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Heated Bridge Technology

Report on ISTEA Sec. 6005 Program

Office of Bridge Technology

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Heated Bridge Technology

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Foreword

This report summarizes the experiences of agencies in five states that designed, constructed, and operated heated bridge deck surfaces for the control of snow and ice accumulation. The work was conducted as part of the Applied Research and Technology (ART) program (section 6005) of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The ART program provided funding to accelerate the testing and evaluation of new technologies that are intended to increase the durability, efficiency, productivity, environmental impact, and safety of highway, transit, and intermodal transportation systems. Heated Bridge Technologies (HBT)—deck surface heating systems designed to prevent snow, ice and frost accumulation on bridge decks—was a component of this program. Only bridges that were eligible for replacement under the Bridge Rehabilitation Program (23 USC 144) were considered for ART program funding. Funding was provided during fiscal years 1992 through 1997. The program goal was to demonstrate durable, environmentally friendly technologies that promote effective reduction of the slippery conditions on bridges caused by ice and snow without use of chemical applications.

Cover: Bridge on Virginia Route 60 crossing the Buffalo River near Amherst, heated with heat pipes; see page 29.

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16. **Abstract**

Heating technologies for prevention of snow and ice accumulation were incorporated in ten bridge decks located in five states, Nebraska, Oregon, Texas, Virginia, and West Virginia, to enhance motorist safety and reduce traffic disruptions. Three different technologies were used to convey heat to the bridge surface: hydronic (heated fluid pumped through pipe or tubing in the pavement close to the surface), heat pipe (passive transfer of heat by vaporization and condensation of a working fluid contained in sealed pipes), and electric (heat generated by electric resistance cables buried in the pavement near the surface). The report gives construction details, cost data, operating characteristics, and experiences during winter operations. At the time this report was prepared, insufficient operating time had accumulated to judge the cost effectiveness of all the installations, but positive control of snow and ice had been demonstrated.

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Bridges, bridge icing, anti-icing, ice removal, snow and ice control, snow melting, winter maintenance, ice control, ice prevention, heat pumps, heat pipes, hydronic, electric heating

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History

Legislative background.

Section 6005 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 established the Applied Research and Technology Program "for the purpose of testing, evaluation, and implementation of technologies which are designed to improve the durability, efficiency, environmental impact, productivity, and safety of highway, transit, and intermodal transportation systems." A Heated Bridge Technology (HBT) program was included as a Designated Technology with the objective "to assess the state of technology with respect to heating the decks of bridges and the feasibility of, and costs and benefits associated with, heating the decks of bridges. . .carried out by installing heating equipment on decks of bridges which are being replaced or rehabilitated. . ." Funding of $4.0 million/yr allowed 80 percent funding for construction of projects, and 100 percent funding for planning, evaluation, and analysis.

Preferential bridge deck icing

The very purpose of a bridge—to span an obstacle—gives rise to a frequently occurring hazard—moisture from water the bridge spans condenses and freezes on the deck. This condition occurs most commonly when the deck loses its heat energy to the night sky more rapidly than energy can be replaced from the body of the bridge structure. A bridge will lose heat from all sides, in contrast to a road built on grade, and therefore the deck will cool more rapidly than the approaches. During the cooler seasons in many parts of the United States, the deck heat loss can produce very transient conditions conducive to preferential bridge deck icing. Icing conditions developing nearly instantaneously around sunrise, then disappearing within 15 min, have been reported a number of times. This condition is particularly hazardous since it can occur without warning. It constitutes a sudden change from the approach road having good traction to a surface where all directional control and braking effect are lost. Serious accidents and fatalities have been the all-too-frequent consequences. Though detectors can sense the presence of ice on a bridge deck, warning signs triggered by icing, which have been used experimentally, have been routinely disregarded by motorists. Application of chemical freezing point depressants will reduce the probability of ice formation, but provide only temporary protection and must be reapplied frequently. The only positive method of preventing ice formation on a bridge deck other than intercepting precipitation before it reaches the deck (e.g., covered bridges) is to maintain the surface above the freezing point of water. This is accomplished by heating the pavement using internal or external sources—external by irradiating with a radiant source, internal by warming the pavement by electrical resistance heating or by heated liquids or vapors using appropriate conductors.

Project oversight

Management of the HBT program was provided by the Federal Highway Administration's Office of Technology Applications, with support provided under contract initially by Tonya, Inc., and later by Henderson Associates. Oversight was provided by a Technical Working Group (TWG) composed of individuals from government, academia, and the private sector. (See list in Appendix B.) In addition, consultants were retained to prepare reports on a number of topics, a list of which is given in Appendix E.

State participation

States were solicited to nominate candidate bridges to receive funding for heated bridge decks. Though 19 candidates from 12 states were proposed, insufficient design lead time and factors concerning eligibility for funding limited the number of funded projects to six. They are:

Nebraska	10th Street Pedestrian Overpass, Lincoln
Oregon	Highland Zoo Interchange, Sunset Highway, Portland
Oregon	North Fork Silver Creek, Silver Falls State Park
Oregon	2nd Street Overcrossing, Hood River County
Texas	16th Street Overpass, Amarillo
Virginia	Route 60 Bridge over Buffalo River, in Amherst County
West Virginia	5&20 Mile Creek Bridge near Winfield, WV

Available technologies

Heating bridge decks by internal means was the focus of the HBT program; thus external heat sources such as infrared luminaires was outside the scope. The available technologies fall into three groups: hydronic, heat pipe, and electrical. The characteristics of each are described below.

Hydronic

Heat transfer fluid which can be heated by a number of different methods (see "Heat sources" below) is circulated through pipes or hoses embedded in a continuous loop near the surface of the pavement. Heat is released to the pavement and warms the surface by conduction. The cooled fluid is returned to the heat source and the cycle repeated.

Heat pipe

A working fluid in a heat pipe is vaporized by a source of heat at one end of the pipe and diffuses to the other (cold) end where it condenses, releasing its stored heat. A wire mesh running the length of the tube returns the liquid working fluid to the heat source by a wicking action (capillary attraction). The tube or pipe does not have to be straight, nor does it have to have a downward slope since capillary force in the wick will counter gravitational force. Tubes constructed without a wick have also been used successfully for heat transfer, but need to have a downward pitch since gravitational force is necessary to return the working fluid from the hot to the cold end. These "Perkins pipes" date from the late nineteenth century, whereas heat pipes, first suggested in 1942, did not come into practical use until after mid-century. The term "heat pipe" was first used in 1963, and is now popularly applied to both types of pipe, though a Perkins pipe is, strictly speaking, a thermal siphon (Dunn 1976, Ivanovskii 1982)(See references in Appendix A).

Electrical

Electrical current encounters resistance when flowing through a conductor and loses energy in the form of heat. This is the principle used for electrical heating of pavements. The heat produced is governed by the force pushing the current flow through the conductor, i.e., the voltage, and the composition of the conductor that offers resistance to flow. Metallic conductors such as high purity copper or silver have low resistance and therefore lose little energy in the form of heat; this, of course, is desirable when maximum current flow is the objective, such as in feeder cables. By introducing non-conducting impurities into a conducting metal, or by using certain metals, resistance will be increased, and a desired amount of heat can be produced depending on the composition or amount of impurity. Commercial heating cables used for pavement heating consist of a resistance wire embedded in highly compressed magnesium oxide for electrical isolation. This is encased in a metal sheath for protection and for good thermal conductivity.

Heat sources

Energy required to heat the fluids for circulating through a hydronic system or for vaporizing the working fluid in a heat pipe can be obtained from high level sources such as fossil-fuel-fired boilers, or low-energy geothermal sources such as well water or the earth itself. Extracting heat from low-energy sources and concentrating it to a high level for circulating through a hydronic system necessitates a two-step process: a heat pump in which a low-level heat source vaporizes a refrigerant (once commonly Freon, now with less atmospherically-aggressive compounds) which then releases its heat in the condenser of a heat exchanger. The fluid circulating through the pavement piping circuit picks up the heat from the heat exchanger. The two fluids never mix since they are in separate piping circuits. Heat pipes may extract the low level of thermal energy contained in well water or the earth without the intermediary of a heat exchanger. The proper working fluid in a heat pipe will be vaporized at the relatively low temperatures present in geothermal sources.

Operational control

If icing conditions were very frequent, it would be practicable from the standpoint of achieving maximum protection to apply heat continuously to a bridge deck. However, icing conditions are random events, and generally continuous heating will not be cost-effective. Therefore some means must be provided for signaling the occurrence of freezing precipitation, or for anticipating the probable occurrence of such conditions based on an analysis of environmental conditions. Sensors embedded in the pavement and sensors in the environment surrounding the bridge will provide this information. Energizing the heating system can be accomplished either manually or automatically. Manual control will require fewer sensors and their associated logic circuits but will require close, if not continual, human observation. Greater sophistication (and instrumentation cost) will be necessary for automatic control. Both control methods require basic instrumentation consisting of pavement surface temperature sensors, and sensors to measure air temperature and the presence of either a wet pavement or falling precipitation. Manual control then involves an operator in a control center observing that the air temperature is dropping and approaching the freezing point of water, and that there is a high probability forecast of falling precipitation. The heating system is then energized based on the judgment of the observer. Automatic control requires the addition of another type of sensor that detects the presence of precipitation. When the simultaneous occurrence of near-freezing temperature and precipitation is detected, the system is energized. Two types of precipitation detectors are commercially available: one that detects falling precipitation by the interruption of a light beam, and another that senses water or ice on the pavement itself. The bridge deck installations funded by the HBT all used deck sensors. Two types of deck sensors were used: the pneumatic ice detector (made by Aanderaa, used on the Virginia bridge), and the conductivity unit (made by Delta-Therm, used on Oregon, Nebraska, West Virginia bridges). The pneumatic device incorporates a porous membrane that is permeable to air when dry or wet but impermeable when covered with ice; a small blower delivers a low volume of low pressure air to the device. The conductivity type measures the electrical resistance between closely spaced mutually insulated conductors. When dry, no leakage current flows between the conductors. When wet, a small leakage current is detected by the control circuitry.

Climatic regimes

Application of heated bridge technologies generally can be justified economically and practically only for installations in a temperate region. A cold climate will have relatively fewer icing events. Cold snow falling on a cold bridge deck surface will not bond strongly. Traffic action therefore may be sufficient to remove the accumulation. Mechanical removal may be necessary, but compacted snow accumulation may not occur very frequently. Thus it is not surprising that all the bridges in the HBT program are in temperate climates. The table that follows documents the climatic factors for these bridge locations. Climatic data are for the stations in the National Weather Service database closest to the bridge sites; thus the entries for Charleston, WV and Lynchburg, VA may not represent the Five and Twenty Creek and Amherst sites as closely as do the other entries. The far right entry for Minneapolis/St. Paul contrasts the conditions for a relatively cold climate where heating may not be a primary method for control of snow and ice on bridge decks.

Meteorological element	Station					
	Amarillo TX	Charleston WV	Lincoln NE	Lynchburg VA	Portland OR	Minneapolis MN
Normal no of days with:						
Max T ≤ 32F (0C)	12.6	19.5	42.3	10.5	3.4	78.7
Min T ≤ 32F (0C)	110.8	100.7	143.3	90.6	41.1	156.6
Min T ≤ 0F (-18C)	2.2	2.0	16.6	0.5	0.0	33.1
Snowfall ≥ 1 in.	5.4	11.5	8.4	5.6	1.7	17.1
Normal annual temp (F)	56.9	55.0	50.8	55.9	53.6	44.9
Heating degree days	4258	4646	6278	4340	4522	7981
% possible sun	74	*	62	59	48	58
Snowfall (in)						
Max monthly	17.3	39.5	19.8	31.8	41.4	46.9
Max in 24 hr	13.5	17.1	13.2	19.0	10.6	21.0
Normal annual	16.9	36.0	26.1	20.8	5.3	56.0
Wind (mi/hr)						
Mean speed	13.1	5.9	9.4	7.0	8.0	10.6
Max 2-min	60	34	49	28	39	37

*Value missing in NOAA Local Climatological Data

Nebraska

Project description

This is a five-span pedestrian viaduct over railroad tracks located near the stadium at the University of Nebraska-Lincoln (Fig. 1). It is 367 m (1204 ft) long, running north-south with a 3.7 m (12 ft) wide deck. The elevated portion is a169.8 m (557 ft) long, 2-girder structure; the mechanically stabilized earth approaches are 70.7 m (232 ft) and 126.5 m (415 ft) long[1]. (Superscripts refer to references found at the end of each state report.) The entire 1599 m^2 (17,211 ft^2) surface is heated. The design objective is the prevention of any sustained snow or ice accumulation. Delta-Therm designed the hydronic system with a design heat flux of 530 W/m^2 (168 Btu/ft^2-hr) and a fluid flow rate of 530 L/min (140 gal/min). Two Taco "1600" Series in-line pumps capable of 1207 kPa (175 psi) operating pressure at 394°C (250°F) move the heating fluid through the system. A flow meter was installed in the pump house. The working fluid is a 35 percent propylene glycol-water solution heated by a natural-gas-fired boiler rated at 908 kW (3,098,000 Btu/hr) input and 732 kW (2,498,000 Btu/hr) output. Expansion tank capacity of 802 L (212 gallons) is provided within the boiler house. The liquid temperature is 54°C (129°F) leaving the boiler, below the 60°C (140°F) rating of the 152 mm (6-in) diameter Schedule 40 polyvinyl chloride (PVC) distribution pipe. The distribution and return pipes are insulated with 51 mm (2 in) of fiberglass. They are suspended below the elevated section of the bridge with a flexible expansion loop installed in the pipe near each abutment (Fig. 2).


Fig. 1. The 367 m (1204 ft) long pedestrian viaduct spans railroad tracks.

There are 13 heating zones, with a 25 mm (1 in) copper distribution manifold and a similar collection manifold for each zone; these are embedded in the concrete deck (Fig. 3). Rubber hydronic hose, also embedded in the bridge deck and sand approach, carries the hot liquid from the distribution manifold through the deck to the collection manifold. The fluid is transported from the boiler to the distribution manifold by 152 mm (6-in) PVC pipe. The 10 mm (3/8 in) inside diameter black hydronic rubber hose is spaced on about 114 mm (4 1/2 in) centers, and runs parallel to the bridge span (see schematic drawing on the next page). They were tied to the bottom of the reinforcing bars. Depth of concrete cover over hoses is nominally 76 mm (3 in). The PVC supply and return pipes are bedded in sand under the on-grade approaches and are not insulated. Data was collected from sensors by a computer located in the boiler house.


Fig. 2. Flexible expansion loops in supply/return pipes underneath walkway. View looking up.

Climatic conditions

Average annual snowfall is 880 mm (35 in). Maximum recorded 24 hr snowfall is 264 mm (10.4 in) (1957). Between October 17 and April 20 there are normally 185 days when the average temperature is below 0°C (32°F) and normally 161 days with temperature below -2°C

(28°F). The region has a mean annual temperature of 11.5°C (52.7°F) and a mean annual precipitation of 643 mm (25.3 in).

Operating controls

Thermistors were installed at three depths in the concrete deck (top, middle, bottom) at five locations: two in the north span of the elevated structure, two in the north approach pavement, and one in an unheated sidewalk near the end of the installation. Fluid supply and return temperatures are also monitored, and flow is measured by a volume flow sensor in the return pipe near the boiler. The system was designed for automatic control, using two Delta-Therm SM-120A heated precipitation sensors installed in the concrete deck. The temperature sensors initiate heating when deck temperature is below 4°C (39°F), ambient temperature is below 2°C (36°F), and moisture is sensed on the deck. System turn-off is set at a deck temperature of 13°C (55°F). However, during

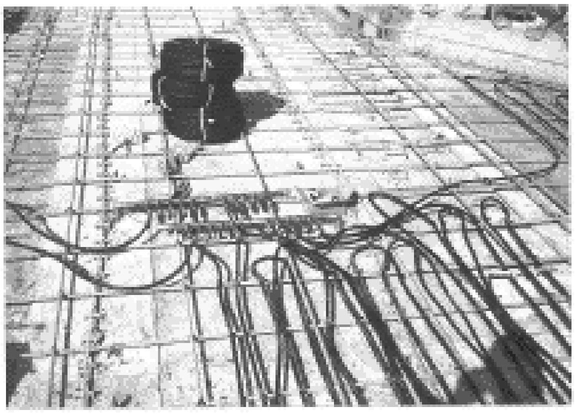
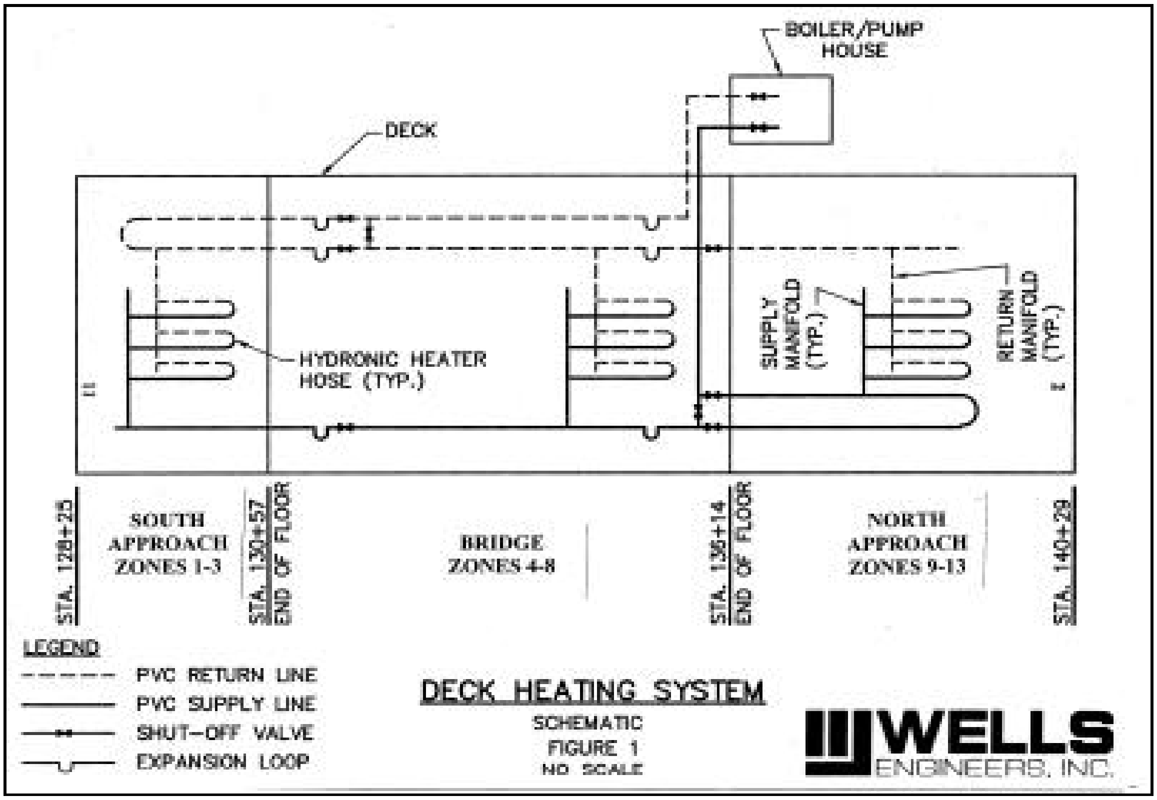


Fig. 3. Distribution manifolds are horzontal copper pipes in center which supply the rubber hydronic tubes.

Fig. 4. Uninsulated PVC supply and return pipes were bedded in sand in approaches on both ends of walkway.



the events described below, control of the heating was performed manually because of improper moisture sensing. All sensors are wired to a computer in the boiler house at ground level near the north end of the structure. To ensure that the heating fluid will not reach its boiling point, the boiler and pumps are started in a sequence that first turns on the pumps, then after a delay starts the boiler. The pumps continue to run for a short period after the boiler shuts down to prevent overheating.

Costs

Design	\$150,000
Construction	\$161/m^2 (\$15/ft^2) (additional for heating installation)
Operating	\$9.25/hr

Operating experience

The system was operated during three winter precipitation events, briefly on December 5 and 16, 1994 (light snow and ice on the 5th, 35 mm (1.4 in) on the 16th), then for 33 hours on December 31, 1994 to January 1, 1995 during a storm with total snow accumulation of 80 mm (3 in). During this event (graphed at the lower right of this page), the moisture sensors failed to indicate presence of moisture because of two conditions: (1) the heated sensors evaporated the moisture, and (2) as snow accumulated it bridged the sensor forming a cap or "igloo" while the sensor remained dry. It was necessary to control the system manually. Snow began to accumulate on the deck, and a layer of slush developed beneath the snow accumulation. Snow was completely melted from the deck walkway after 24 hours. The deck was dry after 32 hours. Snow did accumulate without any melting at the deck surface on the four cantilevered pads extending outside the 3.7 m (12 ft) wide main deck. Heat input to these rest areas for wheelchairs was not sufficient due to the cantilevered design. Small leaks occurred at joints of the supply and return PVC pipe; these were repaired by adding stopleak to the system. However, during a February 1995 event, fluid was observed leaking from the PVC pipe joints. The system was shut down, and plans for repair were initiated.

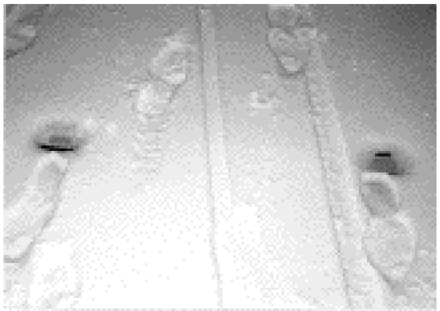
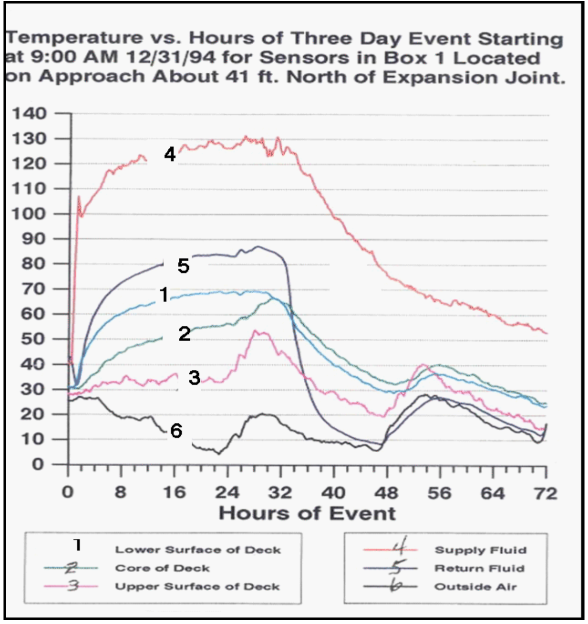


Fig. 5. Snow "igloos" formed over moisture sensors.

The investigation that followed found that bonding of the PVC pipe joints was inadequate[2]. As much as 28 percent of the joint area was not bonded with glue in the joints that were removed from the system and studied. This was ascribed to the lack of experience on the part of the installation contractor and the cold conditions during installation. Leaks also occurred at the fittings between the manifolds and hoses before they were encased in the concrete deck/slab, ascribed to improper tightening and lack of any thread sealant. This problem was corrected during construction. Expansion room for the expansion loops was not adequate at the north abutment and expansion loops were not positioned correctly at the south abutment. The installation allowed expansion of about 254 mm (10 in) at the north abutment, whereas a movement of 533 mm (21 in) was calculated. This may have contributed to joint failure. Bell joints were used on the PVC, rather than the specified coupling sleeve type. Tests made at the University of Nebraska Lincoln[3] found that the coefficient of



thermal expansion of the PVC pipe used in the overpass was about 20 percent higher than the average value reported in Appendix XI of ASTM D2665[4]. Other tests on the pipe for stiffness, wall thickness, load deflection, tensile strength, and flattening were within specifications.

Two snow/heating events were reviewed in a report prepared by the University of Nebraska[5]. The first event began on December 20, 1994; the second began on December 31, 1994, and extended to January 1, 1995. Only the latter will be summarized here. A graph of one of the temperature sensor outputs located on the north approach about 12.5 m (41 ft) from the abutment will help to explain the event (see graph on preceding page). Time zero on the graph is 9:00 am on December 31. The system was turned on at 9:55 am and ran for about 39 hours. The fluid return temperature initially drops because of the surge of cold fluid from the deck hoses, then it begins to rise after about an hour delay which represents the time required for the heated fluid to travel through the entire system. Initially, the deck upper surface warms slightly and stays about 0°C (32°F), the ice melting point. At hour 24 the surface temperature rises, indicating that all the snow has melted. The core and lower deck surface are higher than 0°C (32°F) during snow melting because heat is flowing from the hydronic hoses in the core to both the top and bottom of the deck, and the latter is not losing heat from snow melting. The sharp drop in return fluid temperature at about hour 32 indicates that the pumps had been shut off and the flow has stopped. The pumps continued to run until they were manually shut off at about hour 39 (11:00 pm Jan 1). Once the fluid flow ended at hour 32, all the deck temperatures began to track the air temperature variation. The deck was clearly surface dry by hour 34.

Fig. 6. Deck condition at hour 9.

Fig. 7. Deck condition at hour 31.

Recommendations

PVC pipe has a coefficient of thermal expansion of 0.000052/°C (0.000029/°F). Since there was potential movement of nearly half a meter at each end of the exposed pipe runs in this installation, adequate flexible expansion must be installed.

Investigate use of an alternative to PVC for supply and return lines, though PVC with complete bonding of joints and adequate expansion joints should function well.

Build in access to manifolds for ease of maintenance.

Color should be added to the propylene glycol to facilitate charging of the system to the 35 percent glycol/water mix.

Any heating system should be divided into several appropriate zones, with pipes connecting supply and return lines, to facilitate location and isolation of any leaks that develop.

Visual display of fluid level in supply and return pipes and in expansion tanks should be provided. Valves should be installed at high points in all lines for purging air during system charging. Valves should also be installed at all low points for complete draining of the system.

A sensor should be installed to detect when sufficient snow has been melted from the bridge deck to enable automatic system shutoff with consequent lower operational cost.

Manual override controls should be installed.

Telephone connection and remote system should be installed for efficient system operation.

Future plans

Several alternatives for repair of the system were investigated: repair joint leaks by installing clamps on each joint, replacement of all supply/return lines located under the viaduct, insertion of new 102 mm (4 in) ID pipe inside existing 152 mm (6-in) diameter PVC lines, running continuous polyethylene pipe inserts through existing PVC lines, installation of polyester fiber felt sleeve, and encapsulation of joints with epoxy. All options were rejected, except for inserting new PVC pipe within the existing PVC pipe. This option was advertised, but the lone bid received was over 10 times estimate. Retrofit of the system is being negotiated by the City of Lincoln for replacement of the PVC pipe with welded steel pipe.

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Oregon
Silver Creek

Project description

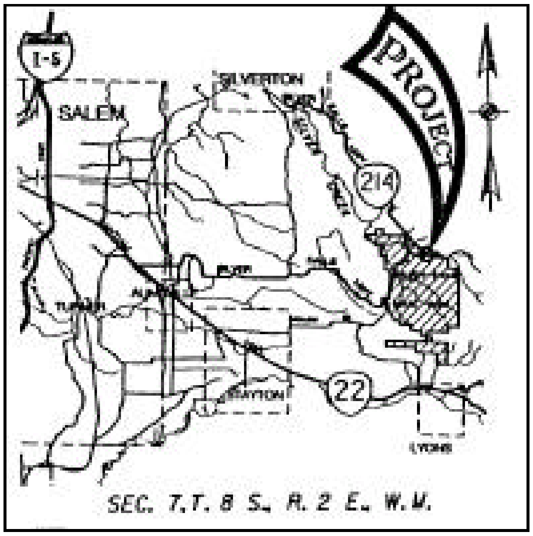


Fig. 1. Silver Creek project location

This two-lane bridge with portland cement concrete deck is on a curve over the North Fork of Silver Creek, in the Cascade Mountain foothills at 274 m (900 ft) elevation, oriented generally north-south, in a wooded, sheltered area (Fig. 1). Winter passenger car traffic is light (ADT = 350), though many trailer trucks transporting timber use this route. Design climatic factors are -23°C (-9°F) and 1.9 m/s (4.2 mi/hr) wind. A hydronic system is installed, supplied by a ground source heat pump. Design surface heat input is 394 W/m^2 (125 Btu/ft^2-hr, 37 W/ft^2).

The heated deck is 32 m (105 ft) long at the centerline and 12.2 m (40 ft) wide; the heated end panels are each 6.1 m (20 ft) long and 12.2 m (40 ft) wide. Total heated area is 576 m^2 (6200 ft^2) (Fig. 2). Transverse slope is 0.08 m/m and longitudinal grade is 1.8 percent. The heat distribution system uses 15.9 mm OD, 12.7 mm ID (5/8 in OD, 1/2 in ID) Wirsbo cross-linked polyethylene tubing on 114 mm (4 1/2-in) centers. The circulating fluid, 35 percent propylene glycol, leaves the heat exchanger at approximately 49°C (120°F); return temperature is around 32°C (90°F) under

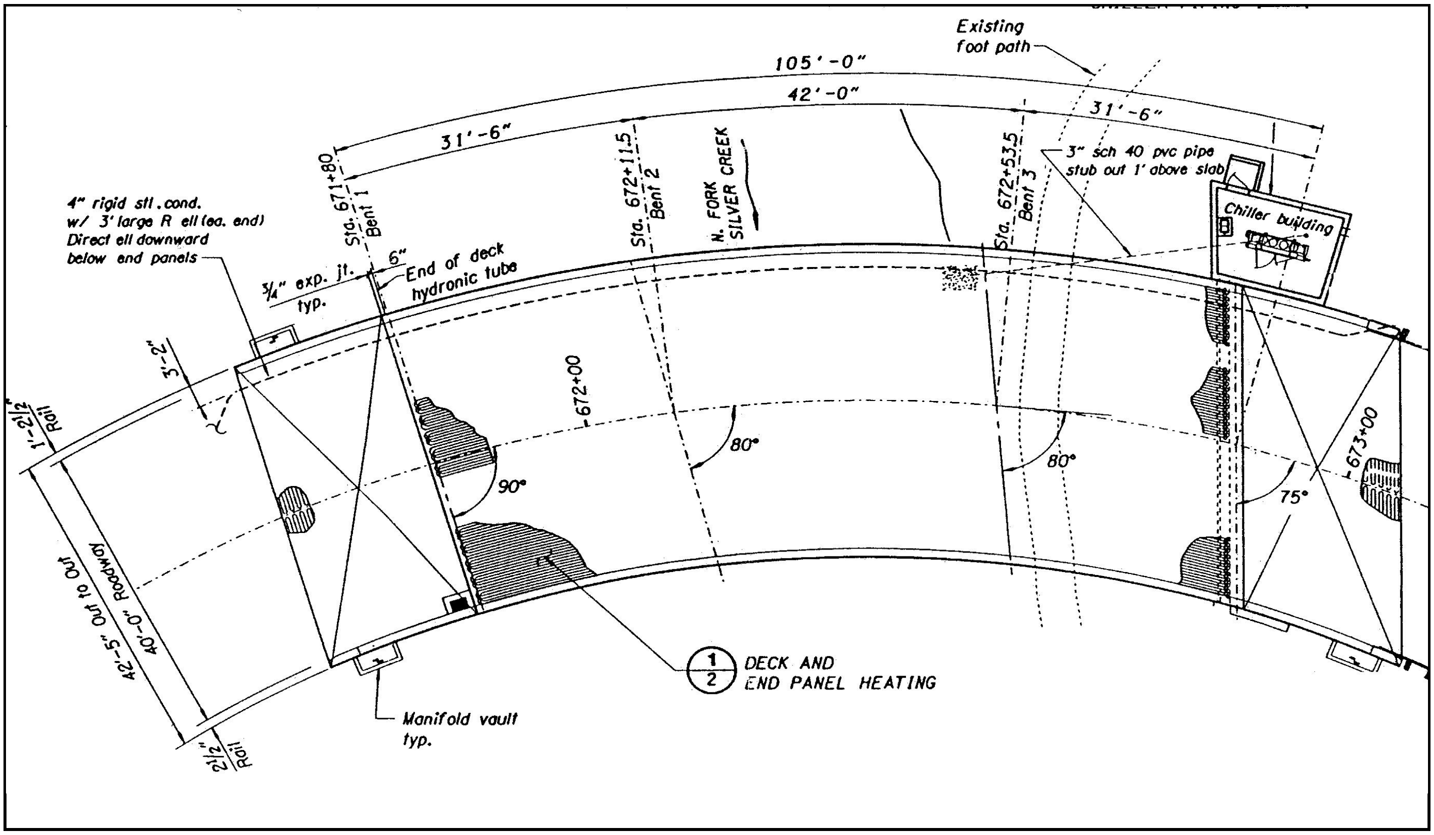


Fig. 2. Plan view of heated deck on Silver Creek bridge.

typical operating conditions. Heat is extracted from well water flowing at 568 L/min (150 gal/min) with a temperature of 11°C (52°F). A 42 kcal/sec (50-ton) Trane liquid scroll chiller is located in a building with approximate dimensions 3.35- x 5.18- x 3.05-m high (11 x 17 x 10 ft) located next to the southeast corner of the bridge; its roof is about deck level.

An additional system has been included for clearing the deck of snow or ice by flooding the surface with well water. A 76 mm (3-in) diameter Schedule 40 pipe is placed on the upslope side of the bridge, within the side rail, and a 6.35 cm (2 1/2-in) high opening at the bottom exposes the 6 mm (1/4 in) diameter holes, in groups of three spaced 38 mm (1 1/2 in) apart, with the groups typically 203 mm (8 in) center to center (Fig. 3). The holes are tapped and pipe plugs with nozzles inserted. A test of the flooding system has been made in above-freezing conditions, and the system operated as designed. A test in freezing weather is planned when conditions allow.

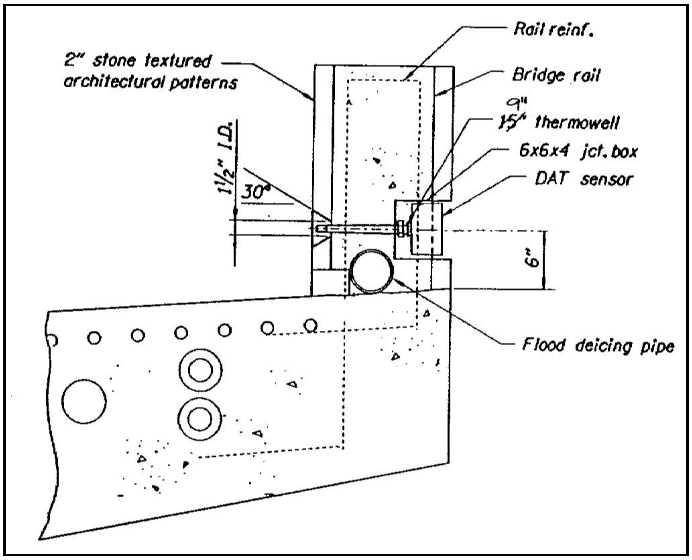


Fig. 3 Deck flooding capability

Operating controls

One Delta-Therm deck temperature sensor is installed in the southbound lane in the wheeltrack, along with a Tekmar snow/ice sensor in the northbound lane at the shoulder. A Tekmar temperature probe is installed in the side rail 150 mm (6-in) above the deck to sense conditions in the air immediately above the deck (Fig. 3). Both a Tekmar *661* snowmelt controller and a Delta-Therm SMC-120A snow sensing system can be used for deck sensing and control. The Tekmar system includes the snow/ice sensor in the deck, an air temperature probe mounted under the deck near Bent 2, and an electronic controller. The exact nature of the control associated with the Tekmar is proprietary but front panel controls include temperature ranges, moisture sensitivity, and minimum system run-times.

The Delta-Therm system includes two moisture sensors, a deck thermostat, the air temperature probe mentioned above, and a relay controller. Bridge operation begins when the normally-open air temperature thermostat closes and the moisture sensors activate. This causes a relay to latch and the system to operate. Operation continues until either the normally-open air temperature sensor opens (above approximately 1.7-2.8°C (35-37°F)), or the normally-closed bridge deck thermostat opens causing the relay to unlatch. The thermal deicing system can be run off of either controller.

The operating controller is connected to the well water pump motor control and heat pump operating control to ensure that evaporator flow is established before compressors are actuated. Heating system variables monitored by the Handar Model 555C digital data acquisition system include supply temperature and pressure, return temperature and pressure, well water inlet temperature and pressure, discharge temperature, flow rate, and deck temperature and ambient temperature. Safety controls include a flood level switch, and an evaporator flow switch which is connected to the chiller to allow operation of the heat pump only when well water flows through the evaporator.

Construction details

A compressed design schedule led to bid announcement before the design was completed. As a consequence, a number of change orders were necessary. If the Oregon Department of

Transportation (ODOT) had been able to determine precisely what it would cost the contractor to carry out the change order, the state would have added a reasonable amount for overhead and profit, and simply paid the contractor that amount. However, it is a common perception in the construction industry that change orders are more expensive than let contracts for the same work, and the designers, inspectors and project managers felt that to hold true in this case.

The original engineering estimate for the change orders was $133,851; the eventual change orders price was $225,000. ODOT based the engineers’ estimate on the contractor’s bid price wherever possible, on published cost data, and on manufacturer’s budget prices. However, after a painstaking and detailed analysis of the contractor’s change order proposal, there was insufficient basis to ask for a decrease in the bid price. ODOT ultimately decided to accept the contractor’s proposal at this price.

The plastic hydronic tubing runs on the deck are longitudinal. Tubes are secured with wire to the transverse rebar, centered approximately between the longitudinal rebar. Tubing is 13 mm (1/2-in) cross-linked polyethylene tubing on 115 mm (4-1/2 in) centers. Each loop connects to a manifold at either end of the loop and is continuous within the bridge deck. Each return connection is individually valved. Manifolds are located under the south end of the bridge adjacent to the abutment.

Tubing bends have a minimum 170 mm (6 3/4-in) radius. Tubing bend guides were used to assure minimum bend radii, and an insulation sheath protects each tube where it exits the concrete deck. Manifold connections are made outside of the deck in a row of tamperproof boxes underneath the south end of the bridge deck.

Tubing was laid between longitudinal rebar and tied with specialty Wirsbo tie wire. Care was taken to allow two aggregate diameters (38 mm, 1.5 in) between the tubing and any significant length of rebar to allow space for compaction of the wet concrete. Special care was taken during construction to assure that each tube was placed in the deck whole and unspliced, and that the tubing was not scratched or kinked during the concrete pour.

The electrical contractor proved to have limited experience in data acquisition and control systems. In combination with limited resources for construction support from the electrical designer, and inexperience in electrical and electronic systems on the part of the construction inspector, this had the result that the state had to rewire and reconfigure most of the control system after construction was complete. This was further complicated by the data acquisition system, which was designed for purely environmental applications; it was difficult and tedious to program it to include the mechanical system.

Costs

Construction	$411,000
Annual maintenance	5,800
Operating	3,400

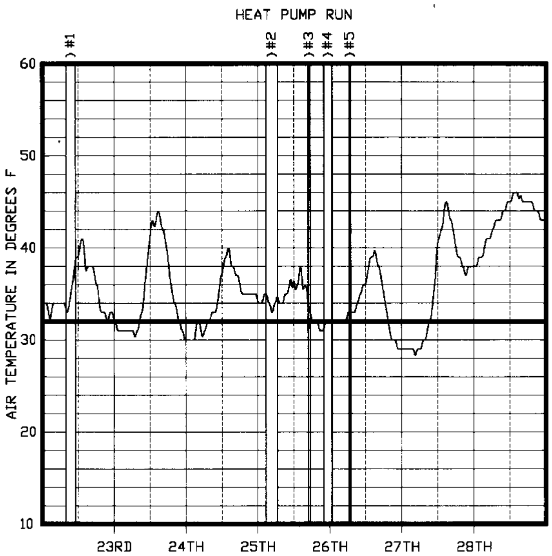
Operating experience

The system has been operational since January of 1995, and has successfully cleared the bridge deck in all observed snow and ice events since then, with some exceptions when the system was down for repairs.

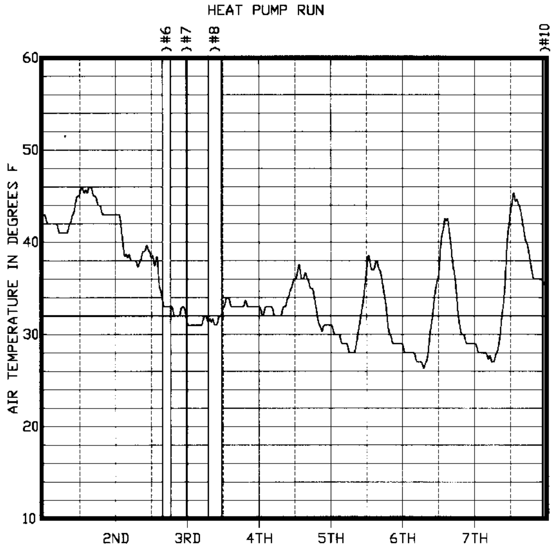
The Tekmar temperature and moisture sensor gave erratic readings, then failed, apparently the result of moisture leakage. It was replaced under warranty. A further problem developed with this sensor: both the sensor and its socket are brass, but the screws originally holding it in place were steel. The heads rusted, with the result that the steel screw shafts had to be drilled out of the brass socket. The new sensor will be reinstalled with a small amount of epoxy instead of screws. In the interim, the system has been run off the Delta-Therm sensor. This was intended as a back-up but has worked well.

The system is idled when the air temperature reaches -6.7°C (20°F) to prevent slush formation in the circulating propylene glycol solution, which would greatly increase its viscosity and overload the pump capacity.

Shown below are records of the heat pump performance during February and March of 1998. Note that in two instances (Runs #3 and 7) the ending temperature was a degree below the starting temperature. In both cases, less than 50 min of operation had occurred.



FEBRUARY 1998 AIR TEMPERATURE AT SILVER CREEK



MARCH 1998 AIR TEMPERATURE AT SILVER CREEK

HEAT PUMP RUN INTERVALS FOR FEBRUARY - MARCH 15 1998

					Air-Temp	
Run	Date	Start Time	Stop Time	Run Time	Start	End
#1	22 Feb 98	7:57 am	11:02 am	3 hr 5 min	33	37
#2	25 Feb 98	2:45 am	6:35 am	3 hr 50 min	35	35
#3	25 Feb 98	4:50 pm	5:26 pm	0 hr 36 min	33	32
#4	25 Feb 98	10:03 pm	12:44 am	2 hr 41 min	31	32
#5	26 Feb 98	6:31 am	7:00 pm	0 hr 29 min	33	33
#6	02 Mar 98	3:41 pm	6:00 pm	2 hr 43 min	33	33
#7	02 Mar 98	11:10 pm	11:57 pm	0 hr 47 min	33	32
#8	03 Mar 98	7:03 am	11:35 am	4 hr 32 min	32	32
#9	05 Mar 98	12:07 am	2:22 pm	2 hr 15 min	Test run	
#10	07 Mar 98	10:42 pm	2:02 am	3 hr 20 min	40	41

Note 1: Delta-Therm Relay Controller used during interval. Total run time during interval initiated by controller was 22 hrs 03 min
Note 2: Air temperature measured approximately 25 ft above bridge at top of mast.

Recommendations

Design

Avoid change orders.

- Allow extra space in mechanical room. A small shelf at desk height would be a very useful feature.
- Check all system components, even in manufacturer-supplied systems for dissimilar metals in corrosion–prone applications.
- Simplify control and monitoring system design whenever possible.
- Specify all field wiring connected to terminal blocks rather than direct connections to control or monitoring equipment.
- Verify programming support for DAQ systems and controllers specifically for deicing application before specifying.
- Use separate inspection, acceptance and liquidated damages criteria for electronics systems installation.
- Check component dimensions in design for inclusion of all systems, especially pumps and motors.
- Field align any coupled rotating shafts, such as in a close-coupled mechanical pump.
- Avoid tamperproof fasteners or excessive numbers of fasteners on access panels, especially if exposed to possible sources of rust.
- Have contractor prove tools for removing any specialty fasteners.
- A telephone/modem connection would greatly facilitate monitoring and maintenance.

Construction

- Remove all removable panels upon installation to test removeability.
- Verify all field wiring prior to payment.
- Avoid the use of electrical connectors in instrumentation lines where moisture or condensation could occur; instead, run unspliced instrumentation lines where practicable.
- Seal conduits to temperature probes where condensation could drain into transmitter housings.
- Verify operation, programming, and calibration of all sensors in the Data-Acquisition System prior to installation of the equipment at the site.
- When installing rain gauges in forest conditions, take precautions to prevent leaves, pine needles, and other organic material from clogging and contaminating the equipment.
- Establish procedures for verifying, testing and calibrating the weather and process instruments at regular intervals.
- Keep portable thermometers, humidity meters, rain gauges, etc., which can be purchased relatively inexpensively, at the site for use in verifying the electronic sensors.

Operation

- Establish service and maintenance logs to be maintained on-site as soon as system becomes operational.
- Make annual check of all accessible parts of the system.
- Quarterly heat pump maintenance may be unnecessary. An annual maintenance check before fall start-up, and a brief check-up at spring shutdown, may be adequate.

Oregon

Highland (Zoo) interchange

Project description

This is an overpass over the Sunset Highway (US 26), a two-lane electrically-heated structure with a surface of latex-modified portland cement concrete on the deck and asphalt concrete on the approaches, which also are heated. Area, including approaches, is 12,714 ft^2. This installation uses Delta-Therm mineral-insulated cable with a design heat output of 30 W/ft^2 (323 W/m^2, 102 Btu/ft^2-hr). Fig. 6 (page 16) shows the cable layout in the bridge deck and Fig. 7 (page 17) the cable layout in the south road and deck approaches. Orientation is north-south, with a high, wooded canyon wall to the south.

Operating controls

A Delta-Therm moisture/temperature sensor is located in the northbound wheeltrack. A road weather instrument system is in the southeast gore; this consists of air temperature, wind speed and direction, precipitation detector, humidity sensor, and pavement ice sensor. The Road Weather Information System (RWIS) is presently used to control the deicing system, and also allows phone/modem hook-up to ODOT's Salem office, the Traffic Management Operations Center (TMOC) in Portland, and the rest of the RWIS network.

Fig. 4. South approach road looking east, heating control cabinet at right.

Fig. 5. Met station is located at south end of heated deck, opposite control cabinet.

Construction details

The concrete deck was prepared for the heating cable installation by sandblasting and cleaning with high-pressure water. The 36 cables, each 500 ft long and spaced 9 in apart, were held in place with silicone-rubber-padded steel loop clamps to avoid damage to the cable. These were fastened to the existing concrete deck using a propane-powered nail gun. Steel clamps were necessary when it was found that plastic could not withstand the force of the nail without shattering or deforming severely. They were placed every 3 ft. Following cable installation on the deck, a 3-in thick microsilica concrete overlay was placed over the cables. This was accomplished by pumping to avoid having truck tires rolling over the cables. Asphalt cover on the approaches was placed by a tracked paving machine using rubber grousers to

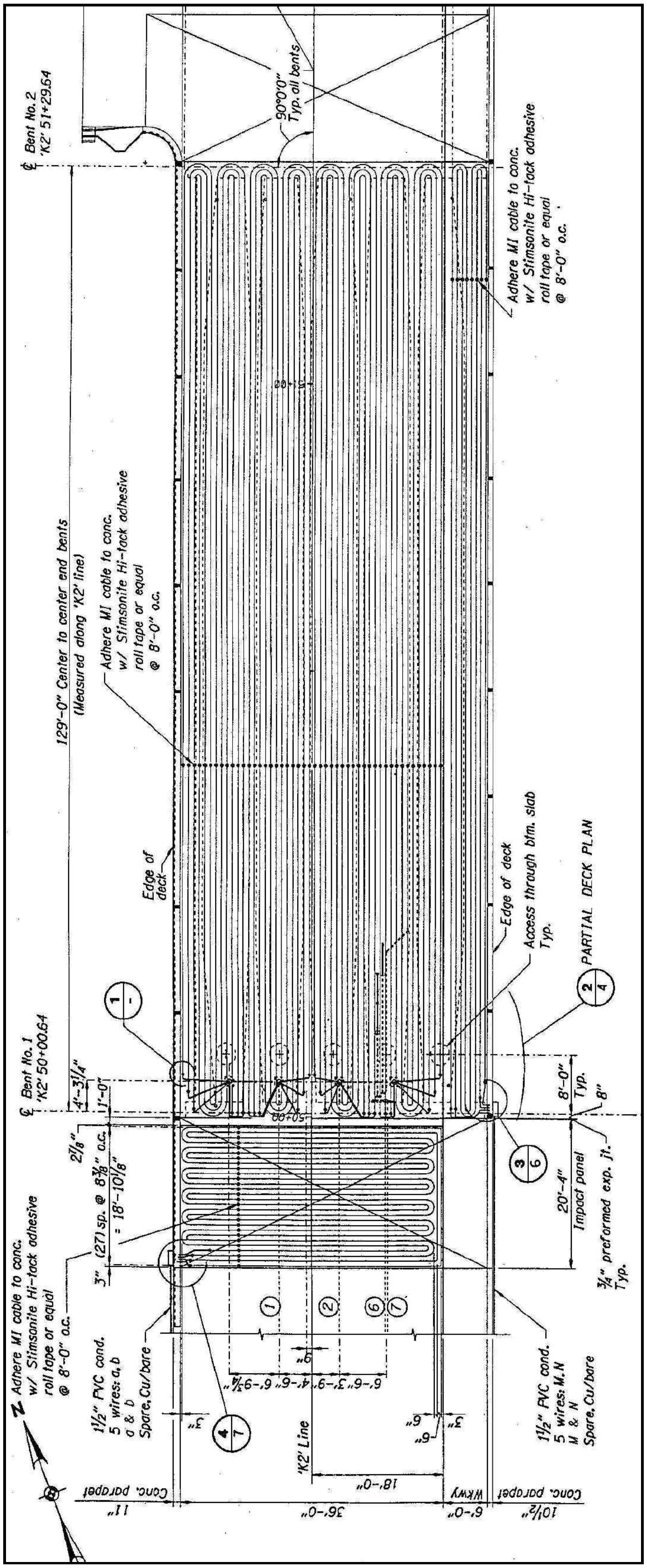


Fig. 6. Plan view of Highland Zoo bridge deck heating system.

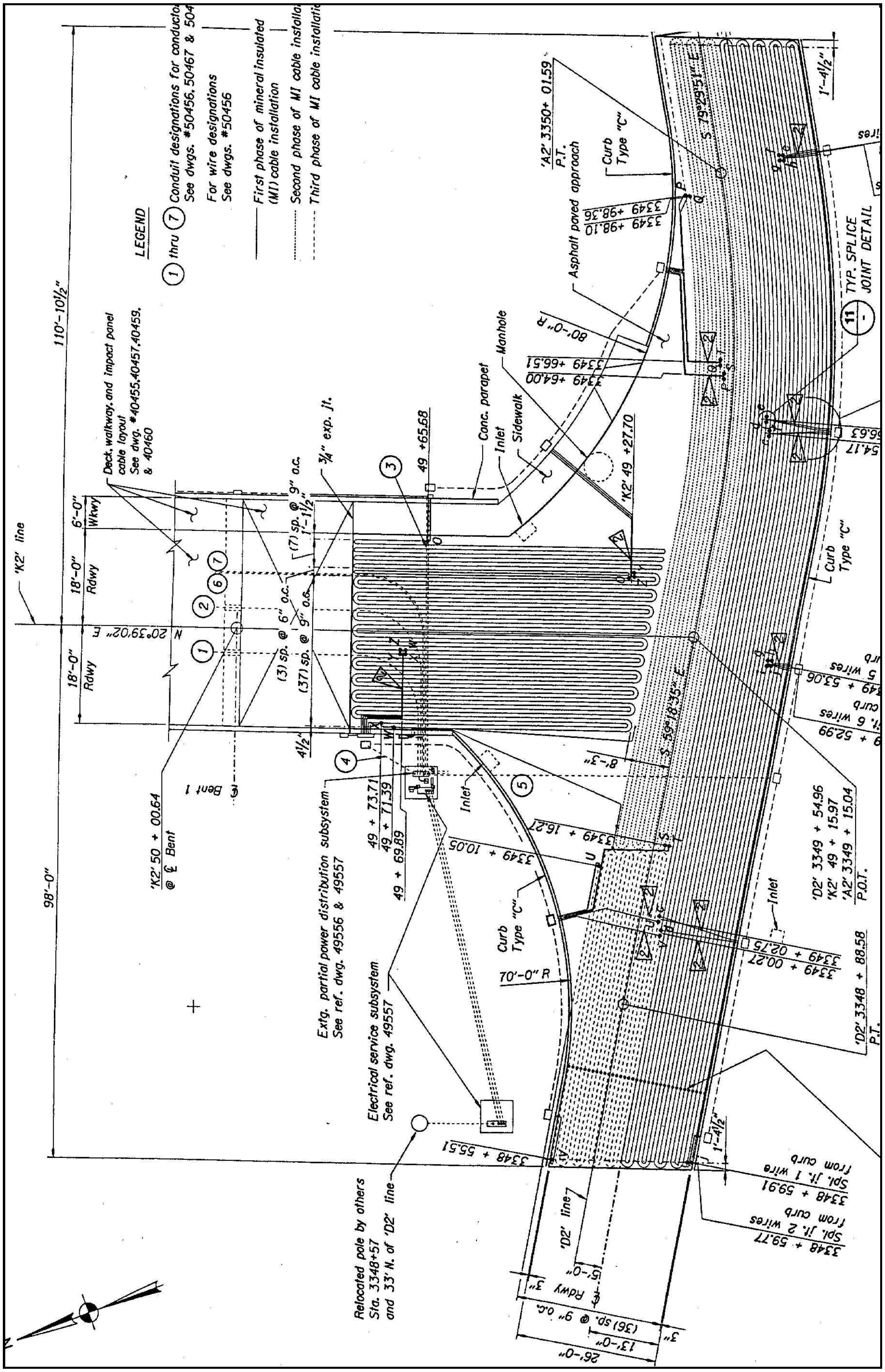


Fig. 7. Plan view of Highland Zoo approach road heating system.

minimize damage to the cable. A test installation had shown that cable expansion when heated to the asphalt application temperature of 300°F caused the cable to expand and push above the 1 1/2 - 2-in asphalt concrete cover. This was controlled by adding a gentle, shallow (less than 4-in. deflection) half-circle to the cable layout once within each strapped section, thus allowing the cable to expand into the loop at high temperature. The rubber on the tracks of the paving equipment was harder than anticipated, with the result that some deformation of the cable was noted, but no penetration. The paver tracks slipped on the cables as the paver pushed the asphalt truck up the grade, which caused cable clamps to twist and penetrate the copper jackets on the cables. Two cables on the south approach failed as a consequence. Repair involved sawing slots in the asphalt and splicing in a new cable to replace the damaged portions of each loop. Slots were filled with asphalt sealing compound.

Costs

Construction	$335,297
Annual operation/maintenance	12,460

Operating experience

Though few snow and ice events have occurred since the system became operational, the deck was kept clear during a 3-day ice storm in December 1996, during which the air temperature averaged 24°F (-4.5°C). During the second winter of operation (1996-97) the resistance moisture sensors failed to activate the heating system. An RWIS was installed for the 1997-98 season and the system programmed to initiate heating when the temperature falls between 20° and 33°F (-6.7° and +0.6°C) and the dewpoint is greater than zero. Energy use has been within estimates (Fig. 8, page 19).

Recommendations

Design

Include monitoring system in original design.

Construction

Verify that approved paver pads are used on each paving machine employed.

Year.month	kWhr	kW	kVAR	Year.month	kWhr	kW	KVAR
96.01	38240	416	8	97.07	2960	11	2
96.02	33120	425	8	97.08	4240	12	2
96.03	17600	395	7	97.09	3680	12	2
96.04	6480	169	3	97.10	3680	12	2
96.05	5600	229	4	97.11	3040	413	7
96.06	3200	260	5	97.12	5840	13	2
96.07	2880	11	2	98.01	16560	436	8
96.08	2720	11	1	98.02	6800	284	5
96.09	3360	11	2	98.03	9360	408	8
96.10	4000	11	2	98.04	5680	15	2
96.11	4080	11	2	98.05	4800	16	2
96.12	16560	280	6	98.06	4400	15	2
97.01	21920	282	6	98.07	4560	15	2
97.02	16640	280	6	98.08	4080	15	3
97.03	13060	280	6	98.09	3520	15	2
97.04	7920	275	5	98.10	5600	15	3
97.05	3200	11	2	98.11	6320	15	3
97.06	2720	11	2	98.12			

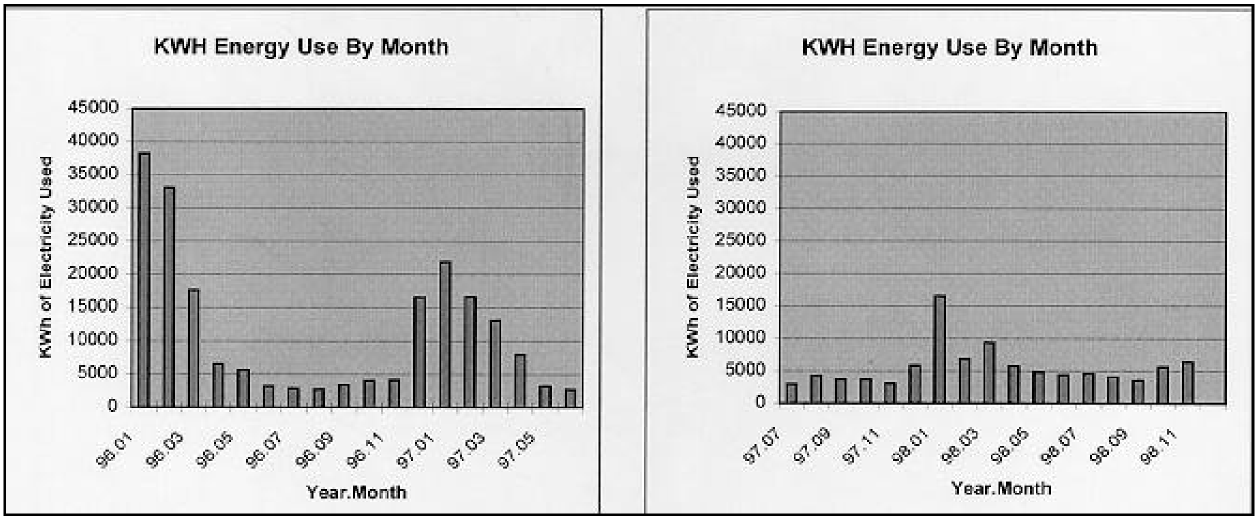


Fig. 8. Monthly use of energy over two heating seasons.

Oregon

Second Street (Hood River) Overcrossing (over UPRR & I-84).

This installation is a hybrid: two sections are electrically heated and two sections are hydronically heated. Each of these is described individually. Fig. 9 is a drawing of the entire installation. A weather station located 1000 ft east of the bridges includes instruments for measuring temperature, humidity, precipitation, wind speed and wind direction. There is a single programmable logic controller (PLC) in control of all the bridge heating tasks and data collection. The on-site weather station and two arrays of resistance temperature detectors (RTD) provide information to the controller that is located in the chiller building under the I-84 bridge. A phone line and modem provide remote access and the system can be monitored or programmed from Salem (ODOT headquarters) or ODOT field offices.

Current control strategy is based on deck temperature and ambient humidity, coordinated with the Delta-Therm “on” and the Tekmar “melt” signal. If the temperature is below 1.7°C (35°F) and the humidity is greater than 95 percent, the PLC starts the operation sequence. After a 30 min minimum run time, if the deck temperature is greater than 2.2°C (36°F), the system starts the shutdown sequence. These temperature and humidity setpoints are adjustable for optimizing system operation.

Operation is staggered, with the heat pump system (I-84 west panel) turning on first to allow for warm-up of the chillers and circulating fluid, the boiler system (I-84 east panel) coming on after 20 minutes, and the electrical systems (I-84 Overcrossing (center panel) and UPRR Overcrossing) after 30 minutes.

I-84 Overcrossing (center panel) data come from a Tekmar unit located in the northbound turning lanes .

UPRR Overcrossing. The deicing system used on the bridge over the railroad is a Delta-Therm electric system using mineral-insulated cable. Area is 18,853 ft^2 (1752 m^2). Design heat output is 60 W/ft^2 (646 W/m^2, 205 Btu/ft^2-hr). There are 144 cables, with lengths up to 540 ft (165 m), with 6-in (152 mm) spacing. Electric supply is 277 volt 3 phase. Layout uses two and four cables per leg in series.

Operating controls

A Delta-Therm SMC-120A is located on the south abutment and the moisture and ambient sensors are located above the controller in the southbound traffic lane. The SMC-120A is not in direct control of the bridge heating system but the output is monitored by the PLC. The weather station and the RTD array conditions will be compared to the programmed operation limits before energizing the heat cables.

Construction details

Original plans were to use a heat pipe system on this span, but the consultant engaged for the design failed to deliver biddable plans by a week before the printing deadline, so an electrical system was designed in-house. Design time as a consequence was very short. Resulting problems include the sacrifice of the time originally scheduled for coordination between electrical and mechanical systems, leading to expensive change orders for addition or resizing of sensors and electrical equipment dedicated to the mechanical system. Some of the cables required additional looping to accommodate excess length upon installation. This suggests for future installations reducing cable lengths by 1 percent from the exact design to allow for installation variations since a slightly underlength cable is easily corrected in the last loop whereas excess is difficult to use where cables are adjacent.

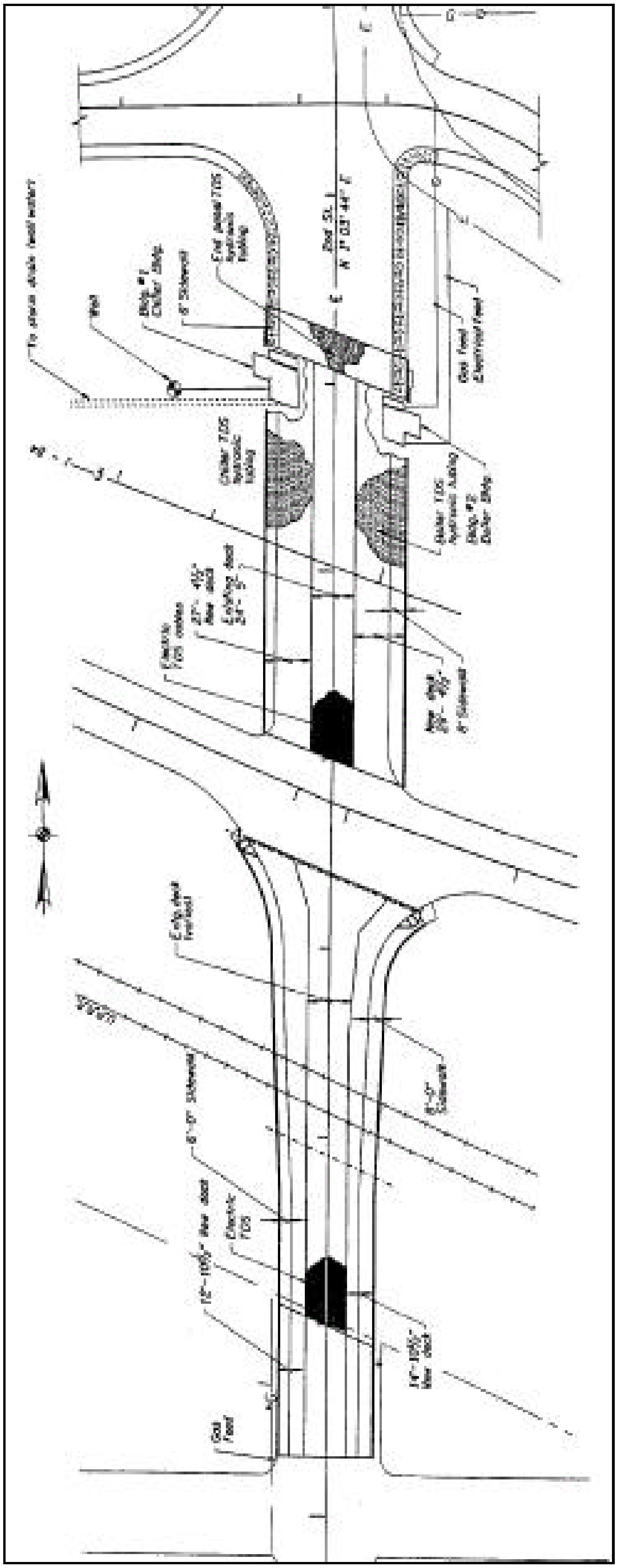


Fig. 9. Bridge on south end (left) is UPRR overcrossing, on right is I-84 overcrossing.

Costs

Construction	$415,324
Annual operation/maintenance	18,455

Operating experience

Test runs in above freezing conditions indicate as-designed operation. First season of operation took place in winter of 1998-99.

I-84 Overcrossing (center panel). This is a Delta-Therm electric system, heating an area of 4378 ft^2 (407 m^2) in the center of the overcrossing (hydronic panels are on both sides, described below). Design heat output is 70 W/ft^2 (754 W/m^2, 239 Btu/ft^2-hr). There are 12 cables, each 830 ft (253 m) long, with 5.75 in. (146 mm) spacing. They are covered with 3 in. (76 mm) of microsilica concrete. Electrical supply is 488 volts 3 phase.

Operating controls

A Delta-Therm SMC-120A, Tekmar Snow Sensor and an array of RTDs are installed. The SMC-120A and Tekmar Snow Sensor are not in direct control of the bridge heating system but their outputs are monitored by the PLC. The weather station and the RTD array conditions will be compared to the programmed operation limits before energizing the heat cables.

Construction details

Similar to the UPRR overcrossing section above.

Costs

Construction	$104,460
Estimated annual operation/maintenance	6,958

Operating experience

Test runs in above freezing conditions indicate as-designed operation. First season of operation will be winter of 1998-99.

I-84 Overcrossing (east panel). A hydronic system, using Wirsbo tubing and manifolds, and in-house design by Oregon Department of Transportation. Heat source is a pair of Parker 1210 natural-gas-fired boilers, heating an area of 6850 ft^2 (636 m^2). Design heat output is 64.5 W/ft^2 (694 W/m^2, 220 Btu/ft^2-hr). Tubing is 5/8-in (16 mm) cross-linked polyethylene tubing on 4-in (102 mm) centers. Each loop connects to a manifold at either end and is continuous within the bridge deck. Each return connection is individually valved. Manifolds are located under the north end of the bridge adjacent to the abutment.

Operating controls

Two Delta-Therm SMC-120A units and an array of RTDs are installed in the deck. One of the Delta-Therm units was installed without the heating circuit in the moisture detectors, with the intention that it will act as a frost sensor. When the standard SMC-120A sends a “moisture present” signal, and the modified unit does not, this will indicate that unmelted frost is present on the modified unit.

Construction details

Tubing was laid between longitudinal rebar and tied with specialty Wirsbo tie wire. Some difficulty was encountered in tubing layout due to having used the imprecise rebar positioning as a placement reference. Care was taken to allow two aggregate diameters (1.5 in, 40 mm) between the tubing and any significant length of rebar to allow space for compaction of the wet concrete.

The contractor opted to use permanent Wirsbo manifolds instead of temporary manifolds for the concrete pour. Connections were difficult to make, and each coupling had to be threaded individually while working in the extremely limited space left by the falsework. Also, the complex tube crossing scheme led to a great deal of confusion as to exactly how to attach tubes to manifolds.

Siting for the gas meter called for a location that could not be struck by highway traffic, but was accessible to the gas delivery trucks. A site was found on the downstream side of the boiler building, when the gas company agreed to a limited truck clearance.

The roof grating and flashing had to be redesigned slightly because external boiler stack caps had been inadvertently omitted during design.

Costs

Construction	$332,800
Estimated annual operation/maintenance	4,135

Operating experience

Test runs in above freezing conditions indicate as-designed operation. First season of operation will be winter of 1998-99.

Recommendations.

Design
  Investigate on-time delivery track record of any design consultants.
  Double-check all equipment dimensions and required accessories.
  Design to avoid creating OSHA-defined confined space.

Construction
  Establish tubing connection registry before beginning to lay tube.
  Provide plumber hand-connecting tubing under deck with a working walkie-talkie.

I-84 Overcrossing (west panel). This is a hydronic system, also using Wirsbo technology. Heated area is 6440 ft^2 (598 m^2). Design heat output is the same as the east panel, 64.5 W/ft^2 (694 W/m^2, 220 Btu/ft^2-hr). Heat source for the west panel is provided by two 60-ton (50 kcal/sec) Trane chillers using well water flowing 250 gal/min (947 L/min) at 59°F (15°C).

Operating controls

A Delta-Therm SMC-120A and an array of RTDs are installed in the deck.

Construction details

Tubing was placed as for east panel.

The well had to be deepened after the driller had demobilized his additional set-up due to a drop in well water temperature from initial samplings to the steady supply. Considerable difficulty ensued in remobilizing the well driller. The deeper well eventually provided excellent flow and temperature water, exceeding design requirements.

However, the additional head required for pumping from greater depth necessitated a larger well pump. The difficulty of implementing this change was exacerbated by a lack of communication with the electrical contractor, who did not get the new drawing calling for a 25-amp motor starter for the well pump until after a 20-amp electrical “”bucket” had been installed for the well pump. Further difficulties were encountered when the electrical contractor claimed that the 25-amp “bucket” could not be fitted into the existing motor control center (MCC). A new MCC was ordered, with the provision that the existing MMC be provided to the state. Upon project completion, delivery of this MCC had to be pursued to close out the project.

Another difficulty was encountered with the electrical cabinets housed in the chiller room. The original design allowed 36 in (915 mm) clear to these cabinets, but upon review of the electrical design after bid (design was not fully complete before bid due to the design effort diverted to the UPRR bridge system design after the consulting designer had to be dropped), the depth of the required cabinet was found to be deeper than expected, and a NEC requirement for 42 in (1067 mm) clear to the cabinet was found to apply. This necessitated a change order to enlarge the building.

Costs

Construction	$307,200
Estimated annual operation/maintenance	9,901

Operating experience

Test runs in above freezing conditions indicate as-designed operation.

Texas

Project description

This project involves north- and south-bound two-lane bridges on US 287 in Amarillo over N. 15th Ave. Each bridge is box beam construction, 17.7 m (58 ft) wide and 44.5 m (146 ft) long. The heating system was designed by Value Engineering. The heated area on each is 799 m^2 (8600 ft^2). The design objective is ice prevention (anti-icing), not snow melting, with a heat flux of 129 W/m^2 (12 W/ft^2, 41 Btu/ft^2-hr). This is a hydronic system with geothermal wells providing the heat source. Each structure uses 50 wells arranged in a star pattern with five wells in each point. Wells are located between the bridges and on the east side of each bridge (Fig. 6). Each 102 mm (4 in) diameter well is 53.6 m (176 ft) deep, not reaching ground water, and contains two pipe loops (Fig. 5a-b). Each is a closed system, grouted with non-shrinking bentonite for good soil contact. The northbound structure uses a McQuay heat pump between the wells and a heat exchanger. Though presently there is no heat pump for the southbound structure, provisions have been included to add one if necessary. Trench-type heat exchangers are used (Fig. 5c-d). The deck circulating fluid is 50 percent propylene glycol-deionized water (obtained from a local power station). Approximately 11,355 L (3000 gal) fluid circulates through each bridge deck, 2650 L (700 gal) of which is in a deck. Each bridge has 32 zones of 19-mm (3/4-in) ID tubing that are continuous between supply and return headers. All connections are on the outside of the deck (Fig. 2). Tubing is suspended under reinforcing steel in transverse loops.

Fig. 1. One of the two two-lane heated bridges on US 287 over N. 15th Ave. in Amarillo.

Fig. 2. Manifold conducting heated solution to embedded heating pipes runs alongside of bridge.

Fig. 3. Close-up of supply and return manifolds (pipes in center) and thermocouple conduits terminating in enclosure at right.

Fig. 4. Heating hoses in place ready for concrete pour; hoses are on 152 mm (6-in.) centers placed 76 mm (3 in) under top of slab, affixed below #4 rebars.

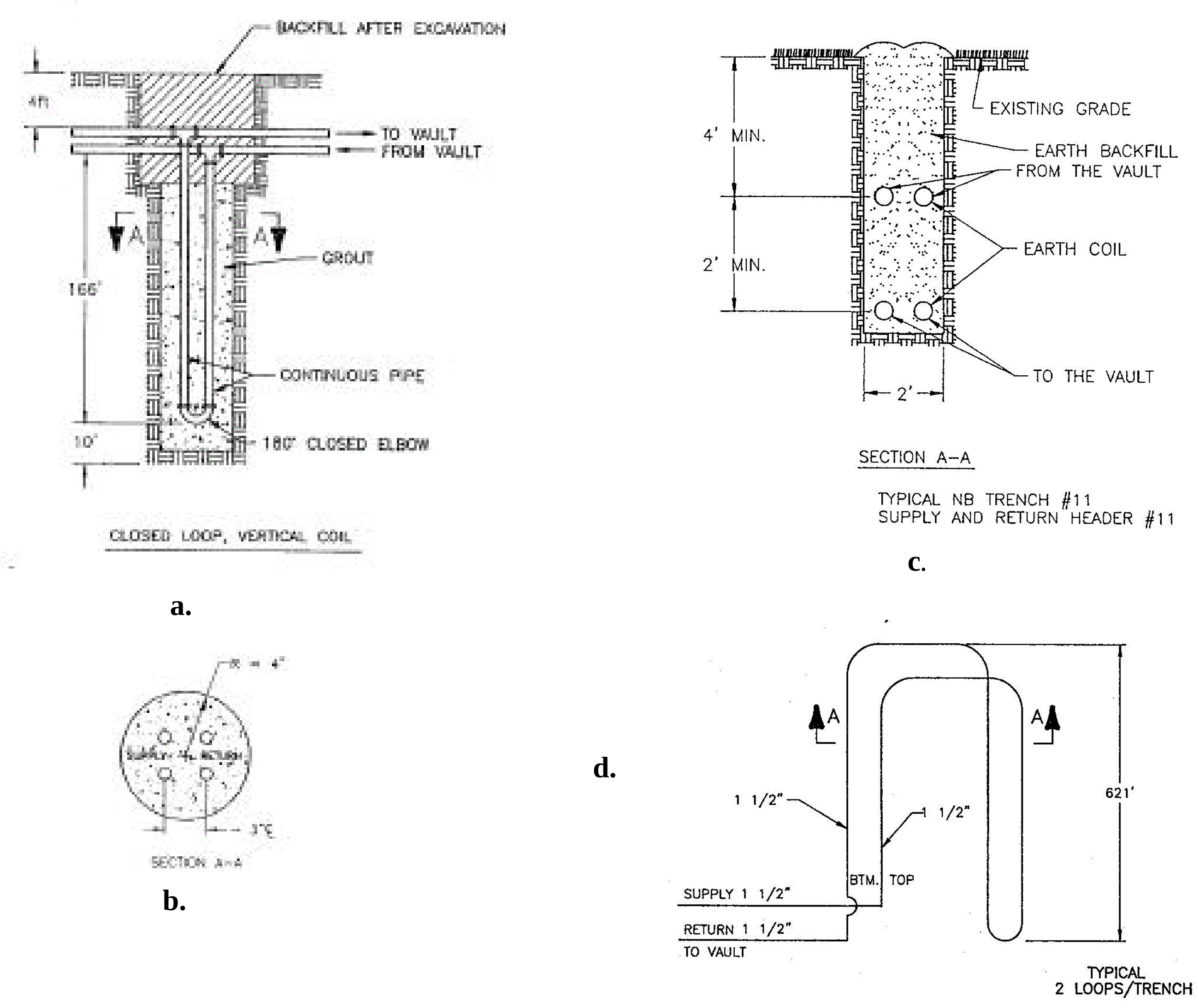


Fig. 5. Geothermal heat is extracted by pipes in vertical wells (Fig. a is an elevation view and Fig. b a plan view showing positioning of vertical pipes) and in horizontal trenches (Fig. c is elevation showing positioning of horizontal pipes and Fig. d the arrangement of one of the 621 ft (2037 m)-long pipe runs).

Climatic conditions

Amarillo is in a region of Texas that experiences many freeze-thaw cycles in winter. The ground does not remain frozen during this season. Generally, the surface of the ground freezes at night, then goes above freezing during the day. Earth is a practicable heat source, and anti-icing is a useable approach. Though the area may receive relatively large snowfalls, once roads are cleared by plows, the surface rapidly returns to the prestorm condition. Since this return period is delayed on bridges because of their lack of subsurface heat, maintaining similar conditions between bridge and adjacent roadway is improved with the anti-icing capability. See meteorological table on page 4.

Operating controls

A Vaisala road weather information system (RWIS) is installed for monitoring bridge and road conditions and for controlling operation of the bridge heating system. Thermocouples are located in the deck near the surface in the centers of the three spans on each structure. Thermocouples are also installed in each approach slab at the outside shoulder and at the right travel lane line. All thermocouples are type K. Heating is automatically initiated when deck temperature reaches 1.7°C (35°F) and there is a forecast of precipitation. Experience has shown that three hours are needed to extract sufficient heat from the geothermal source for the heating system to reach its maximum operating temperature. The Vaisala system logs air temperature, presence of moisture, and presence of chemical. Vaisala ice detectors are also used.

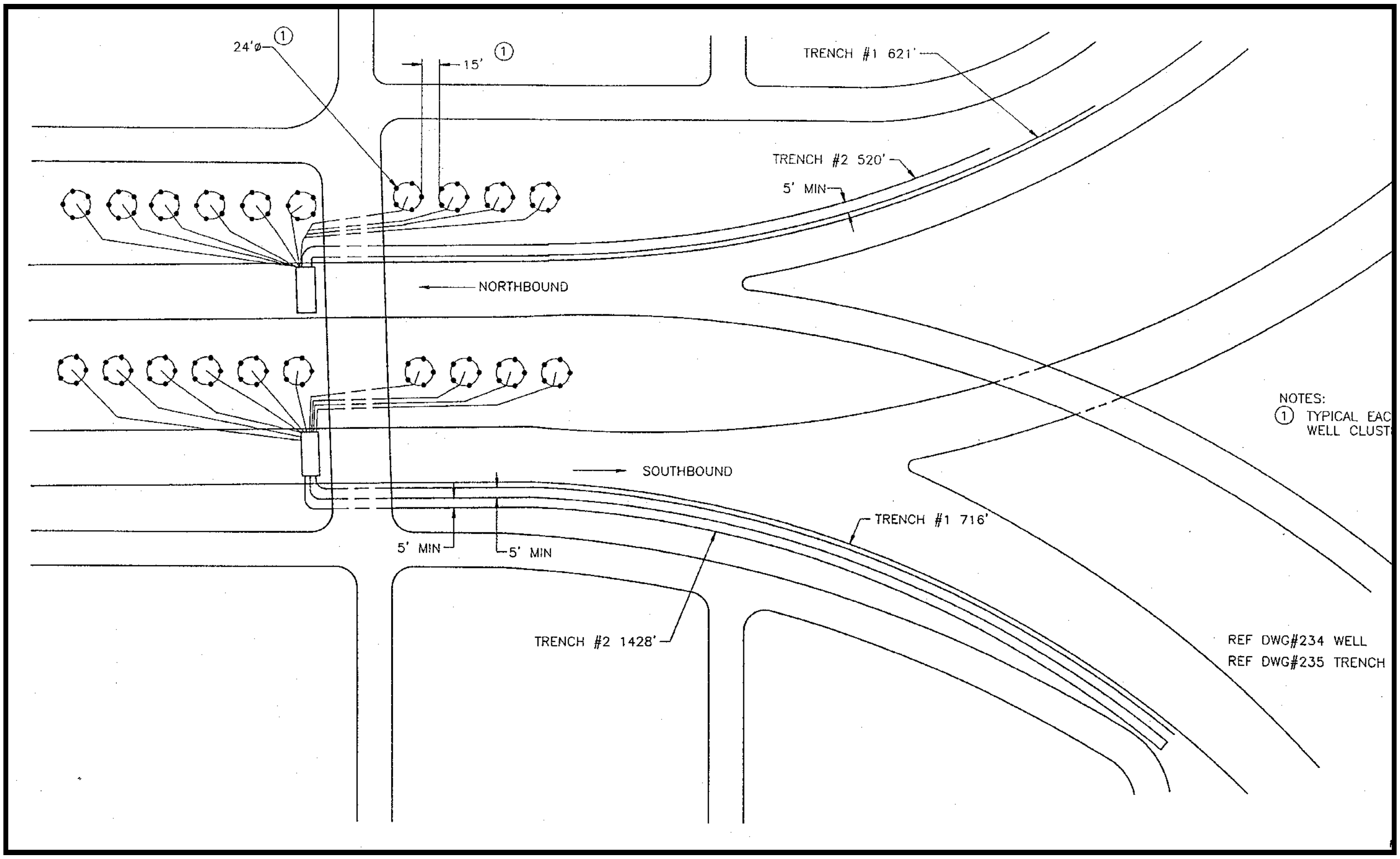


Fig. 6. Location of geothermal wells and trenches adjacent to the bridge spans.

Costs

Construction	$1,200,000
Operating	7500

Operating experience

The heating system has operated as designed and no trouble has been experienced. Operation over two winters has demonstrated that sufficient thermal energy can be extracted from the ground to make unnecessary the heat pump in the northbound heating system.

Though to date no problems have arisen during operation or during seasonal shut-downs, a program has been instituted to enhance serviceability and protect the equipment. Pumps are protected against loss of fluid flow and the system is exercised weekly during the off-season to prevent seal deterioration. Sensors have been installed to indicate a major fluid loss in the equipment vault. Contracts have been let to provide year-round maintenance of the system, including the short operational periods during the off-season. Eight maintenance visits are scheduled during the year. The following items are included in the checklist:

Bridge
- Check bridge pipe, valves, and secure shroud bolts
- Check wiring and sensors
- Check for thermocouple damage

Pumps and piping
- Check pump seals, blow-down strainers, and grease pumps
- Check water levels and pressures
- Check and record glycol concentration
- Check sump pump operation and clean sump
- Identify all leaks and make report (minor leaks fixed by tightening or packing done under maintenance contract, all others to be quoted as change orders)
- Check control cabinet
- Check and record pump run time
- Check and record pump amperage
- Visually inspect connections and repair as necessary.
- Test alarm circuit, telephone line, and phone dialer
- Adjust Micrologix software as needed
- Test flow switches

Heat pump
- Check refrigerant circuit for visible leaks
- Check flow and current draw
- Record run hours
- Check oil levels in compressors
- Check for moisture damage to outer surface due to condensation
- Test flow alarm circuit

Bridge weather station
- Vacuum dust from cabinets
- Test and configure modems as necessary
- Lubricate weather instruments (quarterly)
- Test thermocouple inputs and log data
- Repair or replace defective thermocouples
- Test telephone line and alarm switching
- Replace dialer batteries (quarterly)

Virginia

Project description

This is a two-lane bridge on State Route 60 across Buffalo River, in Amherst County, approximately 24 km (15 mi) north of Lynchburg. The two-span bridge is 35.7 m (117 ft) long and 13.4 m (44 ft) wide. It is a composite structure, with steel beams and portland cement concrete deck. The pcc approach slabs are 6.1 m (20 ft) long and 7.3 m (24 ft) wide. The bridge is on a gentle curve (Fig. 2). The heating system was designed by SETA Technology and is based on a proprietary design (US Patent no. 4,566,527 dated January 28, 1986). It provides for a surface heat output of 630 W/m^2 (200 Btu/ft^2-hr), and consists of 241 steel Perkins tubes (commonly called heat pipes) embedded in the bridge deck and the approaches (Fig. 3). A propane-fired boiler located in a shelter near the bridge heats a 50 percent solution of propylene glycol-water which is pumped through a 89 mm (3 1/2 in) diameter pipe centered within a 152 mm (6-in) pipe that serves as the working fluid reservoir as well as the evaporator portion of the heat pipes. The pipe assembly runs horizontally along one side of the bridge below the deck, shown in the left panel of Fig. 4. The

Fig. 1. Two-span bridge is 35.7 m (117 ft) long and 13.4 m (44 ft) wide.

Fig. 2. Bridge over Buffalo River on Rt. 60 is on a gentle curve.

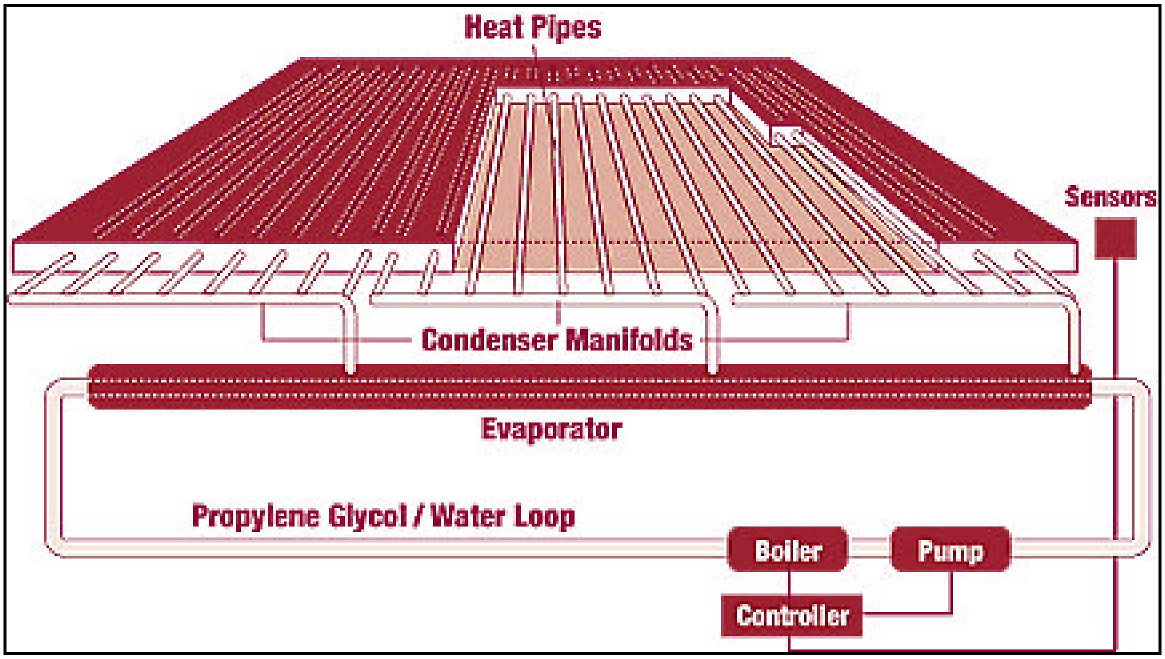


Fig. 3. How heat pipes ("Perkins tubes") are connected to the heat source (see also Fig. 4).

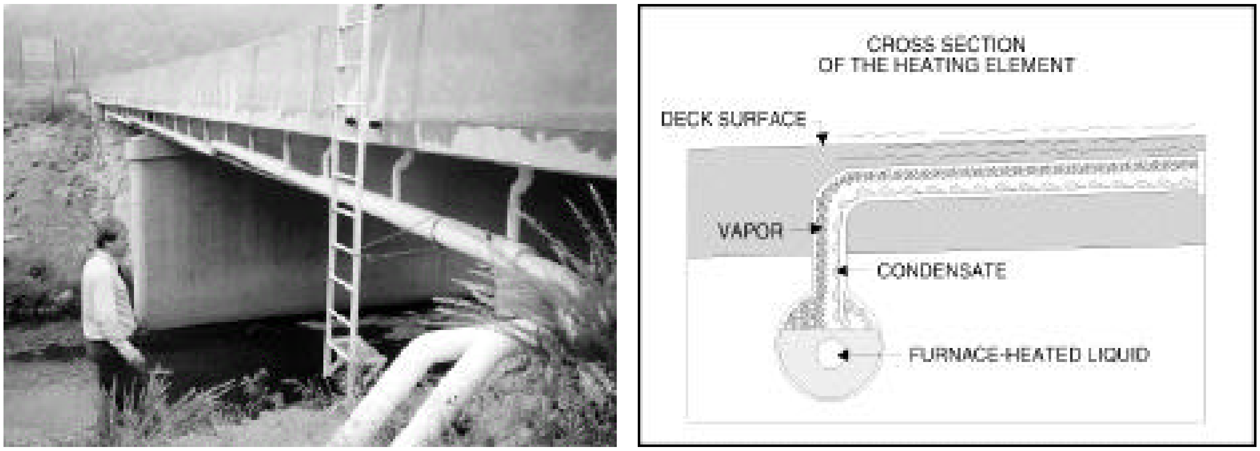


Fig. 4. Left: Heated polypropylene-water solution flows to heat pipes through an 89 mm (3 1/2 in) pipe inside a 152 mm (6 in) manifold on side of bridge. Right: The working fluid is contained within the larger pipe and is vaporized by heat from the furnace-heated liquid pumped through the smaller pipe. The vapor diffuses into the Perkins tube placed .horizontally in the deck, gives up its heat of vaporization, and condenses as it is cooled by loss to the deck. The condensate flows back to the reservoir in the large horizontal pipe and is reheated.

working fluid contained within the large pipe surrounds the smaller heating pipe and is vaporized by heat. However, individual heat pipes are not connected directly to the heat supply pipe but are ganged into groups; a standard module consists of a short vertical riser connected to a manifold serving 10 heat pipes (Fig. 5). These 22 mm (7/8-in) OD, 13 mm (1/2 in) ID tubes run across the 13.4 m (44-ft) width of the deck on 178 mm (7 in) centers. The pipes in the approach slabs are 7.1 m (23 ft 4 in) long and are on 229 mm (9 in) centers. Portland cement concrete cover over the pipes is 82.5 mm (3 1/4 in). All pipes have a slope of 0.065 (m/m or ft/ft) to return the condensate to the evaporator. Initially, the refrigerant HCFC 123 was used as the working fluid. Other fluids were subsequently substituted (see *"Operating experience,"* below). Bridge construction started in 1995 and was completed in the summer of 1996. Inclusion of the heating system had no significant impact on construction duration.

Fig. 5. Risers deliver heated working fluid to a series of evaporators, each serving 10 Perkins tubes in bridge deck.

Climatic conditions

Since no National Weather Service (NWS) station is located near the bridge site, historical data from Washington, DC, and Lynchburg and Roanoke, VA were used for the system design. Handbook data indicated that snow melting would be required approximately 90 hr/yr[1].

Operating controls and monitoring system

Atmospheric instruments include wind speed, air temperature, precipitation, and relative humidity. One pavement temperature probe, flush with deck surface near center of bridge, and a surface condition sensor located on the east approach slab, were installed by SETA for system control. Monitoring instrumentation installed by the Virginia Department of Transportation (VDOT) include Campbell Scientific model 108 thermistors at 26 locations at approximately 25 mm (1 in) below the surface in between heat pipes on the deck and the two approach slabs, an additional six temperature sensors at various depths within the slab for measurement of temperature profiles, a solar radiation sensor, and an Aanderaa model 3428 pneumatic ice detector embedded flush with the deck surface (see locations of sensors in Fig. 6). A Campbell Scientific CR10 datalogger collects the data, which is subsequently transferred to Charlottesville over the phone line at regular intervals. Some of the data, including a digitized infrared view, is updated periodically on the Internet. A Texas Instruments “Nightsight” infrared video camera, with slow-scan recording, 64 levels of black and white, and 0.1°F resolution, is mounted on a 6.1 m (20 ft) pole overlooking the bridge. Time-lapse imagery is recorded on tape. A digital video card installed in the PC controls the data collection process and provides a modem link with the VDOT Research Council in Charlottesville. The video camera also can be controlled by commands over the telephone line. A second video camera and VCR record black and white imagery. Cameras are activated automatically to begin recording when the deck heating commences. The heating system is controlled by a Laboratories Technologies Corp. ControlPro computer program running under Windows 3.1. Heating is initiated by any of three conditions: when the surface sensor indicates snow or ice, the precipitation sensor indicates precipitation and deck surface temperature is below 1.7°C (35°F), or deck surface sensor indicates wet deck and the surface temperature is below 1.7°C (35°F). Heating is shut off when either deck surface sensor indicates clear surface for more than 10 min, or deck surface temperature is above 4.4°C (40°F).

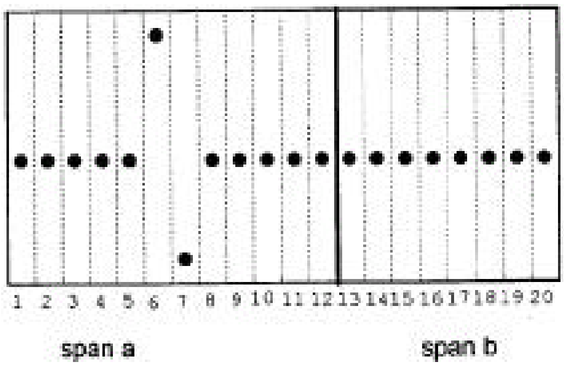


Fig. 6. Locations of temperature sensors in the 20 zones of the two bridge slabs.

Costs

Design/construction		$\$181{,}500$ ($\$35/\mathrm{ft}^2$, $\$10.75/\mathrm{m}^2$)
Operating		
fuel	$1500	
elect	360	
phone	300	2,160/yr

Note: These operating costs were incurred during a period when the system was not functioning properly, and therefore may not be representative of current conditions.

Operating experience

Uneven heating was observed during the first heating in November 1996, with HCFC 123 used as the working fluid in the heat pipes. The high end of the tubes showed little or no heating in all evaporator sections. Some sections heated less than half the width of the bridge. Over the next year and a half several modifications were made to the heating system to improve performance. These are documented in the following listing by date.

> December 1996. Refrigerant HFC-134a replaced HCFC 123 in evaporator no. 2 (units 1,2,3) on the 20th.
>
> January 1997. On the 17th the system contractor installed longitudinal vortex vanes in five evaporator sections to enhance heat transfer between the furnace-heated glycol and the heat pipes. No apparent benefit resulted. In addition, two evaporator pipes were drained of HCFC-123 and replaced with a 30 percent solution of water and ethanol.
>
> February 1997. A 30 percent solution of water and ethanol replaced HCFC-123 in evaporator near west end of bridge. Ice sensor was replaced. Performance is shown in Fig. 7.

July 1997. All evaporators except no. 2 (filled with HFC-134a) were filled with pure ethanol. Performance did not improve. The ethanol failed to heat half the bridge width.

December 1997. All evaporators, except no. 2, were drained of ethanol and charged with HFC-134a. Snow events were recorded on the 27th and 29th. In both cases the system did not activate automatically; the automatic control system failed. An override switch was subsequently installed to bypass the control unit and enable manual operation.

February 1998. Metallurgical-grade ammonia (99.99 percent pure) replaced HCFC-123 in evaporator no. 4 (third unit from east end of deck) on the 13th. This required changing fittings from brass to stainless steel. All other evaporators are filled with HFC-134a. Heating test was made following this modification. Air temperature was 10°C (50°F), surface temperature of ammonia section was 17°C (63°F), indicating significant improvement in heat intensity and uniformity of distribution. It was found that the failure to activate the heating system automatically was due to a faulty deck surface condition sensor.

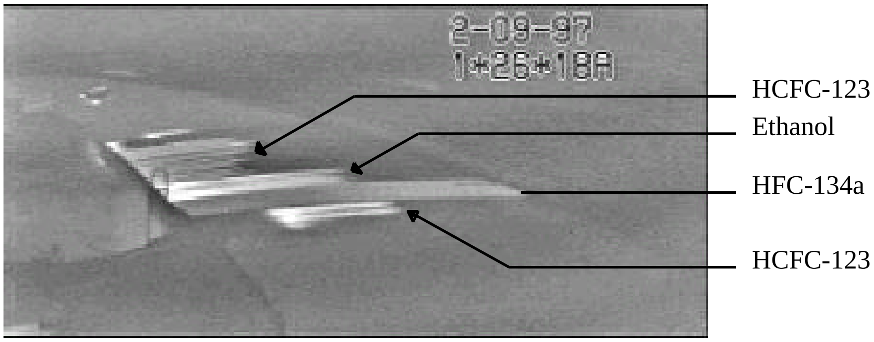


Fig. 7. Uneven heat distribution occurred with the original charge of HCFC-123 in all the heat pipes. Improvement was sought by replacing one evaporator section with HFC-134a and another with ethanol, with results shown here.

Fig. 8. Heat pattern in 1998 after all heat pipes were purged and ammonia was introduced as the working fluid. The short section in foreground is the approach, which shows a higher temperature at the left, but the deck now has very uniform heat distribution.

Comments

Estimates were obtained for four technologies and energy sources: heat pipe using oil-fired boiler, electric (MIC) heating cables, hydronic using natural gas-fired boiler, and hydronic using propane-fired boiler. Heat pipe technology was selected for the Amherst bridge based on annual operating costs about one-tenth that of the other technologies, even though the initial cost was 70-160 percent greater than the alternatives. However, cost overruns during construction raised the estimated cost from \$15 to \$35/ft^2 (\$4.60 to \$10.75/m^2).

The pneumatic ice sensor gives a false report of ice when the small holes, through which low pressure compressed air must pass to indicate no ice, becomes blocked by wet sand. Restoration of intended function requires cleaning out any accumulated debris.

Proper selection of working fluid is critical to proper operation of a heat pipe system. Important properties of three of the fluids used in the Route 60 bridge are given in the table that follows. The chemical name for HCFC-123 is 2,2 dichloro-1,1,1-trifluoroethane, and for HFC-134a is 1,1,1,2-tetrafluoroethane. Data for the refrigerants are extracted from du Pont literature[2], and ammonia[3].

Material	Ammonia		HFC-134a		HCFC-123	
Chemical formula	NH_3		CH_2FCF_3		$CHCl_2CF_3$	
Molecular weight	17.03		102.03		152.93	
Boiling pt @ 1 atm	-28.03°F	-33.35°C	-14.9°F	-26.06°C	82.0°F	27.85°C
Critical temperature	270.3°F	132.5°C	213.9°F	101.08°C	362.63°F	183.68°C
Critical pressure	1639 psia	11390 kPa	588.9 psia	4060.3 kPa	532.0 psia	3668.0 kPa
Critical volume	0.0682 ft^3/lb	0.00426 m^3/kg	0.031 ft^3/lb	0.00194 m^3/kg	0.0291 ft^3/ lb	0.00182 m^3/kg
Critical density	14.67 lb/ft^3	235 kg/m^3	32.17 lb/ft^3	515.3 kg/m^3	34.34 lb/ft^3	550.0 kg/m^3
Heat of vaporization						
@ 0C (32F)	621 Btu/lb	1440 kJ/kg	85.5 Btu/lb	199 kJ/kg	77.3 Btu/lb	179 kJ/kg
@ 38C (100F)	478 Btu/lb	1110 kJ/kg	71.2 Btu/lb	165 kJ/kg	71.6 Btu/lb	166 kJ/kg

Recommendations

A limited proof-of-concept field demonstration should be mandatory prior to purchase, providing the opportunity to determine uniformity of heat distribution by infrared scans or contact temperature measurements.

The ability of the vendor to service and repair the system on a one- or two-day notice should be a major purchasing criterion.

A warranty performance bond should be required for a minimum of two winter operational seasons. If the system is not serviced/repaired in a timely fashion within a warranty period, the bond would then be forfeited.

Infrared scans should be used as proof of heating system uniformity prior to granting final acceptance.

The heating system vendor/supplier should not receive final payment until the system performance has been verified and accepted by the DOT.

The control system should be redundant; failure of a single sensor must not cause the entire system to become inoperable.

The Federal Highway Administration should maintain a central database of all HBT projects, documenting successes and failures, and made available to all agencies considering a heated bridge project.

References(Virginia)

1. “HVAC Applications,” *ASHRAE Handbook*. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers.

2. “Thermodynamic Properties of HCFC-123,” Publication T-123—ENG. “Thermodynamic Properties of HFC-134a,” Publication T-134a—ENG. Wilmington, DE: Du Pont Chemicals.

3. *Handbook of Chemistry and Physics*. Boca Raton, FL: CRC Press, Inc.

West Virginia

Project description

This is a two-lane bridge on US 35 over 5 & 20 Creek located in Putnam County, near Winfield, WV, approximately 48 km (30 mi) northwest of Charleston. The area is approximately 843 m^2 (9070 ft^2) with a portland cement concrete deck. The electrically-heated system was designed by Payne Engineering to provide 517 W/m^2 (48 W/ft^2, 164 Btu/ft^2-hr). Mineral-insulated heating cables supplied by Delta-Therm are embedded on top of the reinforcing steel with a minimum cover of 51 mm (2 in) and a maximum of 76 mm (3 in.). The underside of the bridge between beams, piers, and intermediate diaphragms is insulated with 51-mm (2-in) thick R10 foam insulation. Electrical energy cost in the area is 5-6 cents/kw-hr.

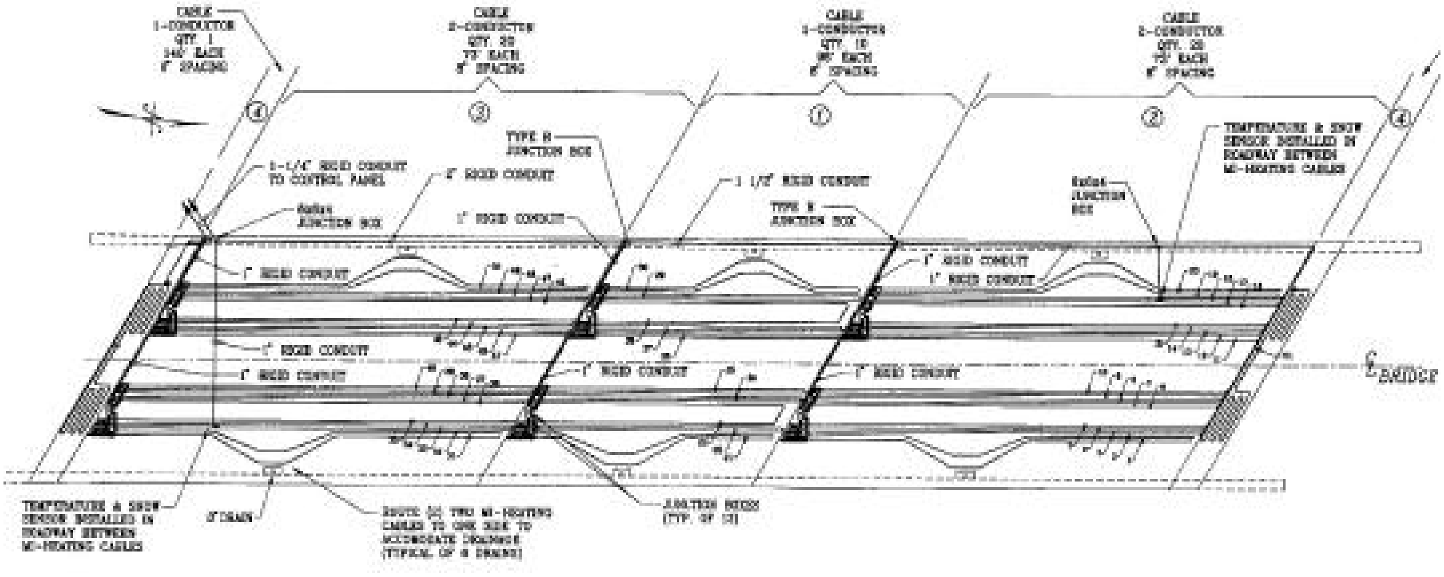
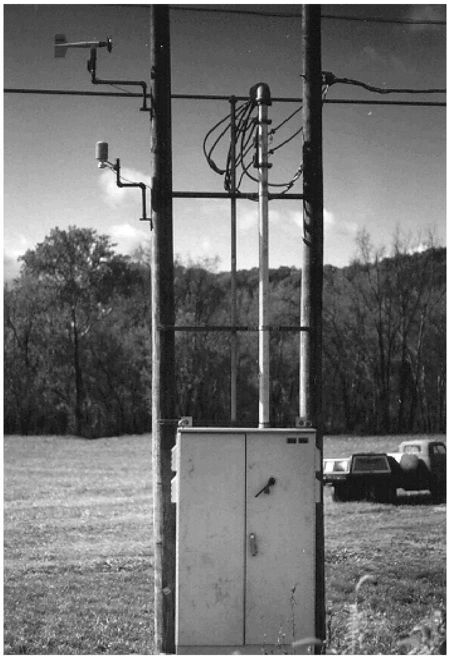


Fig. 1. Plan of electrically-heated bridge deck.

⮙ Fig. 2. View of bridge on US 35 over 5&20 Creek.
Fig. 3. Meteorological station adjacent to bridge. ➢



Climatic conditions

No meteorological records exist at this site. The closest National Weather Service (NWS) station is at Charleston. The information that follows is taken from the NWS Local Climatological Data. Winters vary greatly from one season to another. Snow does not favor any given month, though heavy snowstorms are infrequent and most snowfalls are 102 mm (4-in) or less. Daytime temperatures generally are close to 4.4°C (40°F) but frequently fall below freezing at night. Snow and ice do not usually remain long on the roads. See meteorological table on page 4.

Operating controls

Two sets of sensors are installed, each in the outer wheelpath of each lane. Each set consists of an Environmental Technology SIT-4HD moisture sensor and a thermistor, type G14K. The moisture sensing unit is flush with the deck surface, and the temperature sensor is between 25 and 51 mm (1 and 2 in) below the surface.

Costs

Design	$12,000
Construction	168,000
Operating	606 (1996)
	747 (1997)
	919 (1998)

Operating experience

Winters have been very mild since the heating system was installed, so no substantive performance data are available to evaluate system performance.

Recommendations

Heating cables, conduit and junction boxes should be laid out and located early enough to coordinate with placement of reinforcing bars. It may be necessary to bend some of the bars around the junction boxes.

It may be better to place the junction boxes between rather than at the beams. The reinforcing bar is thinner at these locations, so it should be easier to fit the conduit and junction boxes between the reinforcing meshes.

Use two or more small conduits instead of one large one so they will fit between the reinforcing bars more easily.

Moisture sensors should be placed in the exit end of the lane rather than the entry end. This will allow water to be tracked over the sensor by moving traffic; water lying on the surface would not be tracked over a sensor at the entry end.

The original proposal should include provisions to have extra cables on site to serve as back-ups should a cable be damaged during the pour.

Consider placing the cable at minimum depth from the design surface since it is very likely that when concrete is poured it will actually be deeper than designed. This will place the cable closer to the desired depth.

Summary

Three technologies were used for heating the bridge decks in the Heated Bridge Technology program. None is radically new, but their application by the participating states represented a new departure in nearly all cases. (The major exception: Oregon has had a heated underpass in Klamath Falls for many years, tapping the geothermal sources prevalent in the area for direct piping through the pavement, piping which has recently been replaced as a result of corrosion.) The introduction of new methods always involves learning new techniques, the solving of new problems, and extra costs because of unfamiliarity with the new. The table below summarizes the salient elements of the heated bridge decks and affords a convenient comparison of the installations.

Item	Oregon						Nebraska	Texas	Virginia	West Virginia
	Silver Creek	Highland Zoo	Hood River 2nd St	I-84						
				West	Center	East				
Design objective	snowfree	snowfree	snowfree	snowfree	snowfree	snowfree	snowfree	anti-ice	snowfree	anti-ice
ADT (winter)	350									
System	Hydronic	MIC	MIC	Hydronic	MIC	Hydronic	Hydronic	Hydronic	Heat pipe	MIC
Heated area(ft^2)	6200	12714	18853	6440	4378	6850	17211	2x8600	5185	9070
Heat source	geo	elec	elec	geo	elec	nat gas	nat gas	geo	propane	elec
Design heat flux (W/ft^2)	37	30	60	64.5	70	64.5		12	58	48
Dimensions (ft)										
Deck	40x105	36x129	26x154	27x103	24x103	29x103	12x1204	2x58x146	44x117	44x200
Approaches	2x40x20	36x44							2x24x20	
Surface type										
Deck	pcc	pcc	pcc	pcc	pcc	pcc	pcc	pcc	pcc	pcc
Approaches		ac						pcc		
Cost (htg) ($)	411,000	335,297	415,324	307,200	104,460	332,800	289,000	1,200,000	181,500	180,000
Cost/area ($/$ft^2$)	66	26	22	48	24	49	17	70	35	20
Ann optg/maint cost ($)	9200	12,460	18,455	9900	6960	4135		8880	2160	600-920
Op cost/hr ($)							9.25			
Bridge crossing	water	highway	railroad	highway	highway	highway	pedstrn overpass	highway	water	water
System designer	ODOT	ODOT	ODOT	ODOT	ODOT	ODOT	Delta-Therm	Value Engrg	SETA	Payne Engrg

Notes:

Snowfree	Objective is to keep deck clear of snow and ice under all precipitation conditions.
Anti-ice	Objective is to prevent bonding of ice and compacted snow to the deck.
ADT	Average daily traffic (in winter).
Hydronic	Heat supplied by liquid heated by some means pumped through pipes in deck.
MIC	Mineral insulated electrical resistance heating wire.
Heat pipe	Working fluid vaporized by heat source (usually in ground) liberates its heat of vaporization in colder pipes embedded in deck.
Heat sources	geo - heat extracted from the earth
	elec - electric energy from power grid
	nat gas - natural gas
	propane - compressed gas
Surface type	pcc - portland cement concrete
	ac - asphalt concrete

All of the heated bridge installations achieved their design objectives, based on the limited data from only a season or two of operation. Costs of incorporating a heated system in a bridge that was either undergoing rehabilitation or was new construction differ by a factor of over four, from \$17/ft^2 to \$70/ft^2 (\$183/m^2 to \$753/m^2). It would be unwise to judge the cost-effectiveness of a technology from these costs, however, since remote location, contractor experience, agency contracting policies, and extra costs assigned to a heating system all figure into the final figures. Operational costs will also vary widely depending on heat source and climatic conditions. Cost of a specific energy source may dictate selection of a particular technology. Unless there is some overriding factor related to construction, energy source, or heat flux requirement, no recommendations can be made for selection of the most appropriate technology to use for a new installation. It may be advisable to solicit proposals from vendors of all the technologies.

Appendix A. References

Dunn, Peter D. and D.A. Reay (1976) *Heat Pipes*. New York: Pergamon Press.

Ivanovskii, M.N., V.P. Sorokin, and I.V. Yagodkin (1982) *The Physical Principles of Heat Pipes*. Translated by R. Berman. New York: Oxford University Press.

Appendix B. Technical Working Group (TWG)

Steering Panel

George Romack, FHWA, Office of Engineering, chairman
John M. Hooks, FHWA, Office of Technology Applications
Howard A. Jongedyk, FHWA, Highway Operations Research and Development

Technical Panel

All the state personnel and Mr. Cress contributed to their respective reports in this document.

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Al Imig, City of Lincoln, NE
Meredith E. Mercer, Oregon DOT
L. David Minsk, Consultant
Milton F. Pravda, Square M Associates
Michael W. Taylor, Texas DOT

Appendix C. Commercial Technology Sources

Delta-Therm Corporation (398 W. Liberty Street, Wauconda, IL 60084). The company offers two heated pavement technologies, hydronic and mineral insulated (MI) electric cable. The hydronic system utilizes heated polypropylene glycol or water circulated through ethylene propylene rubber hoses embedded in the bridge deck. The heat source may be electric heat pumps or gas- or oil-fired boilers. The MI cables consist of one or two conductor resistance wires embedded in highly compressed magnesium oxide and covered by copper or Alloy 825 stainless steel sheath.

Dynatherm Corporation (1 Beaver Court, P.O. Box 398, Cockeysville, MD 21030). This system utilizes heat pipes inserted in the earth to make use of its heat source. The earth heat is extracted and transported to the bridge deck through the pipes by means of evaporation of a liquified gas at the lower end and condensation at the upper end. After the latent heat of vaporization is released to the deck, the condensate returns by gravity to the evaporator, thus completing the cycle. There is no need for external mechanical or electrical power.

OAO Thermal Corporation (7500 Greenway Center, Greenbelt, MD 20770). The company has adapted heat pipes as well as other methods such as circulation of river water, electrical heating, solar heating/energy storage to the prevention of bridge freezing. Experience gained in perfecting heat pipes for aerospace applications is now available for application directly to heat pipes or other one- or two-phase fluid systems for bridge deicing.

Payne Engineering (Box 70, South Depot, WV 25560). This system is based on an electric grid system installed in the deck designed to heat 2- to 3-ft swaths in each lane. The deck heating system control incorporates a temperature sensor in the deck that activates half of the control loop when the temperature is below 0°C (32°F); the other half of the control loop is activated by moisture in the snow detector. When the loop is completed, a programmable-power control provides electric current to the heating cables according to a preset cycle.

SETA Corporation (4909 Soldier Road, Laramie, WY 82070). There are basically two methods that can be used in the SETA system. One is similar in concept to the Dynatherm system, which uses earth heat transfer via heat pipes. The other incorporates heat pipes but involves supplying hot fluid by a boiler/pump/control unit mounted on a steel frame or supplying hot fluid from a combination heat exchanger/pump/controller on a steel frame that ties to an existing central heating system.

Value Engineering (108 Copperwood Drive, Bethel Park, PA 15102). The system utilizes heat transfer from the circulation of hot fluid through polypropylene tubing embedded in the concrete. The fluid can be heated either by means of a solar collector or via a buried heat exchanger section. All hardware, i.e., the controller, instrumentation, heat exchanger surfaces, storage tanks, and circulating fluid, are off-the-shelf items.

Wirsbo Company (5925 148th Street West, Apple Valley, MN 55124). This is a hydronic system that uses cross-linked polyethylene tubing technology to provide a plastic with greater durability over a wide range of temperature and pressure combinations. In addition, the tubing is wrapped with five layers of a polymer to prevent oxygen diffusion into the hydronic system.

Sensor manufacturers (used in HBT projects)

Aanderaa Instruments, Inc., 234 Highland Avenue, South Attleboro, MA 02703
Coastal Environmental Systems, 316 Second Avenue South, Seattle, WA 98104
Delta-Therm Corporation, 398 West Liberty Street, Wauconda, IL 60084
Environmental Technology, Inc., 1302 High Street, South Bend, IN 46601
Tekmar Control Systems Ltd., 4611 23rd Street, Vernon, BC, Canada V1T 4K7
Vaisala Inc., 100 Commerce Way, Woburn, MA 01801-1068.

Appendix D. Meetings of Technical Working Group

1998	September 2-3	Denver, CO
1997	August 12-13	Harrisburg, PA
1996	July 15-16	Amarillo, TX
1995	April 18-19	Portland, OR
1994	July 7-8	Lincoln, NE
1994	January 19-20	Washington, DC

Appendix E. Publications Prepared for HBT

Informational Guide for Bridge Deck Heating Systems. (1996) Milton Pravda
System Evaluation Plan for Heated Bridge Technology Program. (1997) Milton Pravda
When Bridge Decks Freeze. 18-min video
Contact FHWA for availability of these publications.

Appendix F. Glossary of Terms

Precipitation

Light rain. Liquid droplets small in size falling at a rate insufficient to result in standing water (puddling) or visible run-off from a road.

Rain. Liquid precipitation falling at a rate sufficient to result in noticeable flow from a road surface or along a road gutter.

Freezing rain. Supercooled droplets of liquid precipitation falling on a surface with a temperature below or slightly above freezing, resulting in a hard, slick, generally thick coating of ice commonly called glaze or clear ice. Non-supercooled raindrops falling on a surface with a temperature well below freezing will also result in glaze.

Sleet. A mixture of rain and of snow that has been partially melted by falling through an atmosphere with a temperature slightly above freezing.

Light snow. Snow falling at the rate of less than 1/2 in per hour; visibility is not affected adversely.

Snow. Snow falling at a rate greater than 1/2 in per hour; visibility may be reduced.

Blowing snow. Old snow picked up by the wind from already deposited accumulations and transported across a road. Sometimes called a "ground blizzard."

Blizzard. Snow falling at the rate of 1 in/hr or more (2.5 cm/hr) with wind speed of at least 35 mph (15.6 m/s) (National Weather Service definition).

Pavement condition

Dry. No wetting of the pavement surface.

Damp. Light coating of moisture on the pavement resulting in slight darkening of PCC, but with no visible water drops.

Wet. Road surface saturated with water from rain or meltwater, whether or not resulting in puddling or runoff.

Slush. Accumulation of snow that lies on an impervious base and is saturated with water in excess of its freely drained capacity. It will not support any weight when stepped or driven on but will "squish" until the base support is reached.

Loose snow. Unconsolidated snow, i.e., snow lacking intergranular bonds, which can be easily blown into drifts or off of a surface.

Packed snow. The infamous "snowpack" or "pack" that results from compaction of wet snow by traffic or by alternate surface melting and refreezing of the water that percolated through the snow or that flowed from poorly drained shoulders.

Frost. Also called hoarfrost. Ice crystals in the form of scales, needles, feathers or fans deposited on surfaces cooled by radiation or by other processes. The deposit may be composed of drops of dew frozen after deposition and of ice formed directly from water vapor at a temperature below 0°C (32°F) (sublimation).

Black ice. Popular term for a very thin coating of clear, bubble-free, homogeneous ice which forms on a pavement with a temperature at or slightly above 0°C (32°F) when the temperature of the air in contact with the ground is below the freezing point of water and small slightly supercooled water droplets deposit on the surface and coalesce (flow together) before freezing.

Glaze ice. A coating of ice thicker than so-called black ice that is formed from *freezing rain*, or from freezing of ponded water or poorly drained meltwater. It may be clear or milky in appearance, and generally is smooth though it sometimes may be somewhat rough.

Heat transfer

Heat pipe. A closed device in which the latent heat of vaporization is transferred by evaporating a working fluid in the heat input region and condensing the vapor in the heat discharge region; the liquid is returned to the heat input area by capillary action in a wick structure.

Heat pump. An assembly of a refrigerant gas compressor, heat exchangers, piping, controls and accessories that can provide heating or cooling; the basic types are air-to-air, water-to-air, water-to-water, earth-to-air, and earth-to-water.

MIC. Mineral insulated cable used for resistance heating.

Highway technologies

Road weather information system (RWIS). The aggregation of sensing and processing software and equipment, communications, and forecasting support, generally consisting of on-site weather and pavement condition sensors and off-site meteorological processing, used for providing timely and road-specific weather forecasts.

Thermal mapping. The practice of recording pavement surface temperature by remote infrared scanning under a range of weather and temperature conditions, to prepare plots of temperature related to their geographical position; used for identifying problem locations such as cold sinks and for siting ice detectors.

Anti-icing. Snow and ice control technique for preventing the formation of a strong bond between ice or compacted snow and the pavement on which it lies, either by use of a chemical freezing-point depressant or by thermally maintaining the pavement at or above the freezing point.

Deicing. Snow and ice control technique for destroying the bond between ice or compacted snow and the pavement as the initial step in removal.

Electrical

AWG. American Wire Gauge, a standard for specifying wire size.

kW. kilowatts (a watt is a unit of power, or energy per unit time; kilowatt is 1000 watts).

kWhr. kilowatt-hour (a unit of energy; kilowatt-hour is 1000 watt-hours).

k*VA.* kilovolt-amperes (a unit of power, specifically the apparent power in a reactive circuit).

kVAR. kilovolt-ampere reactive (a unit of reactive power, which occurs in a circuit with inductive or capacitive loads; it is the imaginary component of complex power).

Appendix G. Bibliography

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