduit to the instrumentation shed. The roadway instrumentation cable and the ground cable were also installed in metal conduit.

Testing and Calibration

The fixed value precision resistors on the instrumentation cables provided a means of correcting the temperatures read by the data system for systematic errors. Several different values of resistance were used so that any nonlinearity in the system response could also be detected and taken into account. Based on twelve months of data from these resistors a systematic correction of 0.4 C° (0.7 F°) was applied to all temperature readings. Thermistors also exhibit a systematic nonlinearity which was almost completely compensated for using a sinusoidal response correction. With both of these corrections taken into account the absolute accuracy of the temperature measurements is ± 0.3 C° (0.5 F°).

Calibration of the radiometers was accomplished by direct comparison of their outputs with a super radiometer which was periodically taken to the field site. The anemometer and humidity detection system

were calibrated in the laboratory periodically. Wind direction and barometric pressure transducers were not calibrated on a routine basis but were periodically checked for consistency.

Results and Conclusions

The data acquisition system has been recording data continuously at one minute intervals since March 1977. During this period two of the sixty thermistors installed at the site have failed. A power supply in the digital system failed causing the loss of two days data, an instance of improper mounting of the magnetic tape caused the loss of six days data, and a power disruption due to a severe storm accounted for the loss of three days data. A decrease in the brush contact force on the anemometer resulted in invalid readings of wind speed during a thirty-day interval.

A detailed study of the accuracy of the temperature measurements indicated that the design of the temperature sensors was not only effective in providing protection from the environment but also led to accurate readings. With the exception of the anemometer the meteorological transducers and the time lapse camera proved extremely reliable.

In summary, of 487 days when data could have been recorded there were eleven days during which all data was lost. In addition there were 36 days when the wind speed data was in error.

The heaters for the dual mode and electric heat pipes utilized nichrome wire resistance heaters which were originally designed to provide 600 w (2050 Btu/hr) each. The high power requirement and compact design led to repeated heater failures. In January of 1978 the heaters for the electric heat pipes were replaced utilizing a design which incorporated shielded nichorme wire and provided 300 w (1025 Btu/hr). Although some noise problems were originally encountered in the operation of the electric heat pipe controllers they were found to be very effective in tracking the temperature of the standard heat pipes. The dual mode heat pipes were operated on numerous occasions with manual control of the heaters on the secondary evaporators. The period for which the heaters could operate prior to depletion of the ammonia in the secondary evaporators was found to be a linear function of the power applied.

A detailed description of the performance of the heat pipe system has been given elsewhere (11) but in the interest of completeness those results will be summarized here. In response to a rather severe environment where the yearly mean temperature was 6.7°C(44°F) and the monthly average temperature for January was -5.3°C (22.5°F) the heat pipes functioned intermittently from September to May. Typically, they provided energy to the deck during the night and in the daylight hours if precipitation occurred. However, even in severely cold weather the solar heating of the deck which occurred during the day was generally sufficient to heat the deck above the earth temperature at depth thereby shutting off the heat pipes. During an eight month period each pipe delivered in excess of 1×10^9 joules (1×10^6 Btu) at an average rate of 125 w/m^2 (40 Btu/hr-ft^2). A monthly summary of the energy flux is given in Figure 9 where it may be noted that the maximum flux occurred in November. The earth surrounding the heat pipes was cooled a maximum of 7C° (13F°) below the undisturbed earth in January; however, the temperature at the surface of the heat pipes recovered to the undisturbed earth temperature by July.

The heated portion of the deck was below freezing 30% of the time that the standard deck was below freezing. Although the surface of the standard (unheated) bridge deck was colder than the surface of the adjacent roadway it was, on the average, only two degrees colder and as a result the roadway had only 7% less time below freezing **than** the standard deck. The roadway, however, experienced twice as many freeze-thaw cycles as the standard deck.

Although the heat pipes were not capable of melting all of the snow as fast as it fell, they were completely successful in eliminating all instances of preferential icing. Figures 10 and 11 are typical of

Figure 9. Energy flux for a single heat pipe.

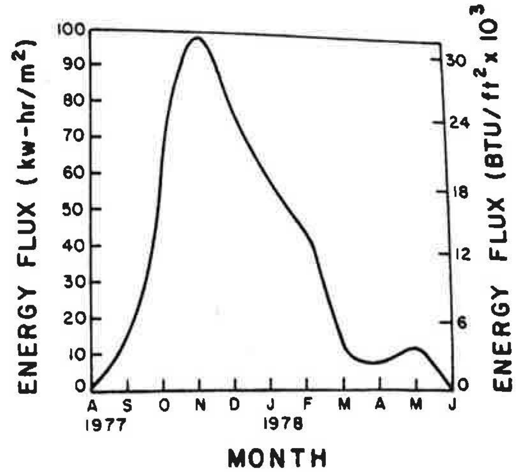


Figure 10. Typical early morning snow pack.

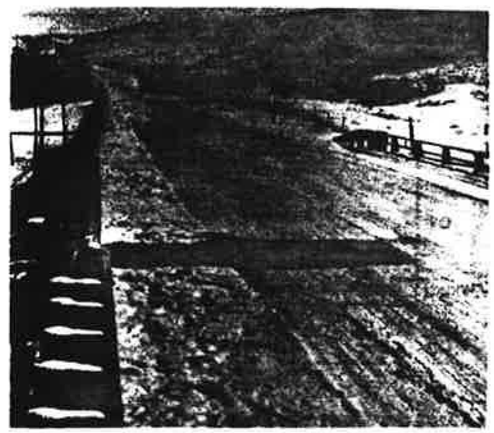
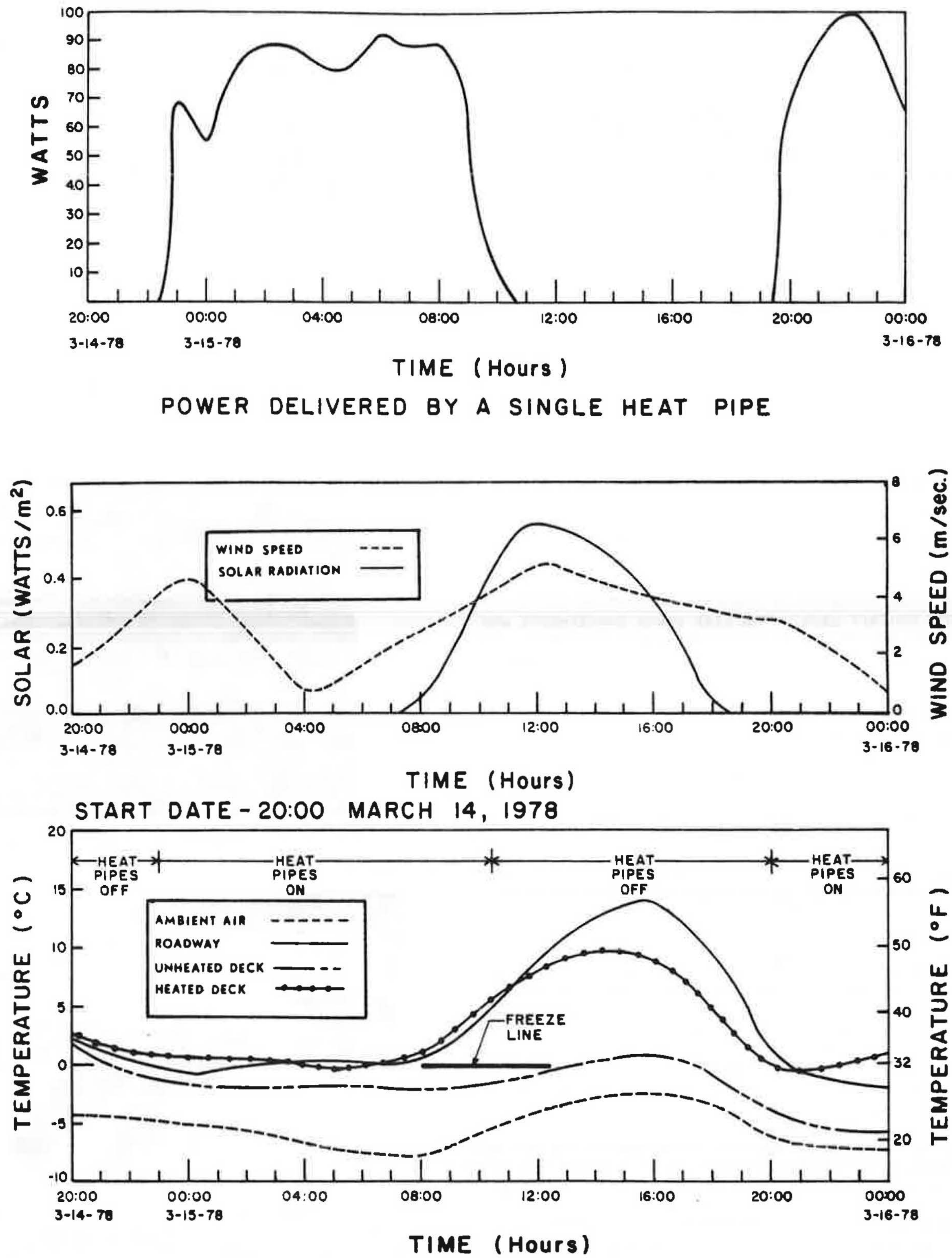


Figure 11. Typical snow pack situation as day progresses.

Figure 12. Typical 28 hour period exhibiting diurnal cycling of heat pipes.



the two most common situations involving accumulated precipitation. The case where the heat pipes were melting the snow and both the roadway and unheated deck were snow covered is shown in Figure 10. Generally, as the day progressed the roadway would clear and the situation shown in Figure 11 would develop.

Figure 12 depicts some of the most significant environmental variables and the corresponding surface temperature for the standard deck, heated deck and the adjacent raodway. Also shown in the figure is the power delivered by a heat pipe. The diurnal cycling of the heat pipes in response to the thermal coupling of the environmental parameters to the deck is evident. For the period of heating shown the average power is 80w (273 Btu/hr) and the peak power is 100w (342 Btu/hr). It may be seen that the heated portion of the deck remained above freezing, corresponding closely to the temperature of the adjacent roadway, whereas the unheated deck was below freezing a significant amount amount of time and experienced a freeze-thaw cycle.

Heat pipes utilizing energy from the upper 15m (50 ft.) of the earth have been demonstrated to be effective in eliminating preferential icing of a section of bridge deck in a quite severe environment. The location of the heat pipes in the bridge and the manner of installation were selected to minimize problems associated with construction of the bridge and interfacing of the bridge and heat pipes. It would not only be difficult to use a similar approach on an entire bridge of any size, but also rather expensive. There are two avenues for future study which could significantly reduce the cost of a heat pipe system and also reduce the potential construction problems. Techniques for manifolding several heat pipes from a single header pipe should be investigated. In addition, techniques for field assembly of a heat pipe composed of two or more segments would compliment the manifolding study.

Acknowledgments

The data acquisition system and heat pipe controllers were designed and fabricated under the direction of George Twitchell, Electronics Engineer, Department of Mechanical Engineering. A number of students in the Mechanical Engineering Department have been involved in the project. John Niethammer and Mark Weber assisted in the construction of the heat pipes. Doug Stephen assisted all of the above personnel with the installation of the heat pipes. Data reduction has occupied Doug Stephen, Tom Munro, Bruce Wise, Steven Ownbey and Victor Dlugoszewski.

References

1. S.W. Chi, Heat Pipe Theory and Practice. McGraw-Hill Book Comapny, New York, 1976.
2. W.B. Bienert, M.F. Pravda, et al., Nuclear Wastes in Comparison with Other Heat Sources for Deicing, Bridges, Ramps and Pavements, FHWA-DTM-70-6, 1970.
3. W.B. Bienert, M.F. Pravda, H.J. Suelau, and D.A. Wolf. Snow and Ice Removal from Pavement Using Stored Earth Energy. FHWA_RD_75-6, 1974.
4. C.P. Brinkman, Space-Age Technology for Deicing Hazardous Highway Locations. Public Roads, V39, pp. 89-95.
5. Don Long and John S. Baldwin, Earth Heat-the answer to highway ice?, Construction News, December 1977, pp. 8-12.
6. A.A. Ferrara and G. Yenetchi, Prevention of Preferential Bridge Icing Using Heat Pipes, Final Report, FHWA RD-76-167, September 1976.
7. K.M. Pell, J.E. Nydahl et al., Thermal Response of Bridges, Transportation Research Record, No. 576, 1976.
8. E. Faccini, Heat Transfer Simulation of the Geothermal Heating of Bridge Decks Using Heat Pipes, Thesis, University of Wyoming, 1976.
9. R. McIntosh, National Aeronautics and space Administration, Goddard Spaceflight Center, Greenbelt, Maryland (Private Communication).
10. K.M. Pell, J.E. Nydahl, and V.A. Cundy, Thermodynamics of Bridges, Roadways and Runways. DOT-TST-75-41, November 1974.
11. V.A. Cundy, J.E. Nydahl and K.M. Pell, Geothermal Heating of Bridge Decks, Proceedings of the Second International Snow Removal and Ice Control Research Symposium, Hanover, N.H., May 1978.