Geothermal Heating of Bridge Decks

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The capability of gravity operated heat pipes to couple geothermal energy to a bridge deck for snow and ice control has been investigated experimentally. A 1.8 x 4.9m (6 x 16 ft.) section of a concrete bridge deck was equipped with 15 heat pipes located on 15 cm (6 in.) centers, 5 cm (2 in.) below the deck surface. The site was heavily instrumented to allow quantitative comparison of the performance of the heated deck, unheated deck and adjacent roadway. One of the major objectives of the project was to provide performance characteristics on the heat pipes for simulation studies. This required additional instrumentation in the deck and in the ground. The power provided by the heat pipes was inadequate to melt the snow as fast as it fell during the most severe storms; however, throughout the 1977-78 winter the surface of the heated portion of the deck was always in better condition than the adjacent roadway. A total of 1.0 x 10^9 joules (9.5 x 10^5 Btu) was delivered to the deck by each pipe at an average rate of 125 w/m^2 (40 Btu/hr-ft.^{2}) during the winter season. It was concluded that heat pipes are an effective means of snow and ice control on bridge decks which should be considered for high risk locations.

Gaugler first introduced the heat pipe in 1944 but it was the reintroduction of the concept by Trefethin (1) in 1962 that stimulated its initial development. Heat pipes have proven to be extremely simple and efficient devices for transferring thermal energy and are therefore used in a wide and growing number of applications. In 1970 Bienert, Pravda, et al. (2) proposed the use of gravity operated heat pipes to transfer low grade energy from the ground beneath runways and highway structures to the surface in order to reduce or possibly prevent their icing.

This idea has been tested by placing gravity operated heat pipes in a small concrete slab at the Fairbank Highway Research Station in McLean, VA (3, 4) and in a 366 m (1200 ft.) long interchange ramp in Oak Hill, WV (5). The purpose of this paper is to report on the preliminary results of the first heat pipe system installed in an elevated highway structure. The overall objective of the project was to generate an empirical data base on the in situ performance of a gravity operated heat pipe system for use in the development of a numerical model to aid in design of these systems.

The design, fabrication, and installation of the heat pipes as well as the instrumentation of the complete system has been described in detail in reference 6. A brief summary is included here to facilitate the interpretation of the experimental data.

Figure 1 depicts a gravity operated heat pipe installed in the bridge deck. The heat pipes are 24.4 m (80 ft.) long and were fabricated from seamless, cold rolled, low carbon steel tubing with an outside diameter of 2.54 cm (1 in.) and a 0.32 cm (1/8 in.) wall thickness. These tubes were evacuated and filled with 0.2 kg (0.45 lbm) of ammonia which is also the condensable fluid that was used in the other two demonstration projects. Over the temperature range that the heat pipes are exposed to, part of the ammonia resides as a liquid in a pool at the bottom of the tube while the remaining ammonia is in the vapor phase filling the rest of the tube. Anytime the deck temperature falls below the temperature of the ground in contact with a heat pipe, the vapor in the deck section condenses and flows towards the bottom of the tube. At the same time, energy is conducted from the ground to the colder heat pipe where it evaporates part of the liquid ammonia. The spring in the evaporator section is used to enhance the area that is 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 is therefore ideally suited for this application where low grade energy is 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.

Figure 2 presents an overview of the experimental site which is a concrete bridge over Sybille Creek, located on State Highway No. 34 in southeastern Wyoming. Twelve standard heat pipes of the type depicted in Figure 1, along with three short electric heat pipes were installed a small section of the bridge deck. Temperature controllers were used to maintain the electrically heated pipes at the same temperature as one of the standard ground heat pipes. The amount of power transferred by the conventional heat pipes was then inferred from a measurement of the electrical power delivered to

Figure 1. Gravity operated heat pipe.

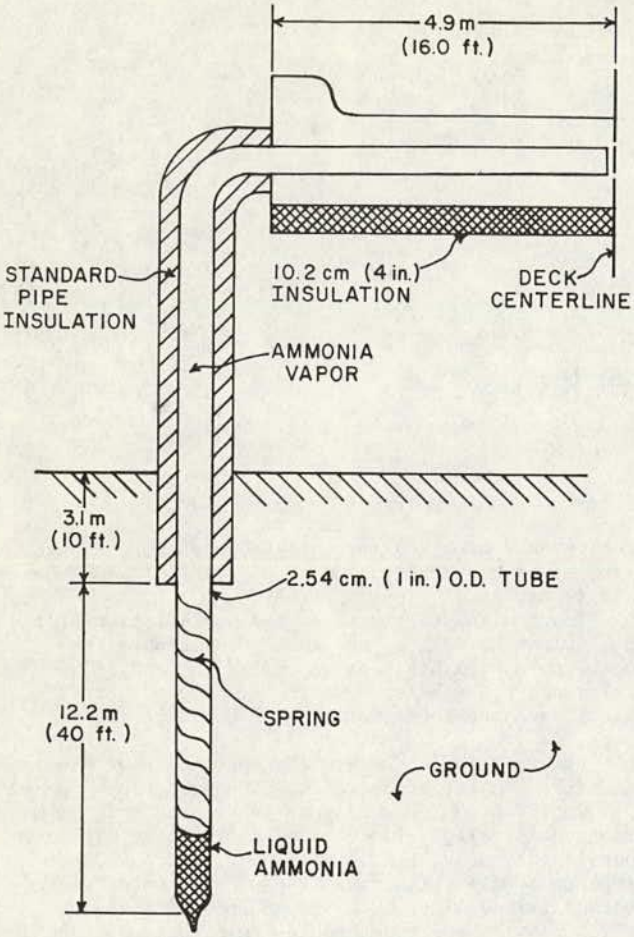
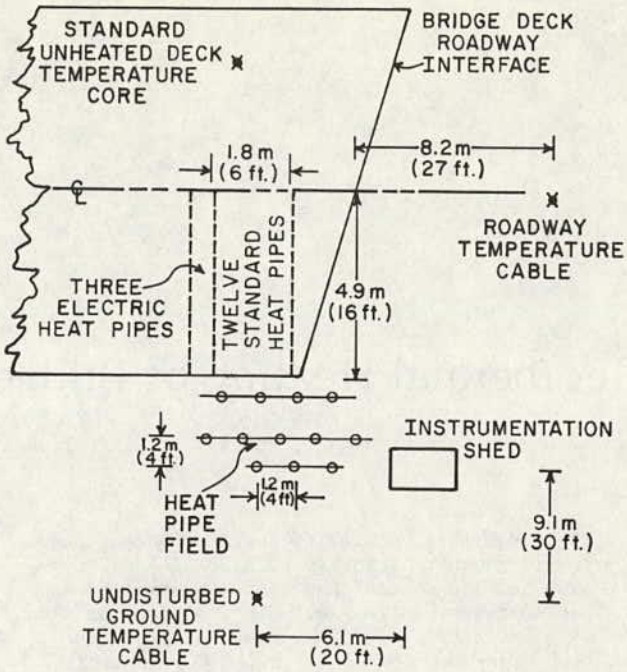
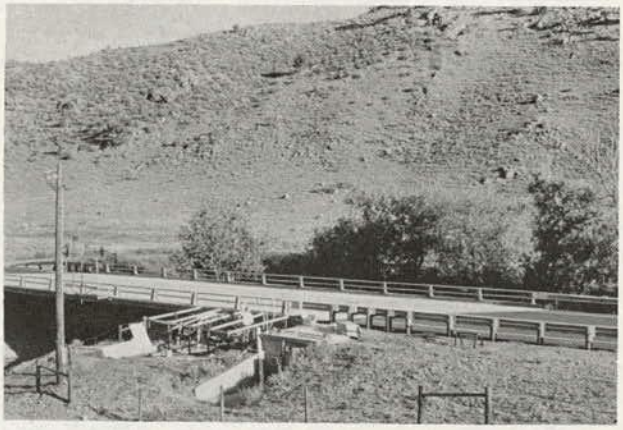


Figure 2. Experimental heat pipe site.





the electric pipes.

Experimental Results

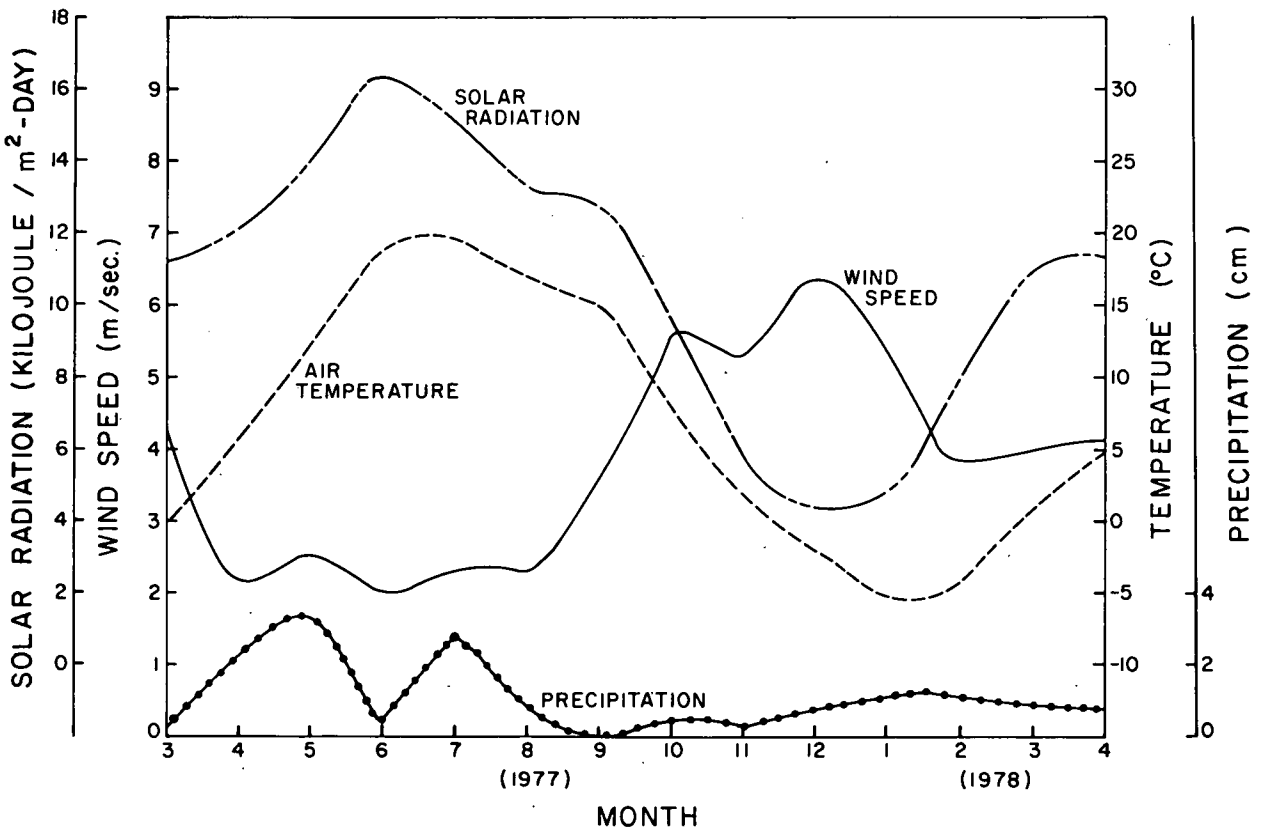
Environmental Data. The environmental parameters that influence the temperature response of a bridge deck were measured at the site and are summarized in Figure 3. This figure presents the monthly average air temperature, solar radiation, wind speed, and precipitation, and indicates that the test site, which is at an elevation of 1817 m (5960 ft.), would present a quite severe test of the gravity operated heat pipe system. The mean ambient temperature is only 6.7°C (44°F). Winter essentially begins in October and can last well into May. Based on this information alone, it could be anticipated that the heat pipes may be completely dormant for only five months of the year.

January was the most forbidding month during the winter. The monthly average air temperature dropped to -5.3°C (22.5°F), the average wind speed climbed to 5.5 m/sec (12.3 mph) and 2.7 cm (1.1 in) water equivalent of snow fell. The degree-days below freezing, which is obtained by integrating the portion of the temperature versus time curve that fell below the freeze line, was 83 degree Centigrade-days for this month. The lowest temperature observed during the winter of 1977-1978 was -26°C (-15°F) on December 9, 1977.

Surface Data. Figure 4 denotes the percentage of the time that the heat pipes operated during each month and also contrasts the monthly average upper surface temperature of the unheated deck with the section that contained the heat pipes. This figure indicates that the heat pipes began to operate in September and did not become completely dormant until June. The heat pipes caused the average surface temperatures of the two sections to begin to differ in October. The temperature difference reached a maximum in January of 5.6°C (10°F) when the heat pipes were operating 89 percent of the time. This breaks down to 79 percent during the day and 100 percent of each night which was found to be a typical day-night ratio (0.8) during the other severe winter months. In terms of monthly averages, the standard deck is shown to be frozen from November through February while the monthly average temperature of the heated deck stays above 1°C (34°F).

The surface conditions of the two deck sections were also recorded through time-lapse photography during the daylight hours (6). An analysis of the

Figure 3. Monthly average environmental parameters.



photographic record from October 10, 1977, through March 15, 1978, indicates that the standard bridge deck was snow packed for 331 hours while the heat pipe section had snow on it approximately 1/3 of this time. A section was considered to be snow covered any time it was covered with more than just very small patches of snow. For instance, the heat pipe section shown on the time-lapse photo taken on November 20, 1977 (Figure 5) was considered to be snow covered even though it had melted away approximately 50 percent of its snow cover. January, the most severe month, accounted for 136 of the 331 hours that the standard bridge deck was snow packed while the heated section was considered to be covered 1/2 of this time.

Mechanical snow removal through the action of traffic and plowing were both minimal at this site. There were many instances under these conditions where the heat pipes did not keep up in terms of melting all the snow as it fell, but were able to maintain the deck surface above freezing. In these cases, the snow formed an insulating layer over a wet surface. The temperature data indicates that the surface temperature of the standard deck was below freezing 242 of the 331 hours that it was snow packed while the heat pipe portion was covered and frozen (failed) only 36 hours.

Since the time-lapse camera was only functional during daylight hours, snowfall or snowpack information during the night was inferred from early morning or late afternoon photographic data. The standard unheated bridge deck entered a night clear and was found the next morning snow packed 21 times, as compared to 14 for the heated deck. Of these events, the standard surface was below freezing 234 hours with the heated deck below freezing only 92 hours.

Unfortunately, not enough of the adjacent roadway fell in the field of view of the camera to allow a determination of its surface conditions during the day. Other visual information is available which implies that the surface condition of the heat pipe section was always better than the roadway in terms of snow pack. This contention is also supported by Table I which tabulates the freezing characteristic of the air, roadway, heat pipe section and the standard bridge section for a 62 day period from January 24 to March 28, 1978. The comparison is limited to only 62 days due to a failure of the surface temperature transducer in the roadway. Table 1 indicates that the standard deck and the adjacent roadway were below freezing approximately the same amount of time while the heat pipe section was frozen only 1/3 of this time. In terms of the severity of the freezes, the heat pipe section had only 1/10 the degree-days below freezing that the standard deck amassed as compared to 3/4 for the roadway. This table also implies that the average temperature during a freeze was -0.9°C (30°F) for the heated bridge section, -2.5°C (27.5°F) for the roadway and -2.9°C (26.8°F) for the standard bridge section. There is no significant difference in the number of freeze-thaw cycles between the heated and unheated sections of the bridge due to the fact that the heat pipe section can hover around freezing. This allows the heat pipe section to go through several short freeze-thaw cycles while the unheated section may only experience a single hard freeze.

Figure 4. Monthly average surface temperatures and percentage of the time the heat pipes are operational.

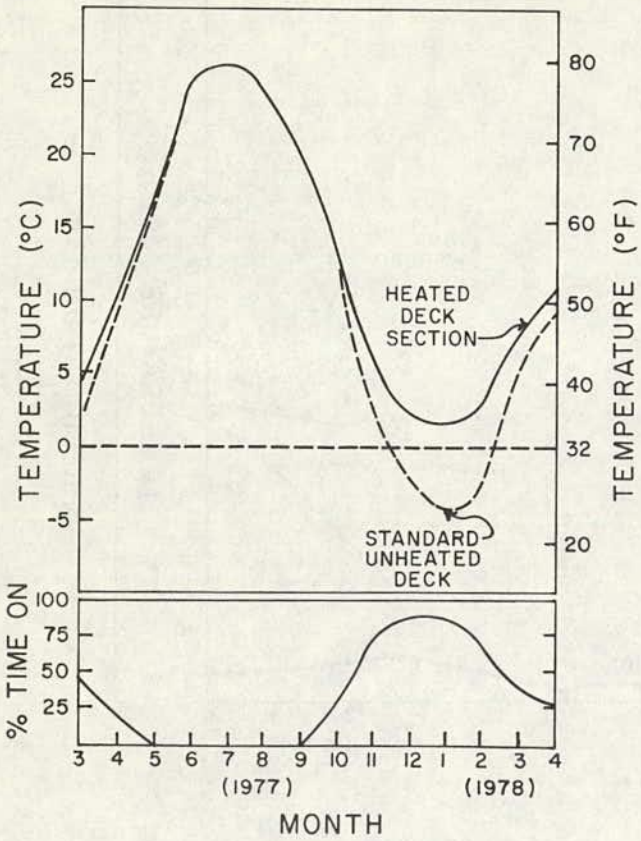
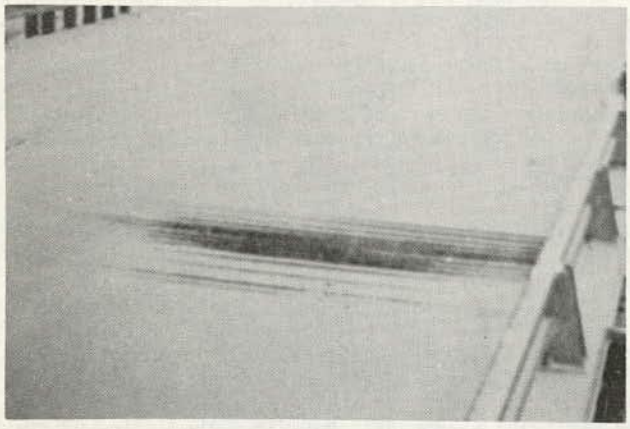


Figure 5. Time-lapse photograph showing entire bridge deck snow packed.



The above discussion reviewed the long term performance of the heat pipe system with respect to surface conditions. Actual thermal response of the heated and unheated bridge deck surfaces and the roadway surface to a typical snow event is shown in Figure 6. The hourly averages for the solar radiation, wind speed, air temperature and the three surface temperatures are plotted for March 14, and March 15, 1978 in Figure 6a. Snowfall began at 10 p.m. on March 14 and continued until 6 a.m. the next morning. A total accumulation of 10.2 cm (4 in.) was observed. The heat pipes came on approximately one hour after the snow began to fall and operated until 10 a.m. the following morning. The heated portion of the deck and the roadway hovered above the freezing point while the standard deck was frozen during the snow event. Figure 6b shows the surface condition at 9 a.m. following the snow fall and indicates that the heat pipe section was totally clear whereas the standard deck and roadway were completely snow packed. Time lapse photographs show that this condition existed at sunrise. The day of March 15 was a clear sunny day as evidenced by the solar radiation data. Since the roadway was not frozen, its snow cover rapidly melted when exposed to the solar radiation following which its surface temperature rose rapidly as did the temperature of the heat pipe section. The difference in the peak temperatures of these two surfaces is due to the variation in their solar absorptivities. The low solar absorbtivity of snow and the fact that the deck was frozen combined in causing the standard deck to remain snow covered. These surface conditions may be contrasted in Figure 6c which was taken around noon. This is a graphic example of preferential icing which is quite common at this site. The standard deck does not clear until the next day. Note that the air temperature drops to -9°C (16°F) the following night which caused both the heat pipe section and the roadway section to drop below freezing. The heat pipes began to operate during this evening at 8 p.m. and ran until 11 a.m. the next day, March 16. This is typical diurnal cycling that is experienced by the heat pipes and emphasizes the importance of solar radiation on the clear deck during daylight hours since the major source of energy may change from geothermal to solar.

This diurnal cycling may be seen in Figure 6a where the periods that the heat pipes were off and on are indicated. Note that in spite of the fact that there is no active control system the pipes tend to operate when additional energy is required. Energy is, in a sense, wasted when the pipes are operating throughout a clear cold night. They do however shut off when the solar heating during the day raises the deck surface temperature above the temperature of the earth at depth. On the other hand if the surface is snow packed it is at or below freezing and the heat pipes function as long

Table 1. Relative freezing characteristics January 24 through March 28, 1978.

Temperature Transducer	No. of Days Frozen	(°C)-Days Below Freezing	No. of Freeze-Thaw Cycles
Ambient Air	34	121	52
Standard Deck Surface	29	84	28
Roadway Surface	27	62	45
Heated Deck Surface	9	8	25

Figure 6. Hourly average surface temperatures and environmental data for the two day period March 14 through March 15, 1978.

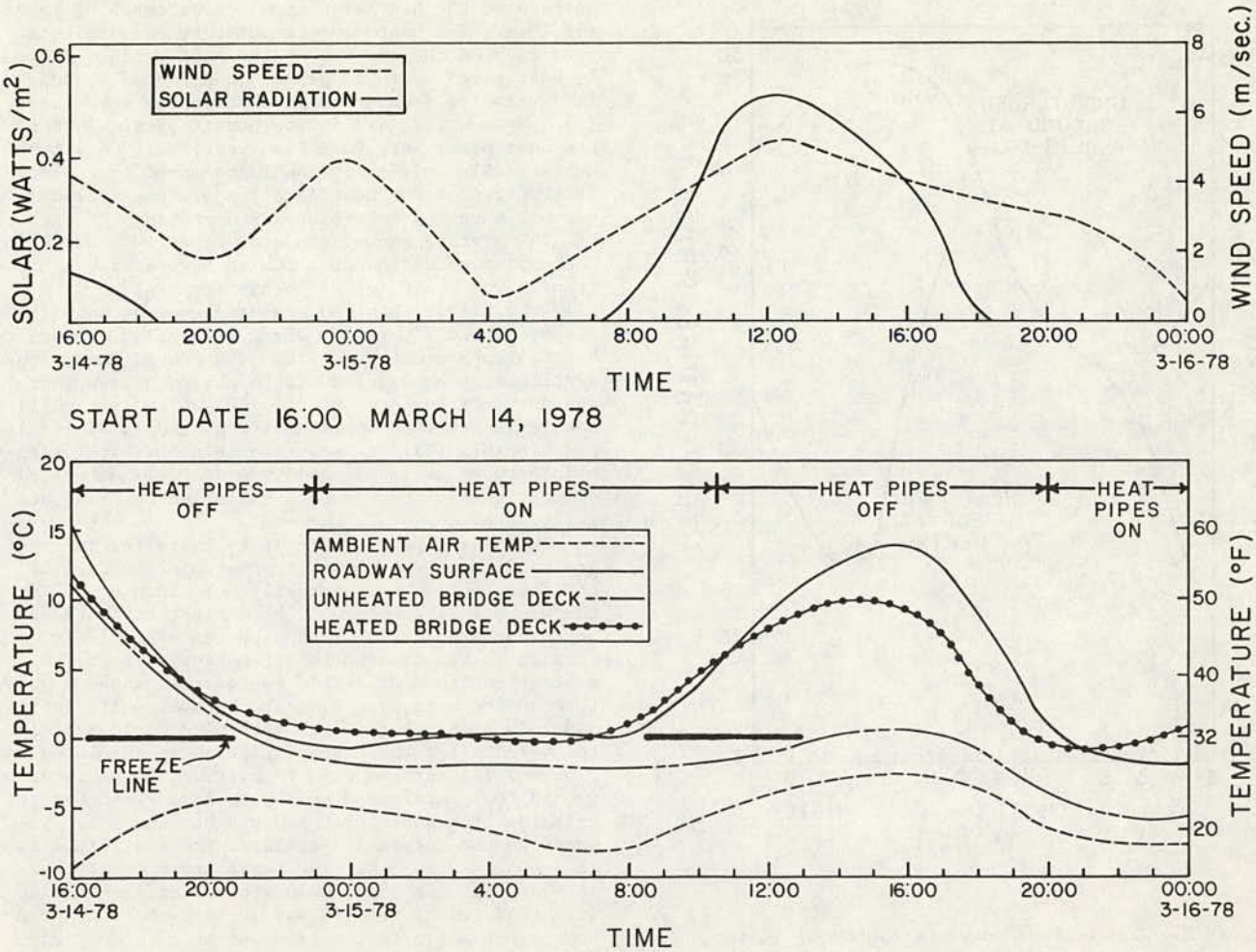


Figure 6a. Surface response and environmental data.

Figure 6b. Surface conditions at 9:00 a.m. - March 15, 1978.

Figure 6c. Surface conditions at noon - March 15, 1978.

Figure 7. Monthly average ground temperature at depth.

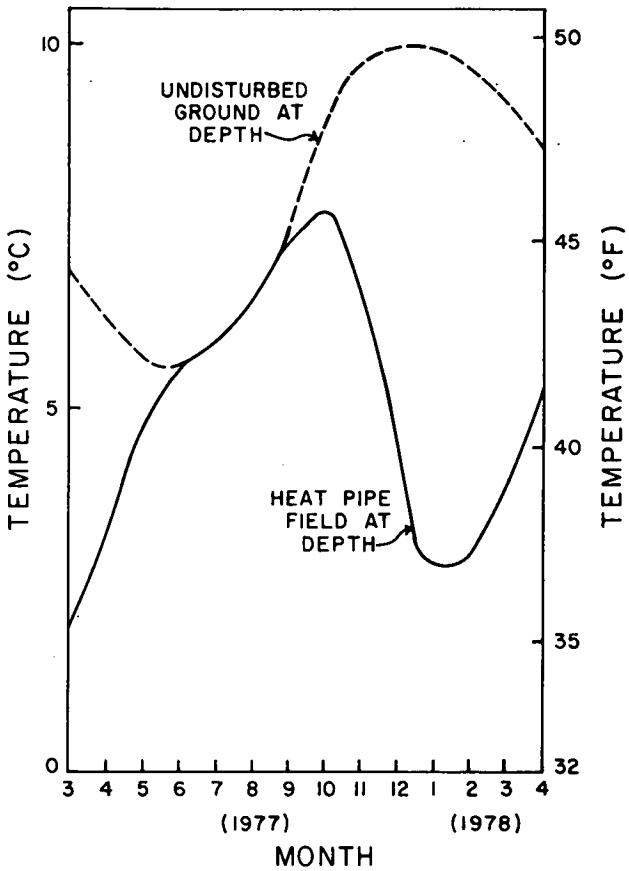
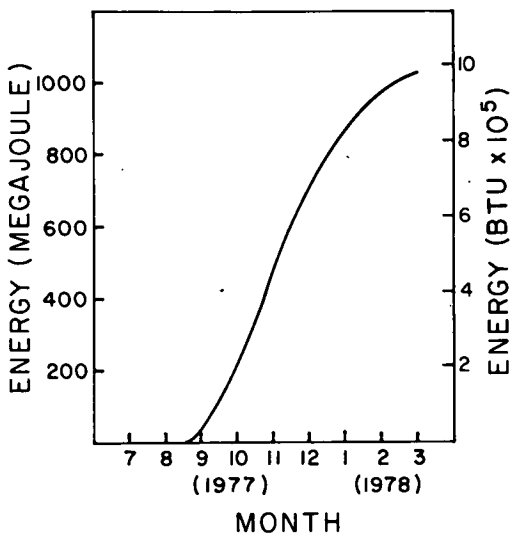


Figure 8. Cumulative energy extracted by a single heat pipe.



as the earth temperature remains above freezing.

Ground Response Data. During the period that the heat pipes are operating, energy is being removed from the earth which leads to a depression of the earth temperature in the neighborhood of the heat pipe. This effect is shown graphically in Figure 7 which compares the monthly average temperature of the undistrubed ground and the temperature on the surface of the heat pipe at a common depth of 16.2m (53 ft.). The heat pipe temperature measurements were made on the surface of the center pipe. Normally heat pipes would be placed in a fanned shaped configuration to reduce the interaction between pipes (5). However, to aid in the numerical simulation, the heat pipes were installed vertically on 4 foot centers (Figure 2). It should be noted that monthly averages of the heat pipe temperature includes periods when the heat pipe was operating.

The average annual temperature at this depth in the undisturbed ground, which is saturated weathered granite was 8.3°C (47°F). This temperature is slightly higher than the measured average annual air temperature 6.7°C (44°F) which is usually assumed to be the temperature at depth. The ground temperature oscillates sinusoidally with a period of one year and an amplitude of 2.6°C (4.7°F) which is significantly larger than amplitudes measured in Minnesota and Virginia (3). A very favorable phase relationship between maximum ground temperatures and periods of peak energy requirements was shown to exist at this depth.

The heat pipes were intially installed in the ground in October, 1976 with the upper portion of the pipe, which was eventually bent into place in the deck, left exposed to the ambient environment until January, 1977. Each pipe was effectively coupled to the atmosphere attempting to heat the ambient environment. This caused the ground temperature in the heat pipe field to be abnormally depressed. In spite of this the heat pipe field rapidly recovered after the exposed pipes were insulated and Figure 7 illustrates this recovery. The undisturbed ground temperature and heat pipe field temperature coincide from June through September which corresponds to the dorminant period of the heat pipes as is shown in Figure 4. The temperature on the surface of the heat pipe begins to depart from the undisturbed ground temperature in September when the heat pipes begin to function and the slope of the heat pipe temperature acutally becomes negative in October. A continuous and nearly constant rate of decrease in the local earth temperature near the heat pipes occurs until February, when recovery is initiated in spite of the fact the heat pipes are operational 70 percent of the time. The heat pipe field appears to repeat the rapid recovery observed at the end of the previous winter. There is no indication that there is a permanent depression in the heat pipe field temperature.

Energy Data. The electric heat pipe control system did not function properly until the end of the winter. The data that was obtained implies that the heat pipe has a constant conductance between the evaporator and condenser section when operating. Using a value of conductance derived from the data a number of performance parameters were calculated.

Figure 8 presents the cumulative energy extracted by each conventional heat pipe for the 1977-78 winter. The heat pipes were operational intermittently 8 months of the year during which time they delivered an average 125 w/m^2 (40 Btu/hr-ft.^{2}) to the deck. It may be seen that over the three month period from October through December the energy delivered per month reached a fairly constant rate of 218 megajoules (2.1 x 10^{5}Btu). Throughout this period the heat pipes were operating, that is transferring energy to the deck, 63 percent of the time and the average power delivered to the deck when the pipes were operating was 173 w/m^2 (59.6 Btu/hr-ft.^{2}). Referring to Figure 8 it may be seen that

the maximum monthly average rate of energy extraction occurred during November, 1977 when 194 w/m^2 (61.4 $Btu/hr\text{-}ft.^2$) were provided.

As the winter progressed into January and February, which exhibit the most severe environmental parameters (Figure 3), the rate of energy extraction from the earth decreased despite the fact that the temperature of the undisturbed ground was near maximum and the amount of time that the pipes were operating increased to 80 percent. This is due to the fact that the temperature of the earth proximate to the heat pipes had dropped to an average value on the order of 2°C (35.6°F). This localized temperature decrease leading to a decline in the rate of energy extraction is the major factor in heat pipe system design since it influences both the energy and power which can be extracted.

All of the power values quoted are based on averages using that portion of the time during which the heat pipes were operating, regardless of power output, for an entire month. The values are not indicative of the peak power delivered by the heat pipes and due to the fact that the electric heat pipe controllers were not functional during the early part of the winter no estimate of the peak power can be given.

The monthly average values of power quoted above may be contrasted with short term averages obtained for the two periods, indicated on Figure 6a, when the heat pipes were operating. A maximum power of 134 w/m^2 (43 $Btu/hr\text{-}ft.^2$) and an average power of 100 w/m^2 (32 $Btu/hr\text{-}ft.^2$) were obtained.

Conclusions

The heat pipes have been in operation for 18 months and performance of the system has been continuously monitored for more than one year. A data base has been generated which can be used to refine computer simulations of the thermal response of gravity operated heat pipe systems.

The experimental program has demonstrated that a geothermal heat pipe system can be effective in prevention of preferential icing between a bridge deck and the adjacent roadway. All of the data taken indicates that preferential icing of the heated portion of the deck relative to the roadway was completely eliminated. In fact, for purposes of eliminating preferential icing the capacity of the heating system could be significantly reduced, for example, by increasing the center to center pipe spacing in the deck in future installations.

Throughout the 1977-78 winter season there were only 36 daylight hours when the surface of the concrete deck over the heat pipes was both snow packed and below freezing. The system did not provide sufficient power to keep the surface completely clear during the most severe snow storms, however, there were no situations where the accumulation of snow on the heat pipe field exceeded 5cm (2 in.) in depth. The total energy provided by the system during the winter was almost 50 times greater than required for a Class III design in Cheyenne, WY (7). Since no estimate of the peak power provided can be made it is not possible to assess the system in this respect.

One of the dominant questions which persists with respect to design of large scale heat pipe systems is whether the earth temperature in the heat pipe field becomes permanently depressed. In spite of the fact that the field recovered very rapidly during the spring for this project, the relatively small field employed precludes any general conclusions in this regard.

The portion of the deck incorporating the heat pipes was intentionally selected adjacent to an abutment wall in order that the pipes would be located in a relatively rigid portion of the deck. In addition this location allowed the pipes to enter the deck through its side below the curbing. These design features minimized the problems associated with incorporating the pipes in the deck during the construction of the bridge and also minimized mechanical problems associated such as flexure and differential expansion. These as well as a variety of other significant problems associated with the design of a practical deck heating system were not addressed in this study.

The project has demonstrated that geothermal heating of bridge decks can be an effective means of ameliorating adverse environmental effects on elevated structures even in severe environments. Future studies addressed at decreasing system costs and practical problems associated with large scale system integration are warranted.

Acknowledgements

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