FINAL REPORT

EVALUATION OF VIRGINIA'S FIRST HEATED BRIDGE

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This study is a contribution to the Heated Bridge Technology Program established in 1991 under the Intermodal Surface Transportation Efficiency Act. The goal of the program was to find durable and environmentally friendly heated bridge technologies for ice and snow removal.

The purpose of this study was to evaluate the first heated bridge built in Virginia. The bridge is on Route 60 over the Buffalo River in Amherst County. The project was monitored from its construction in 1995 through winter operations terminating in spring 2000. Data were collected remotely using an electronic datalogger interfaced with various temperature and environmental sensors. In addition, an infrared camera was used to examine heat distribution across the bridge deck.

The results of the study demonstrated that heat pipe technology could provide a feasible option for heating decks. However, substantial problems were encountered in getting the system to perform as designed. It appears that the control aspect of this technology requires additional improvements to ensure reliable operation under field conditions.

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INTRODUCTION

Overview

A bridge deck typically cools much more quickly than a road on grade because it loses heat from the underside as well as the surface, thus creating a greater potential for icing. Short of periodic application of chemicals, the only positive method to prevent ice from forming on the bridge deck is to maintain its temperature above the freezing point. This can be accomplished using internal (embedded) or external (radiant) heat sources.

One result of the 1991 Intermodal Surface Transportation Act was the formation of the Applied Research and Technology Program, designed to accelerate testing and evaluation of new technologies. Among the technologies included in the evaluation was that involving heating bridges, i.e., the Heated Bridge Technology (HBT) Program. In addition to decreasing the potential for traffic accidents, HBT may offer a viable alternative to the use of de-icing salts, which can cause premature deterioration of bridges. De-icing salts are generally detrimental to all components of a bridge. A typical bridge is designed for a service life of approximately 75 years, but the application of de-icing chemicals commonly results in extensive repairs after 20 years or less. Thus, the concept of adapting HBT to reduce maintenance costs, in addition to improving traffic safety, is a sound one in principle.

Virginia was one of only five states that responded to the HBT program, which provided for reimbursement of 80% of construction costs and 100% of the planning and evaluation costs on a project. The Virginia Department of Transportation's (VDOT) Structure & Bridge Division, in cooperation with the Federal Highway Administration (FHWA), requested that the Virginia Transportation Research Council (VTRC) carry out the study.

Existing Technologies for Heating Bridge Decks

Currently available technologies for internally heating bridge decks comprise primarily three types of systems: electrical, hydronic, and heat pipe. In the electrical system, heat is generated by a current flow in an insulated metallic cable embedded within a bridge deck. Typically, the cable is laid out in a serpentine pattern to provide uniform heat distribution across the surface. As the cable warms up because of the passage of electrical current, it conveys heat to the surrounding material. Commercial heating cables have been used on projects involving pavements, sidewalks, and loading ramps.

In the hydronic system, heat transfer relies on the flow of a hot liquid instead of electricity. Typically, a continuous loop of a rigid or flexible pipe is used. Hot liquid is circulated through this closed-circuit loop by a hydraulic pump. As the liquid cools, following heat transfer to the surrounding medium (deck), it is returned to a heat source (boiler) for re-heating.

In the heat pipe system, a pipe containing a relatively small quantity of heat-transfer fluid is permanently sealed in a vacuum, as shown in Figure 1. As external heat is supplied to the evaporator section, the fluid vaporizes. The vapor pressure causes flow along the pipe. When the vapor arrives at the cooler portion of the pipe, it condenses, releasing latent heat of vaporization. The condensed fluid returns to be reheated through a capillary wick. Because of the internal vacuum, the rate of heat transfer in a heat pipe system is extremely fast, and the resulting heat distribution along the pipe is typically uniform (isothermal condition). Tubes constructed without a wick can also be used for heat transfer, but they need to rely on gravitational forces for returning the working fluid for reheating. Strictly speaking, the no-wick design is classified as a Perkins tube, or thermosyphon, although the term *heat pipe* is generically applied to both cases (Dunn, 1976).

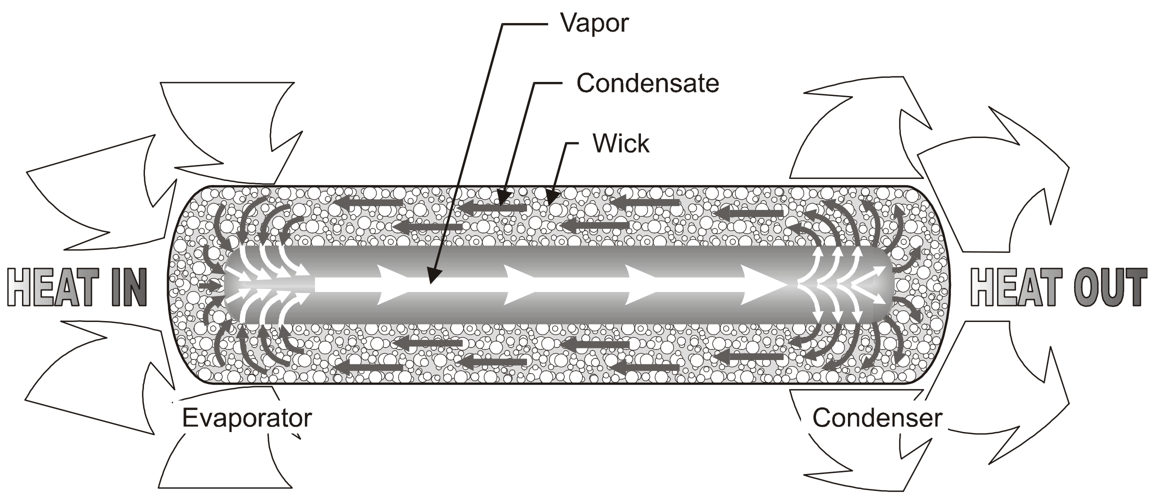

Figure 1. Heat Pipe Principle

The heat pipe technology was developed nearly 40 years ago at the U.S. Department of Energy's Los Alamos National Laboratory, primarily for aerospace applications (Los Alamos National Laboratory, 2000), including generating nuclear-electrical power in space and cooling leading edges of hypersonic vehicles (Reid et al., 1991). These early heat pipes contained water or sodium. Current models use lithium inside a molybdenum pipe, operating at white-hot temperatures approaching 1200 °C (2200 °F). These heat pipes can transfer heat energy at a power density approximately 4 times greater than the heat emitted from the sun's surface. Modern applications of this technology include the use of miniature heat pipes that cool electronic chips in computers.

The use of Perkins tubes, or heat pipes without a wick, dates back to the late 19th century. A number of systems were developed in Europe to provide heat distribution to a large number of buildings, typically referred to as district heating. One such system was designed by Angier March Perkins (Pierce, 2000). The Perkins system was relatively simple, using a sealed piping network and no moving parts. It relied on convection to create flow. The Perkins high-pressure distribution system was remarkably efficient, heating buildings with water at about 260 °C (500 °F). Many Perkins systems were in operation until well into the 20th century.

PURPOSE AND SCOPE

The objective of the HBT program was to evaluate environmentally friendly, cost-effective, and durable heating systems for bridge decks to remove snow and ice. The primary purpose of this study was to provide answers to the following questions:

1. Is the selected heating system activating itself properly and early enough during each storm event?
2. Is the system distributing heat uniformly across the entire deck and approach slab surface?
3. Is the heating system effective?
4. Is the system effective only under a certain limit of weather severity?
5. Did any traffic accidents occur on the deck when icy conditions were reported in the general area?
6. Were any problems encountered during construction?
7. What are the actual costs of operating and maintaining the system?
8. What routine maintenance is required?
9. Has there been any adverse effect on the durability of the deck?

The scope of this study involved a field evaluation of a single, proprietary system installation. The HBT project selected by VDOT was a bridge replacement on Route 60 over the Buffalo River in Amherst County, approximately 24 km (15 mi) northwest of Lynchburg. The two-span bridge is 35.7 m (117 ft) long and 13.4 m (44 ft) wide with simple span steel beams and a concrete deck. It has approach slabs 6.1 m (20 ft) long and 7.3 m (24 ft) wide at each end. The bridge site is in the eastern foothills of the Blue Ridge Mountains where road conditions during winter can be treacherous.

This report addresses only the observations and experiences gained from the heat pipe system employed on the Route 60 Bridge. Details and comparisons of other heated bridge technologies used in the HBT evaluation program are available elsewhere (Minsk, 1999).

METHODS

Completion of the study objectives involved four tasks:

1. selecting a heating system for the bridge deck
2. selecting a monitoring system for the deck
3. installing the systems
4. monitoring and evaluating the systems in terms of operation, costs, occurrence of traffic accidents, and effect of the heating on the bridge deck.

Selecting the Heating System

Overview

The bridge, excluding the heating system, was designed at VDOT's Lynchburg District Bridge Office. VDOT solicited proposals for the heating system from specialty contractors. The submittals consisted of the following:

1. electrical heating cables (by Delta-Therm Corp.)
2. hydronic system with a natural gas boiler (by Delta-Therm Corp.)
3. hydronic system with a propane-fired boiler (by Delta-Therm Corp.)
4. heat pipe system (by SETA Technology).

Estimated construction and operating costs were analyzed in the selection process. The heating system selected was the heat pipe system, a proprietary design developed by SETA Technology of Laramie, Wyoming. The design was based on U.S. Patent No. 4,566,527, dated January 28, 1986. The patent applies to the mechanism of heat transfer (coupling) between the primary fluid and the working fluid in the heat pipe.

This system was chosen because the projected annual operating expenses was approximately one tenth that of the other candidates ($729 versus $6,002 to $7,372), although the initial cost was estimated to be 70% to 160% more than the alternatives.

Description of Heating System

Plans supplied by SETA Technology indicate that the system was designed to generate a surface heat output of 700 W/m^2 (225 BTU/ft^2-h), using Freon HCFC 123 as the working fluid. Since no National Weather Service station was located near the site, the design was based on the historical data obtained from Washington, D.C., Lynchburg, and Roanoke. Available data indicated that snow melting would be required approximately 90 hours per year (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1995). SETA Technology claimed that the system would keep the bridge deck and approaches clear of snow and ice under all precipitation conditions.

Figure 2 is a schematic diagram of the system. Figure 3 shows a transverse cross section through one of the heat pipes (Perkins tubes).

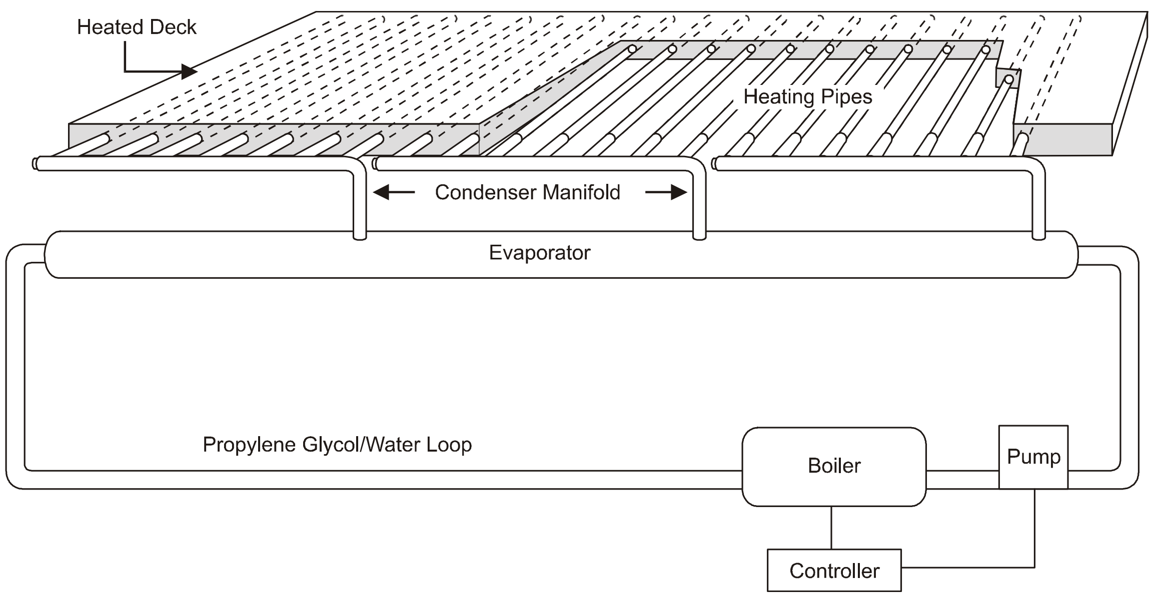

Figure 2. Schematic of Heat Pipe System

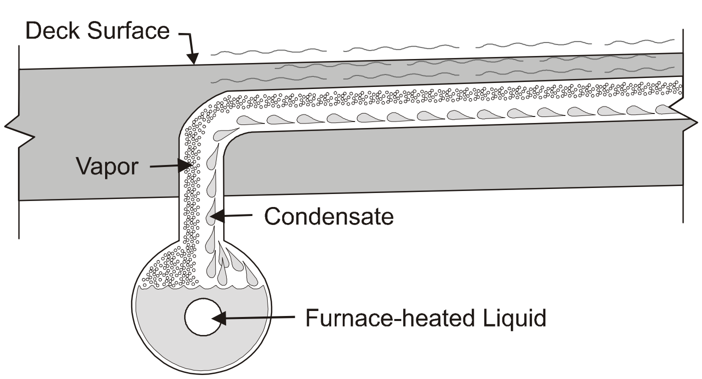

Figure 3. Cross Section of Heating Element

The total heated area was 567 m^2 (6,108 ft^2). A total of 241 heat pipes were embedded in the bridge deck and approach slabs, oriented perpendicular to the travel lanes. These hermetically sealed steel pipes were 22 mm (7/8 in) outer diameter and 13 mm (1/2 in) inner diameter and were protected against corrosion by an epoxy coating applied on the outside. The pipes were installed at the level of the top reinforcing mat, on 178-mm (7-in) centers in the deck and on 229-mm (9-in) centers in the approach slabs. The pipes were placed at a 6.5% slope, matching the transverse deck slope, to allow the condensed fluid to drip back to the evaporator. Approximately 3,200 m (2 mi) of steel piping was used on the project.

The individual heat pipes were attached to a horizontal condenser manifold, which in turn linked through a vertical riser pipe with the evaporator. A typical installation module consisted of 10 heat pipes branching from a single manifold. The opposite end of each heat pipe was closed. Thus, each pipe acted independently in supplying heat to the deck surface.

The evaporator consists of a pipe with an inner diameter of 152 mm (6 in) containing working fluid and is coupled with vertical risers, as shown in Figure 4. A pipe with an inner diameter of 89 mm (3½ in) carrying a 50% glycol solution runs longitudinally through the center of the evaporator. The smaller pipe forms a closed loop, supplying heat generated by a propane-fired boiler (Teledyne Laars, Mighty Term; 1,478,250 BTU/h output). A hydraulic pump is used to circulate water/glycol mixture in the primary supply loop. As heat is transferred to the working fluid in the evaporator, the mixture is returned to the boiler for reheating. The circulating water/glycol temperature was set at 88 °C (190 °F).

Figure 4. View of Evaporators and Risers

A dedicated computer, operating under Windows 3.11, controls activation of the boiler and hydraulic pump. A proprietary control program (Labtech Control, Version 5.04) analyzes sensor inputs and activates heating when any of the following conditions is encountered:

1. The surface condition sensor indicates snow or ice.

2. The precipitation sensor indicates precipitation and the deck surface temperature is below 1.7 °C (35 °F).

3. The surface condition sensor indicates a wet deck and the surface temperature is below 1.7 °C (35 °F).

The heating system is programmed to shut off when the deck sensor reports a temperature above 4.4 °C (40 °F) or a clear surface (no ice/moisture) for more than 10 minutes. The control system was installed in a nearby building, together with the boiler and hydraulic pump. Figure 5 shows the control computer and the propane-fired boiler.

Activation of the system is controlled by one surface condition sensor, HSC-2, made by Environmental Technology, Inc. Originally, the sensor was to be mounted in the bridge deck. However, at the time of installation, the electrical conduits leading to the deck were found to be blocked, which necessitated placing the sensor in the approach slab (slab on grade).

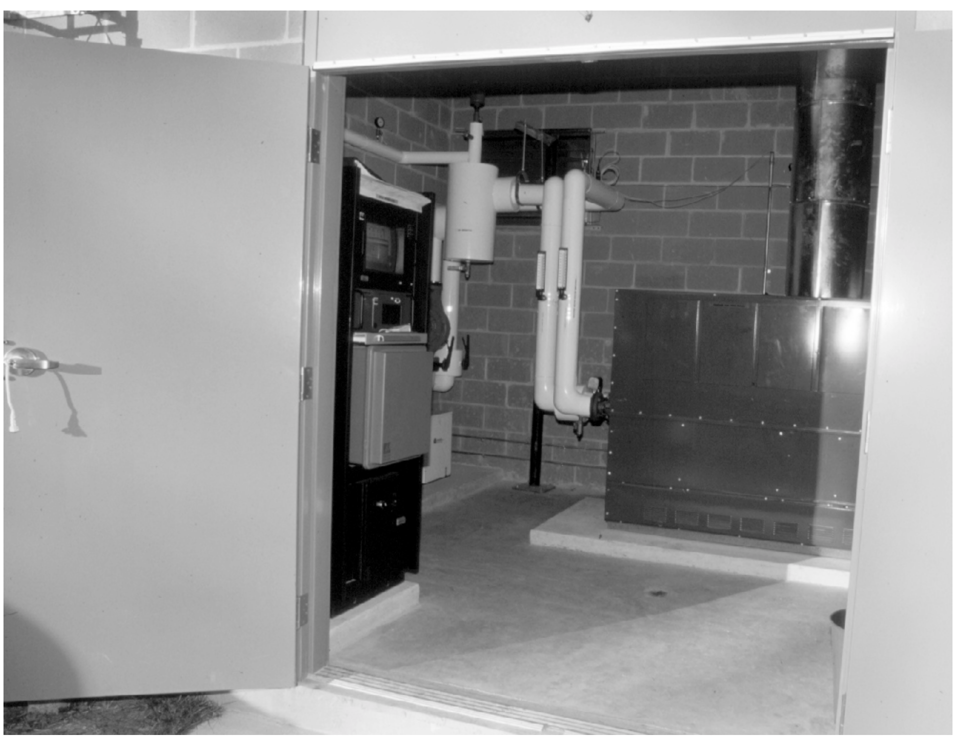

Figure 5. View of Control Computer, Boiler, and Piping

Other environmental sensors interface with the control system and include wind speed and direction, temperature, humidity, and precipitation (particle sensing) sensors. These sensors were mounted on a tower mast. Only the precipitation and surface condition sensors are used for activating the heating system.

Selecting the Monitoring System

The monitoring system was designed to operate independently of the heated bridge control system. The objective was the automatic collection of the data needed to perform the evaluation. The instrumentation for temperature monitoring included 32 thermistors (Campbell Scientific, Model 108, 0.4 °C accuracy) placed in the deck and the approach slabs, as shown in Figure 6. Thermistors 1 through 26 were positioned at approximately 25 mm (1 in) below the surface and between individual heat pipes. Thermistors 27 through 32 were spaced between heat pipes and at various elevations within the deck section. Heat pipes propagate from condensers located along the top of the plan view. Figure 7 shows a thermistor module installed prior to concrete placement.

Ice formation on the deck was sensed with an Aanderra Model 3428 pneumatic ice detector. The detector operates by periodically sending a small quantity of air through a porous membrane, flush-mounted on the deck, and monitoring the line pressure. When icing occurs, causing the membrane to become blocked, the air pressure rises, triggering an alarm condition.

In addition to measuring the temperature of the deck and approach slab near the surface, the monitoring system included weather station sensors (made by Campbell Scientific), consisting of wind speed, solar radiation, relative humidity, ambient air temperature, and

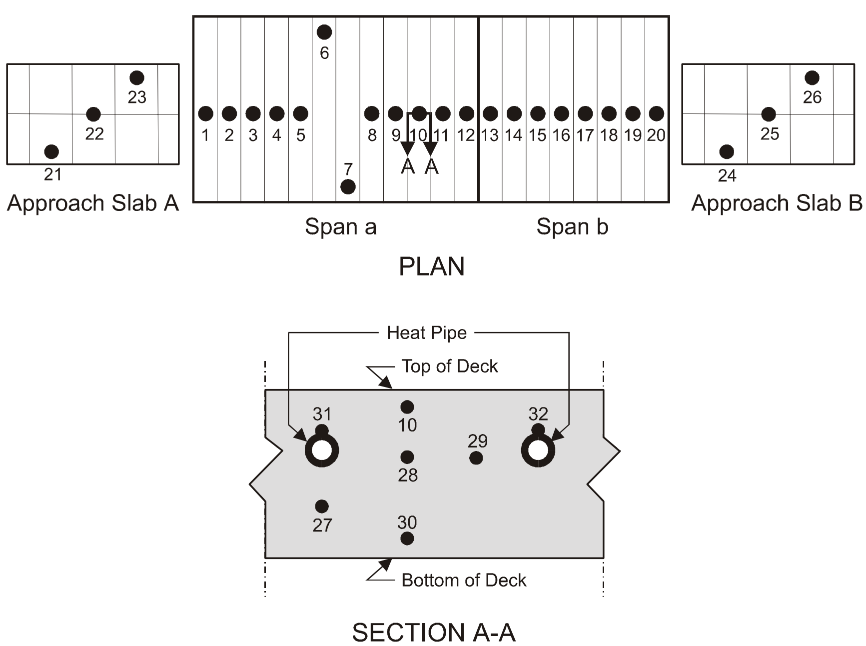

Figure 6. Layout of Temperature Monitoring Probes

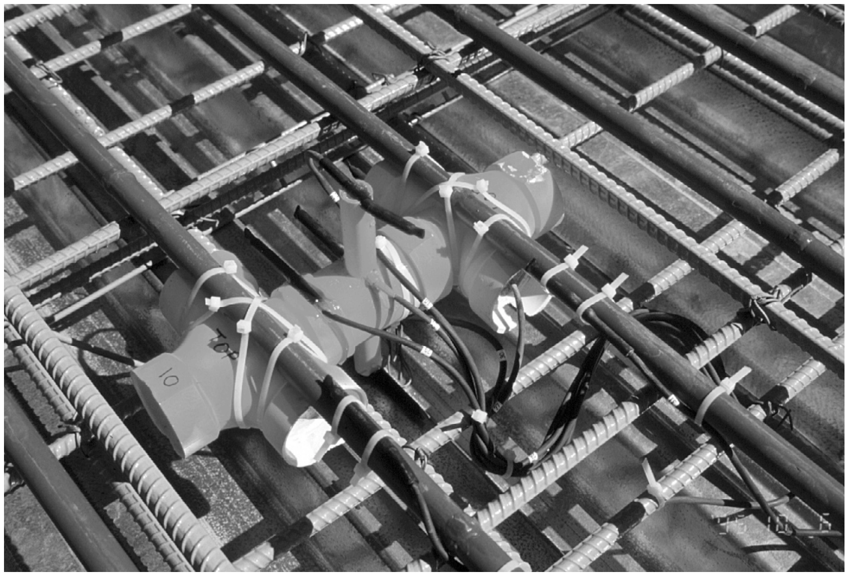

Figure 7. View of Temperature Probe Module Attached to Heat Pipes

precipitation. The precipitation sensor was a conventional tipping-bucket rain gage, augmented with a thermostatically controlled internal heater to prevent freezing. Other instrumentation, comprising electrical relays, sensed the on/off status of the boiler, hydraulic pump operation, and electrical power supply.

Heat distribution across the bridge deck was monitored using a Texas Instruments Nightsight infrared camera, permanently mounted on a 6-m (20-ft) pole adjacent to the bridge. A bulletproof case was installed around the camera to minimize the possibility of damage by vandalism. The camera, designed to sense different amounts of infrared energy and convert it to visible light, had a temperature resolution of less than 1 °C. Operating in the 8- to 12-micron range of the infrared spectrum, it provided a black and white "heat" picture that was digitized (JPG format) and stored at periodic intervals using a video digitizing card and a desktop personal computer (PC) (386 processor). During the operation of the heating system, the infrared signal was automatically recorded on a videocassette recorder (VCR) (Burle TC3910) activated by the power-on status of the boiler. As a monitoring backup, a conventional black and white camera was installed and linked with a manually operated VCR.

The monitoring sensors were interfaced with a Campbell Scientific CR10 electronic datalogger. Approximately 2600 m (8,500 ft) of cable was used for connections. A control program was developed to scan sensors and collect and store data every 10 minutes. To provide automatic data transfer to VTRC, a desktop PC, operating under DOS, was set up to retrieve information from the CR-10, process it, and establish remote modem communication at periodic intervals. Figures 8 and 9 show the monitoring instrumentation in the boiler building. The system was designed to allow for automatic posting of particular data on the Internet. The phone line communication link was established between the on-site PC and the office-based SPARC 4 workstation, running a Linux operating system and Apache web server. In addition to regular data transfer, typically at 1-hour intervals, software patches were sent to the remote PC when needed.

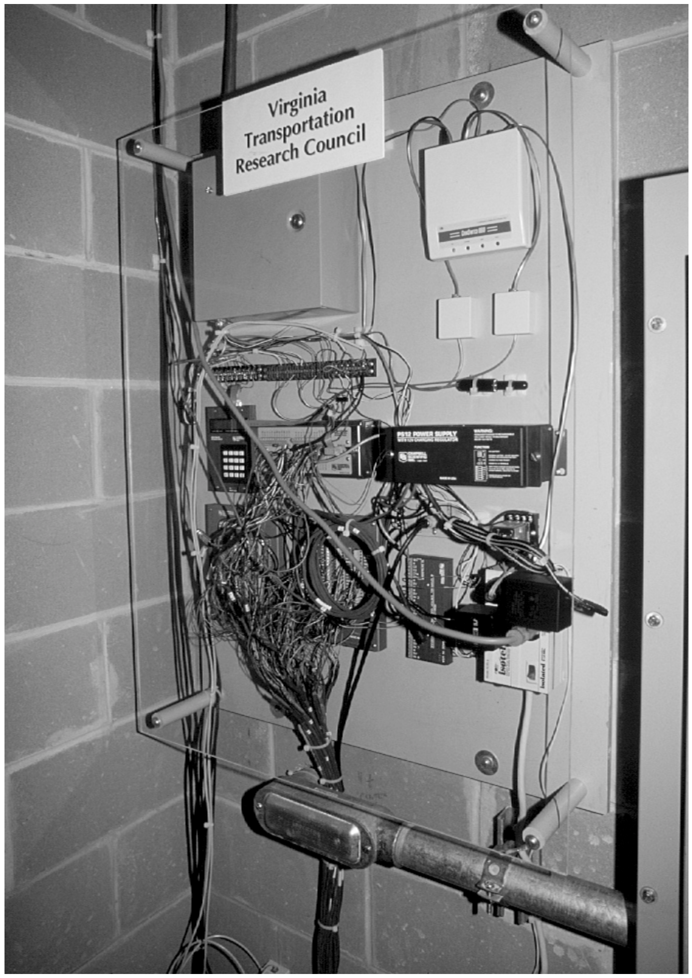

Figure 8. Monitoring Instrumentation

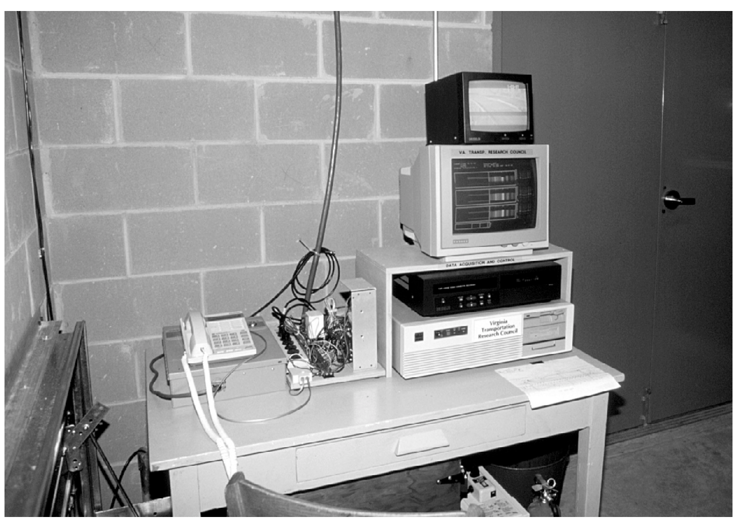

Figure 9. Monitoring Computer, VCR, and Infrared Monitor

To ensure greater reliability, a backup mode of accessing the infrared camera picture and switching the instrumentation was set up using the phone line video transmitter/receiver (slow-scan) manufactured by Northern Information Technology, Inc. (Models 2200T/3500R).

The monitoring system was developed in-house and installed by VTRC. It has been operating successfully in the 4 years following construction. Large quantities of sensor data and dozens of VCR tapes have been collected for processing.

Installing the Systems

Construction of the new bridge commenced in spring 1995. The heating system was installed under the supervision of SETA Technology. No significant problems were reported. One minor delay occurred when reinforcement of the parapet was completed prior to placement of the condenser manifold, necessitating extra work to ensure a proper fit. VTRC personnel installed the monitoring system simultaneously. The project was completed in November 1996. Figure 10 shows the elevation view of the completed bridge.

Figure 10. Elevation View of Heated Bridge

RESULTS

Operation

The initial operation of the heating system revealed an uneven distribution of heat at the deck surface. Figure 11 shows an infrared scan of the bridge during a test conducted on

Figure 11. Infrared View of Bridge After Construction

December 3, 1996. Light areas indicate "hot" locations. It became evident that heat was not being transferred uniformly across the deck, as indicated by inconsistent shading.

To address this problem, a number of repairs and modifications were made by SETA Technology, as follows:

- *December 1996.* Freon HCFC 123 was replaced by Freon HFC 134a in one of the evaporators. A slight improvement in the form of a relatively uniform band of low-intensity heat was observed in the affected deck section.

- *January 1997.* Longitudinal vortex vanes were installed in five evaporator sections to enhance heat transfer between the primary water/glycol mix and the working fluid. Two evaporator pipes were drained of HCFC 123 and filled with water/ethanol (30%) solution. No significant improvement was observed.

- *February 1997.* Water/ethanol solution was introduced into one additional evaporator. Problems with uniform heat distribution persisted.

- *July 1997.* All evaporators, except for one containing HFC 134a, were filled with pure ethanol. Performance did not improve.

- *December 1997.* All evaporators were charged with HFC 134a. The system did not activate during snow events on December 27 and 29 because of a control system failure.

- *February 1998.* Metallurgical-grade ammonia (99.99% pure) was placed in one evaporator. A significant improvement in heat intensity and uniformity was observed in the affected section. It was discovered that the system did not activate because of a fault with the surface condition sensor (lightning/electrical damage suspected). A manual override switch was installed to operate the furnace in case of a control system failure. The surface condition sensor was replaced after the winter season.

- *January 1999.* All evaporators were purged and filled with metallurgical-grade ammonia. Uniform heating across the entire bridge deck surface was observed.

- *December 1999.* The control PC was replaced to correct the Y2K problem. The surface condition sensor was also replaced, and additional circuitry was installed in the control PC to prevent lightning-induced damage.

Figure 12 shows the infrared scan of the bridge during a storm event on January 20, 2000. A bright area in the foreground represents approach slab A, where the surface condition sensor that controls the operation of the heating system was installed. Heat pipe evaporators were located under the “left” parapet. Sensor data from January 19 through 21, 2000, are presented in

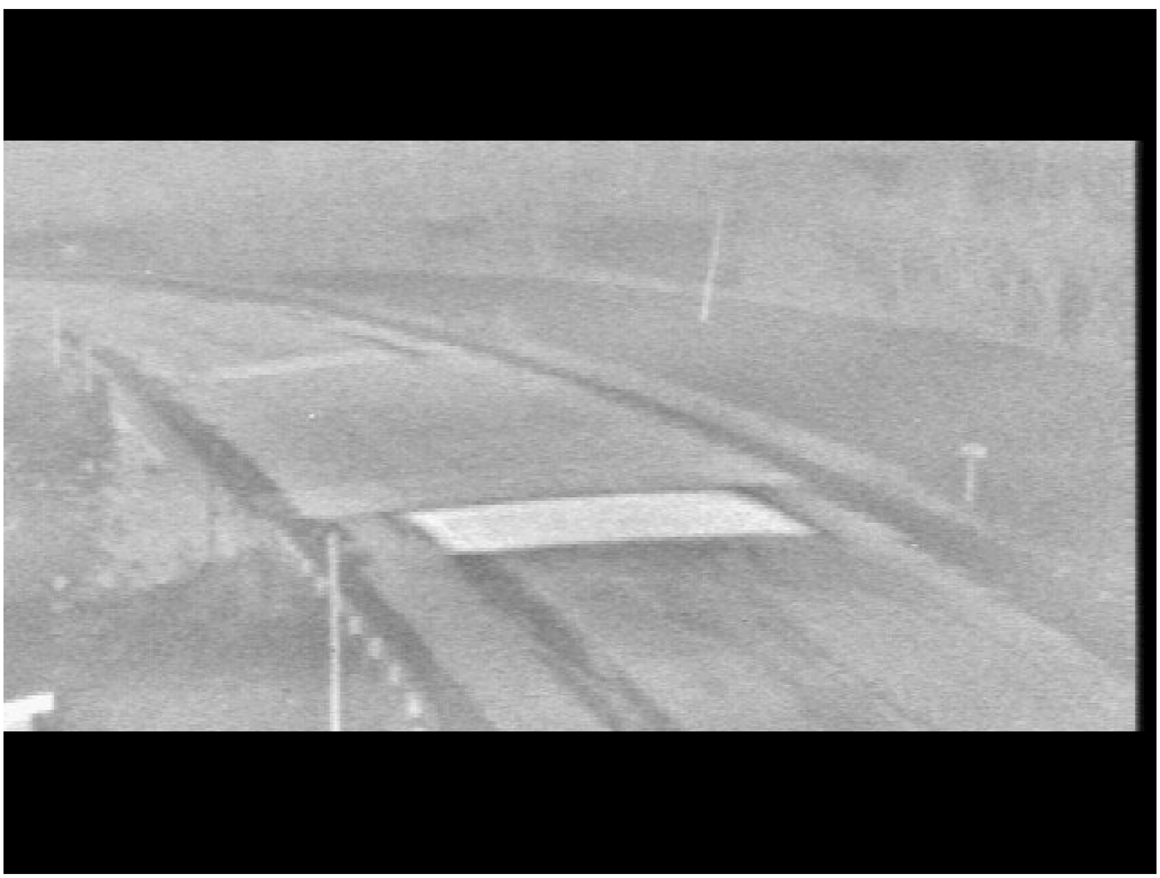

Figure 12. Infrared View on January 20, 2000, at 9:10 A.M.

the Appendix. These data illustrate the winter performance of the heat pipe system following the ammonia conversion. Near-surface temperature probe readings (probes 1 through 20) indicated a relatively uniform distribution of heat across the deck. The ice condition data (Ice/No Ice) shown in the Appendix originated from the Aanderra ice detector, mounted on span A, on a shoulder adjacent to the left parapet.

Costs

The cost data are summarized in Table 1.

Table 1. Cost Data

Item	Cost
Construction	$323/m^2 (deck area); $181,500 total
Retrofit	$18.73/m^2
Operating	$18/h (gas); $312/yr (electricity)
Maintenance	$500/yr

Construction Costs

The construction cost of the entire heating system was $181,500, which did not deviate from the original contract lump sum price. The total cost can be expressed as $323/m^2 ($30/ft^2) of the heated surface, although the aggregate includes a relatively fixed cost of the boiler building with mechanical equipment.

Retrofit Costs

The cost of the ammonia retrofit was $8,981 (funding by FHWA), resulting in a cost of $18.73/m^2 ($1.74/ft^2) of the heated surface.

Operating Costs

During the latest winter season, from November 5, 1999, to April 18, 2000, the ammonia-filled system operated 92 hours. The boiler used approximately 66 L (17.4 gal) of propane per hour of operation. With an average fuel unit cost of $0.269/L ($1.020/gal), the operating cost was approximately $18/h.

The electricity delivered to the boiler building cost approximately $40 per month of operation and approximately $19 per month off-season. The system operates an average of 4 months per year.

Maintenance Costs

The current annual maintenance expenditure is $500 (equipment check and adjustment twice a year), excluding any repairs. No significant maintenance repairs were required to date.

Traffic Accidents

No traffic accidents at the bridge were reported following construction at the end of 1996. For a period prior to construction, from 07/01/94 to 08/01/97, four accidents, one injury, and no fatalities occurred (HTRIS Accident Analysis). However, these incidents did not occur on the bridge but rather on a 3.2-km (2-mi) road segment that included the bridge. Thus, the available data were insufficient to evaluate the effect of the bridge on reducing accidents.

Effect of Heating on Bridge Deck

Following construction, the deck surface was visually inspected at the beginning and at the end of each winter season. No evidence of deterioration that could be traced to heat-induced damage was noted.

DISCUSSION

Problems encountered at the Route 60 Bridge indicate that proper selection of the working fluid is critical to the satisfactory operation of the heating system. The heat throughput of a Perkins tube is proportional to the heat of vaporization of the working fluid at operating temperature, fluid density, vapor density, and difference in elevation between pipe ends (Pravda, 1997). At 38 °C (100 °F), the maximum heat throughput for a 12-m (40-ft) pipe with a 13-mm (1/2-in) internal diameter (as used on this project) is as follows:

Working Fluid	*Heat Throughput (Watts)*	*Heat Throughput (BTU/h)*
Water	445	1,520
Freon HCFC 123	516	1,760
Freon HFC 134a	1,050	3,600
Ammonia	2,460	8,410

It is evident that ammonia offers a much higher heat-carrying capacity than the Freons. The improvement in heat intensity and uniformity of distribution following a change from Freon to ammonia was recorded by the monitoring instrumentation installed at the heated bridge. With reference to the Appendix, which covers sensor data for January 19 through 21, 2000, it can be concluded that the heating system provided a relatively uniform heat distribution across the entire deck surface. The heating system reacted to surface conditions occurring at approach slab A, instead of the bridge deck, because of the inappropriate location of the surface condition sensor. Temperature probe 22, situated closest to the sensor, provided readings of system activation generally consistent with design set points. Unfortunately, the condition of approach slab A was not at all indicative of the condition of the bridge deck, which is affected by the cooling effect from below. The sensor was relocated to the bridge deck in October 2000.

From an environmental standpoint, Freon HCFC 123 has a much lower ozone depletion potential than chlorofluorocarbons (CFCs), but it is included in the list of controlled substances under the Montreal Protocol. HCFCs are to be phased out by the year 2020. As a result of animal toxicity studies, the DuPont Corporation lowered their acceptable exposure limit for HCFC 123 to 10 parts per million (ppm) for an 8- to 12-hour workday and advised that worker exposure should be controlled (U.S. Department of Energy, 1992).

Ammonia (NH_3) has been used in many countries as the leading working fluid in refrigeration and cold storage plants. Thermodynamically, ammonia is an excellent alternative to CFCs and HCFCs. Environmentally, it is considered a hazardous material under the Occupational Safety and Health Administration (U.S. Department of Labor, 1996). Storage and handling of ammonia are covered by strict codes and regulations developed to address its toxic and flammable properties. Because of the corrosive nature of ammonia, brass fittings cannot be used in the installation.

A major difference between the HCFC- and the ammonia-based Perkins tube (heat pipe) system is the operating pressure. The critical pressures of ammonia and HCFC 123 are 11,390 kPa (1,639 psi) and 3,668 kPa (532 psi), respectively (Minsk, 1999). Initially, SETA Technology was concerned that an unacceptably high pressure might develop with the ammonia design if the control PC failed to shut down the system. Subsequently, SETA Technology determined that “it is very unlikely that the working fluid temperatures could get high enough to be a problem in any reasonable scenario” and approved the conversion (Pell, 1998).

From a technical standpoint, the use of a relatively short primary loop, combined with a series of parallel heat pipes, offers advantages compared with a conventional hydronic system consisting of a long, continuous loop. A smaller hydraulic pump can be employed, and in the event of leakage, the system can be readily accessible for repairs. The primary loop on the Route 60 Bridge is placed outside the deck. In the event working fluid leaks from a heat pipe, the loss of coverage is likely to be limited to the area served by one evaporator, with the remaining modules still operating.

The weakest link in the entire heating system appears to be the control unit. For more than one storm event, the surface condition sensor failed to activate the furnace. The problem was traced to lightning damage as the most likely cause. In addition, the placement of the sensor on the approach slab prevented the heating system from activating early enough in response to the more critical condition of the deck surface.

The projected operating cost of $18/h for propane consumption compares favorably with the costs for electrical and hydronic systems considered in the initial selection. Assuming quite conservatively that the heating system needed to operate 50% longer than the 92 hours recorded in the last winter season, the propane cost would have been $2,484 . With an average of 4 months of operation in the winter at approximately $40/mo and $19/mo off-season, the cost for electricity would be $312/yr. Combined with an annual maintenance cost of $500, the total operating cost for the Route 60 Bridge will be approximately $3,300/yr when the surface condition sensor is installed on the deck. In contrast, the operating cost of the closest alternative hydronic system was initially estimated at $6,000/yr.

Lessons learned from the Route 60 project show that although the heat pipe technology can be used effectively to prevent snow and ice accumulation, a reliable deck heating system is still a work in progress. More robust controls need to be developed by the industry so that the failure of a single sensor cannot disable the entire system. Perhaps more important, an active and essentially mechanical system requires a substantial effort in terms of time, personnel, and expertise to ensure that all components are functioning safely and effectively.

CONCLUSIONS

- Applying heat pipe technology to heating bridge decks is feasible.
- Selecting a proper working fluid for heat pipes is critical to effective deck heating.
- The surface condition sensor should be placed on the bridge deck.
- The heat pipe system does not pose a construction problem.
- Operating costs for the heat pipe system are lower than for an alternate electrical or hydronic system.
- The heating system does not seem to have any adverse effects on the durability of the bridge deck.
- The use of an infrared camera can be very effective in evaluating heat distribution and intensity across the deck surface.

RECOMMENDATIONS

1. Make the control system redundant; the failure of a single sensor can cause the entire heating system to become inoperable.

2. Place the sensor on the bridge deck, as its location is critical to the proper operation of the heating system.

3. Use infrared scans as a measure of the performance of the heating system prior to granting final acceptance.

ACKNOWLEDGMENTS

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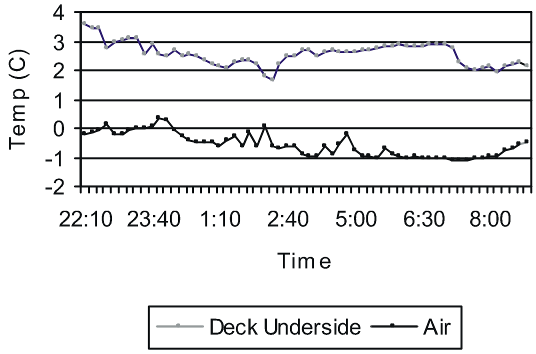
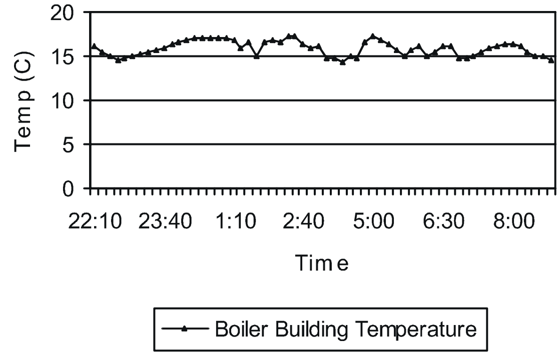
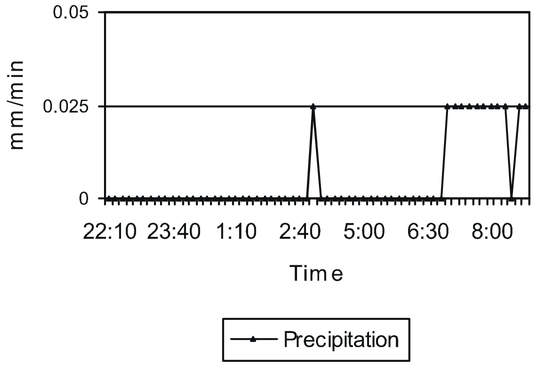
APPENDIX

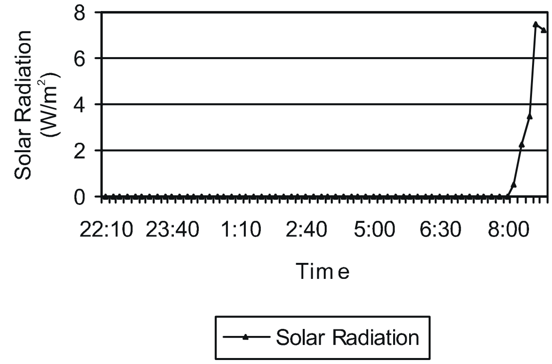
Monitoring Sensor Data for the Period January 19–21, 2000

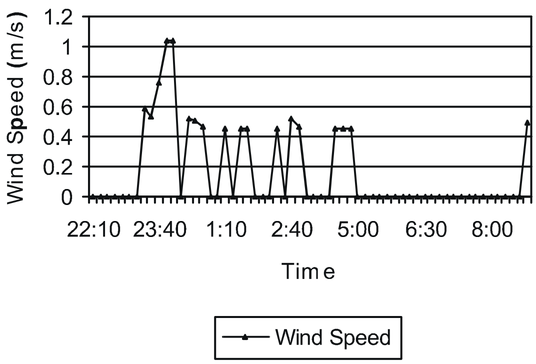
AMBIENT CONDITIONS
January 19, 2000, to January 20, 2000

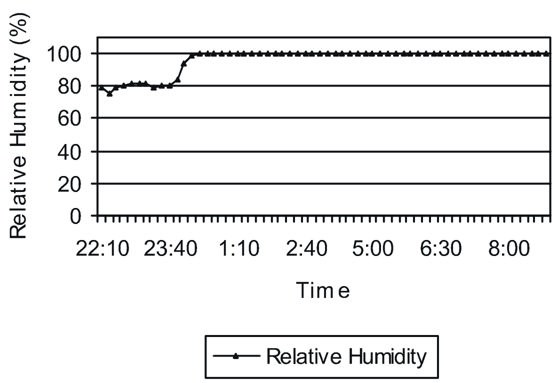


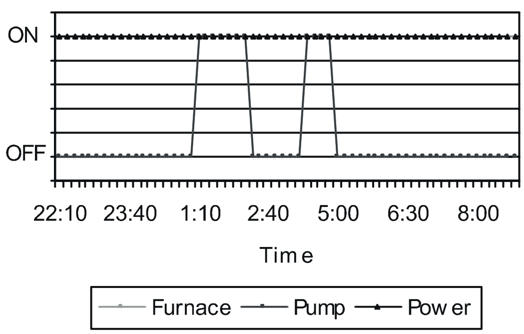


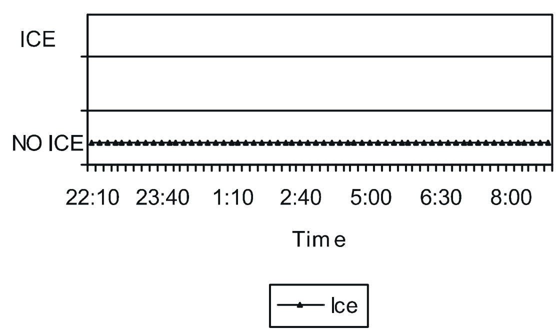




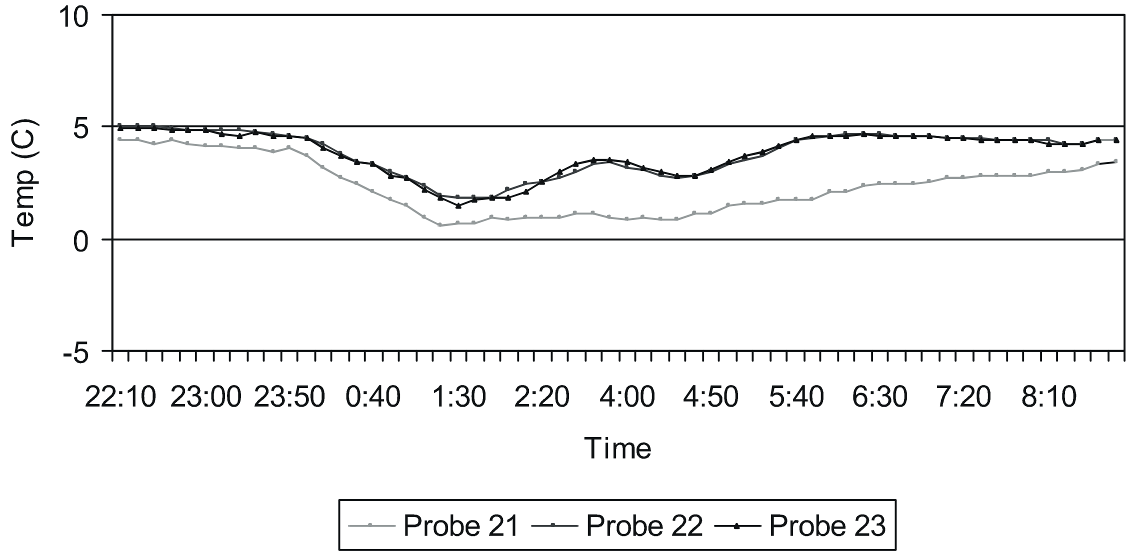


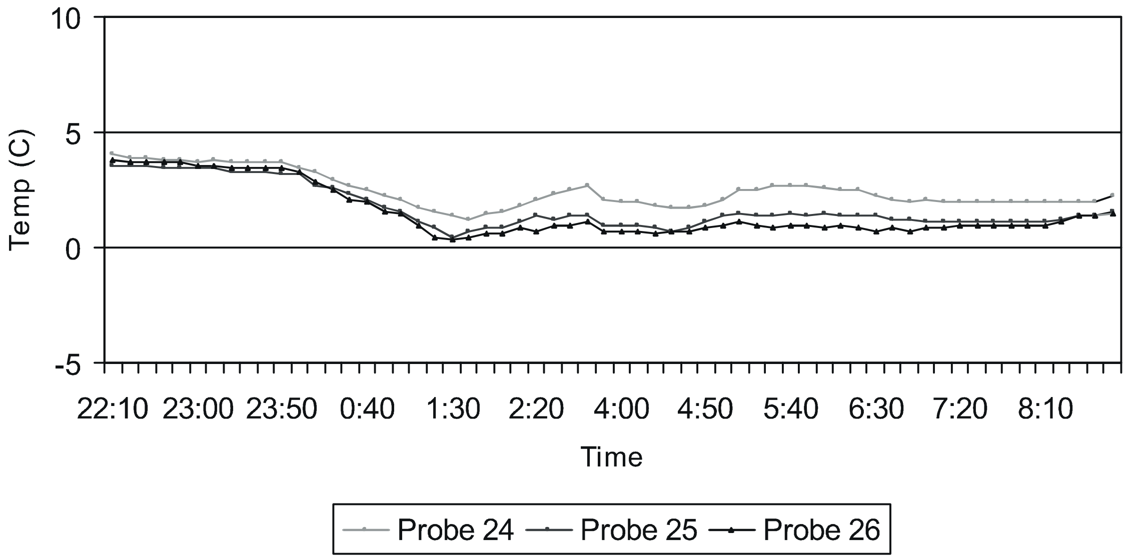


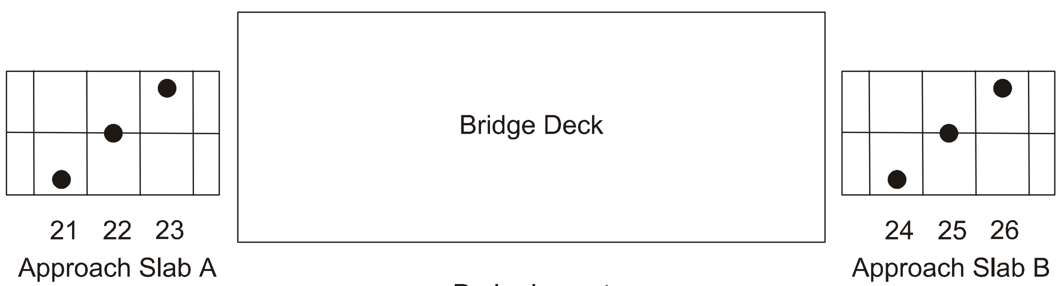




APPROACH SLAB TEMPERATURE
January 19, 2000, to January 20, 2000

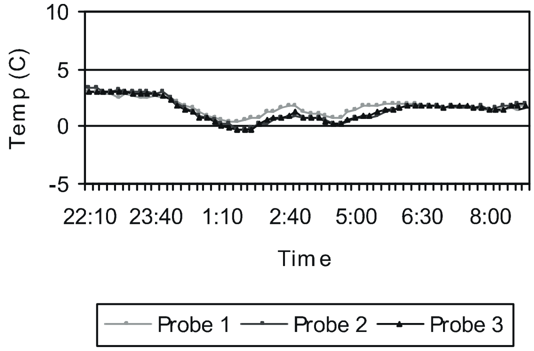


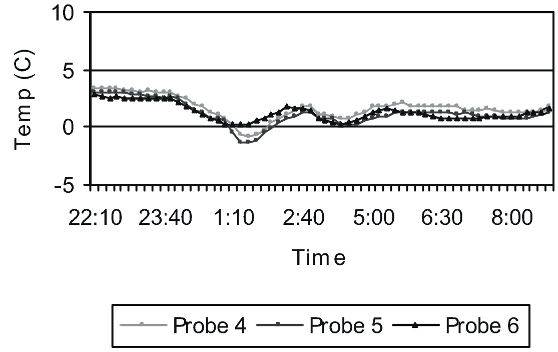


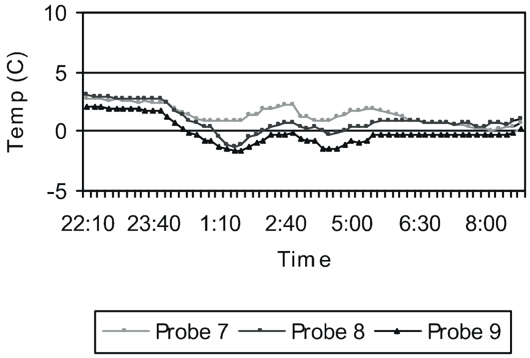


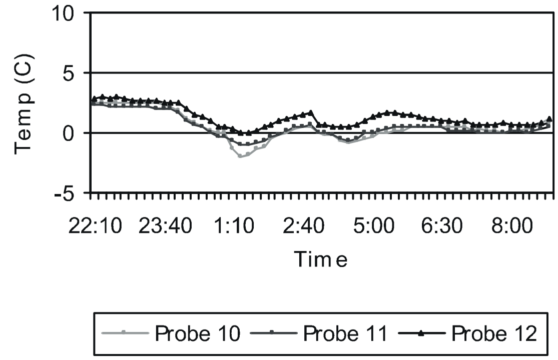
Probe Layout

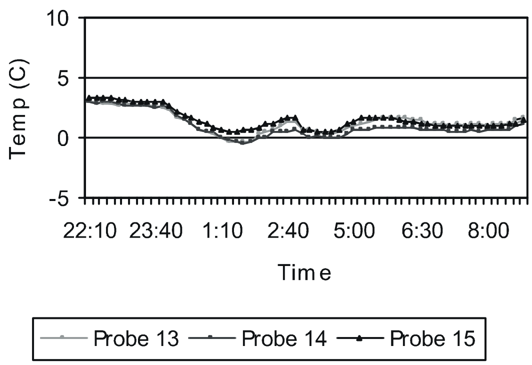
DECK TEMPERATURE
January 19, 2000, to January 20, 2000

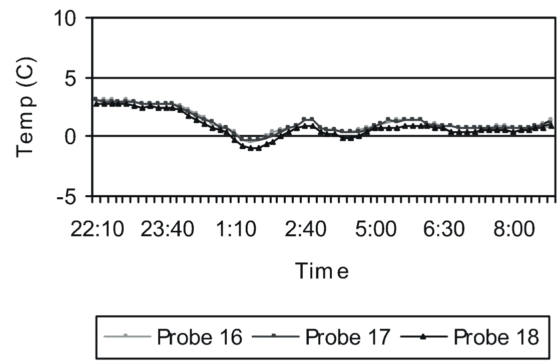


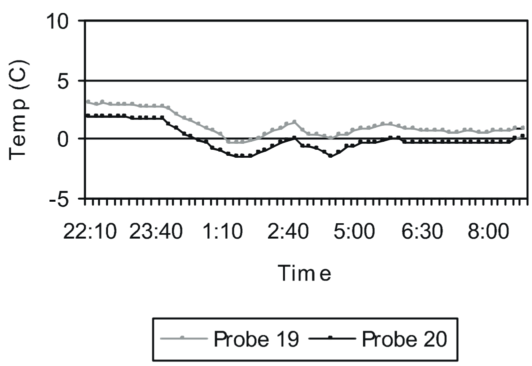


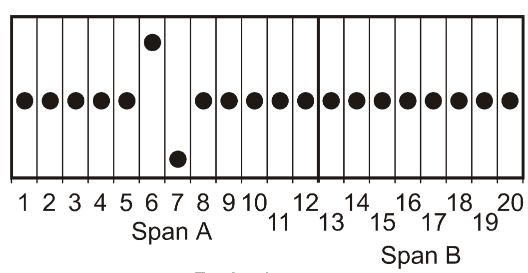






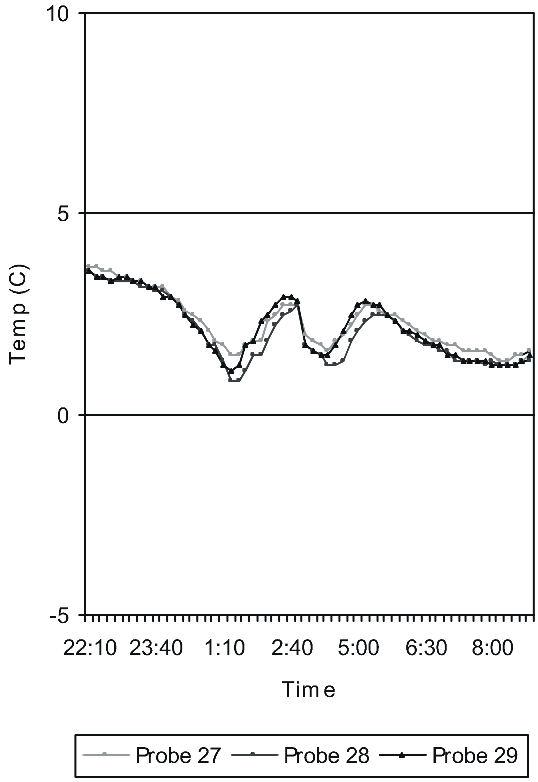


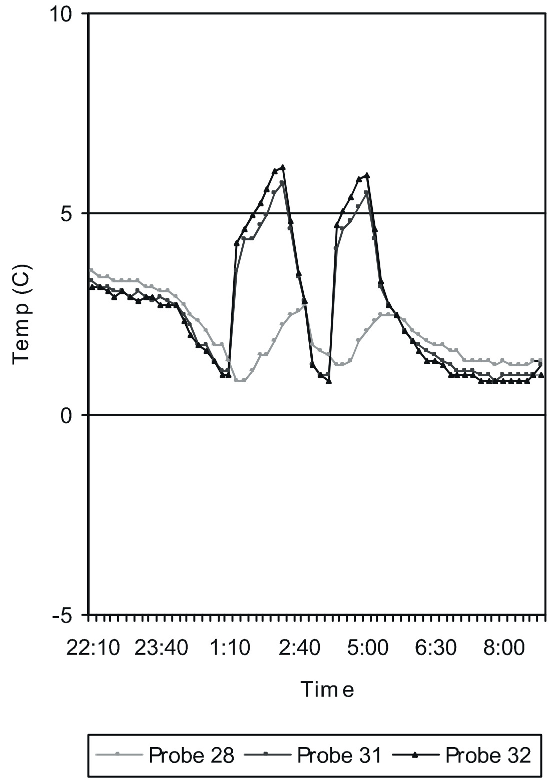


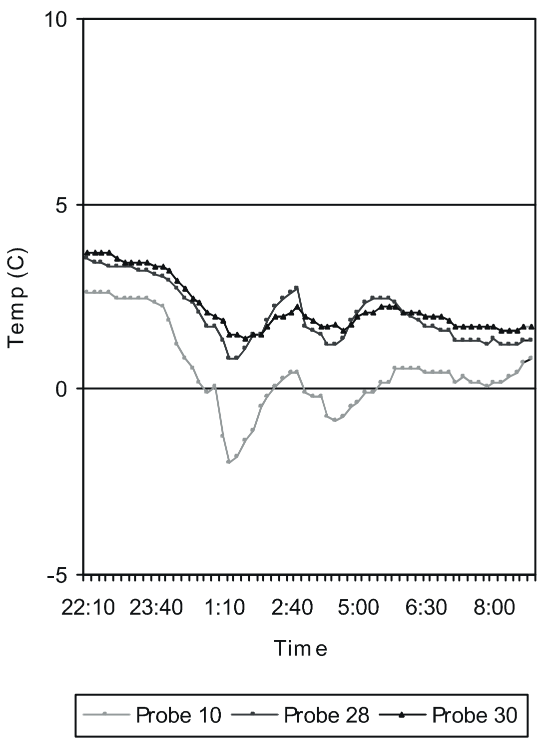


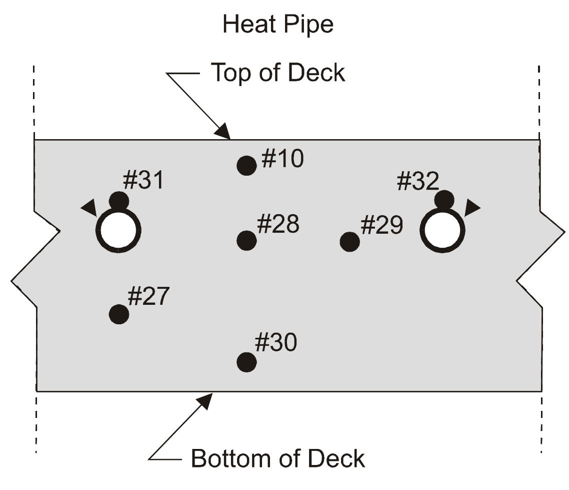
Probe Layout

DECK TEMPERATURE
January 19, 2000, to January 20, 2000



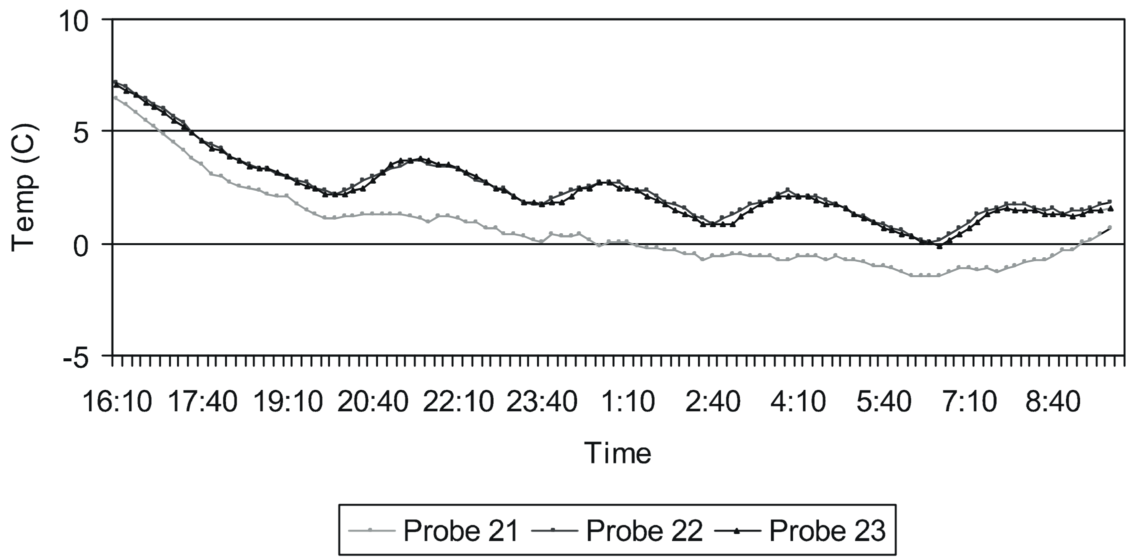


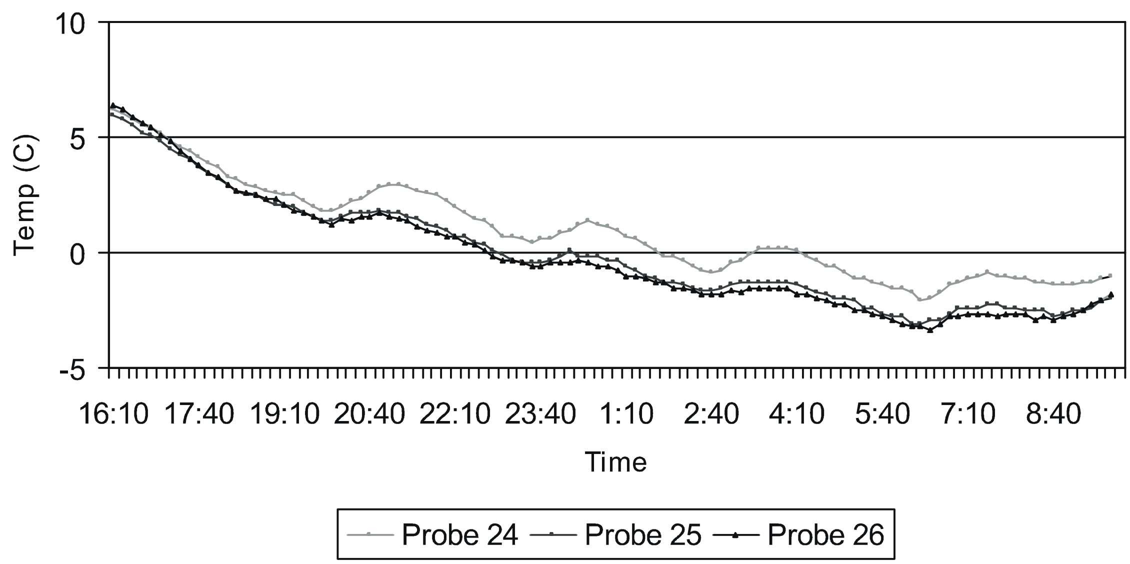


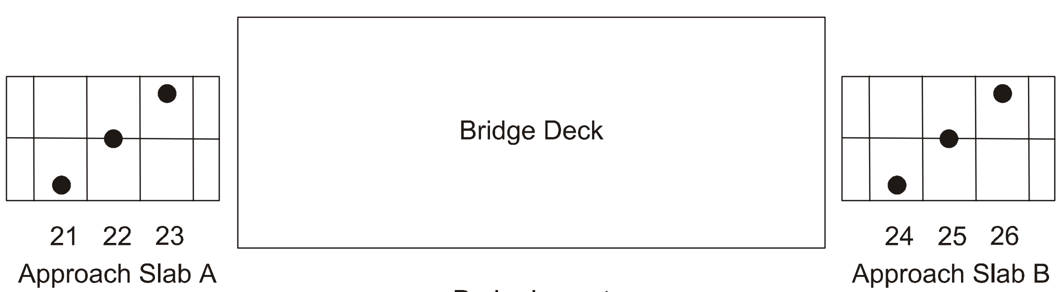


Section
Probe Layout

APPROACH SLAB TEMPERATURE
January 20, 2000, to January 21, 2000

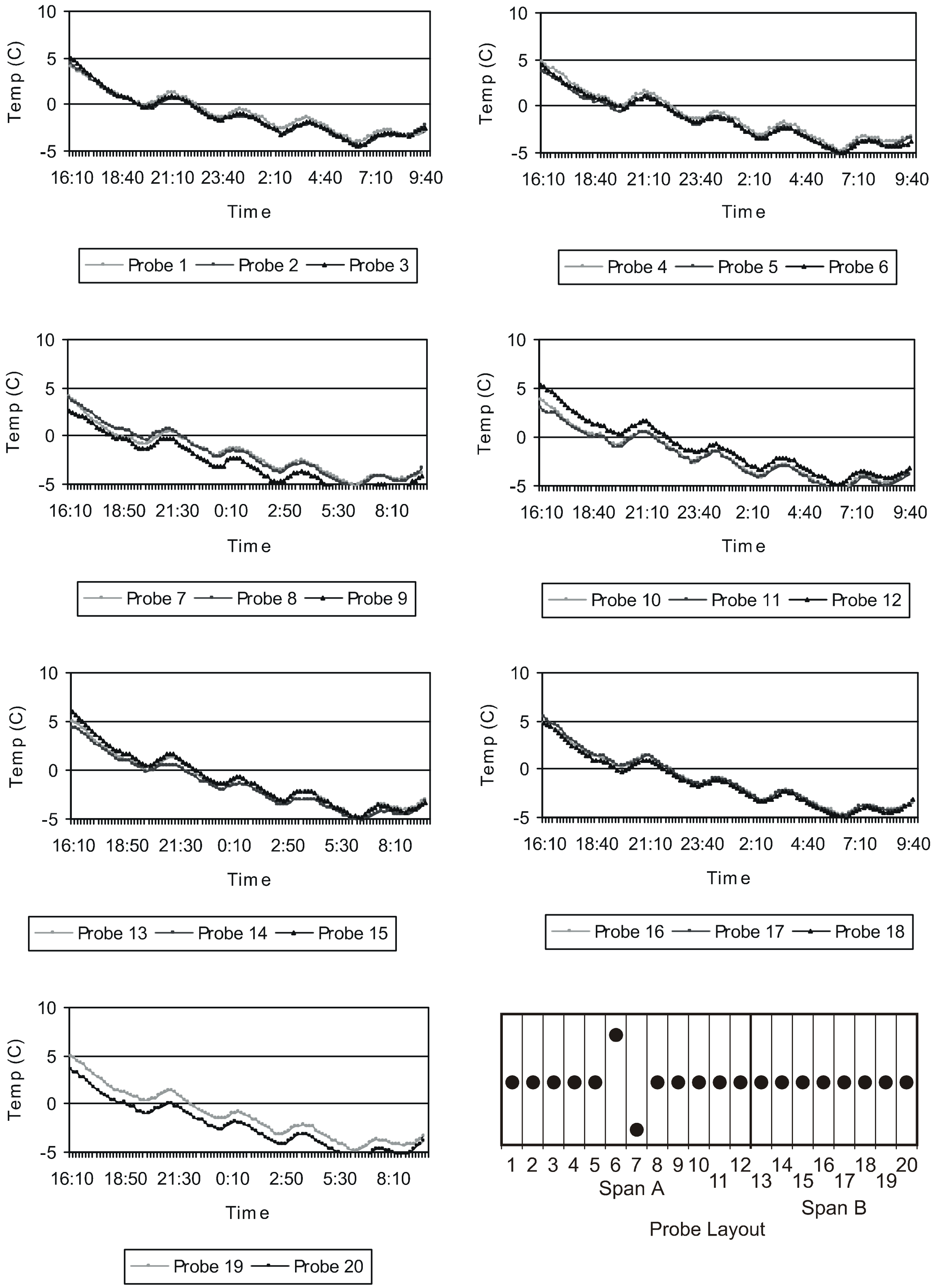






Probe Layout

DECK TEMPERATURE
January 20, 2000, to January 21, 2000



Probe Layout

DECK TEMPERATURE
January 20, 2000, to January 21, 2000