Geothermal Heating of Highway Structures

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A report is given on the Colorado Department of Highways feasibility study to incorporate geothermal heating systems at critical locations in the proposed Interstate through Glenwood Canyon. The investigation was prompted by the concern that the proximity of the Colorado River and the extensive shading by the canyon walls may cause significant icing and preferential freezing problems on portions of the elevated structures. The direct application of the locally available geothermal water in the bridge decks to reduce these hazards was precluded primarily due to the possibility of freezing but also because of fouling and corrosion problems. The use of heat pipes as intermediate heat exchangers between the water and the deck was proposed to eliminate the possibility of water freezing in the deck and because of its effectiveness in similar applications. Ammonia-charged gravity-operated heat pipes were constructed by using two different evaporator designs and several condenser spacings in order to experimentally determine the performance of these heating systems. The snow-cover duration above all these heat exchangers relative to the unheated control was reduced by 96 percent or more even though the modules were extremely fouled by the geothermal water. The water-flow rate and temperature were 35 gal/min (133 L/min) and 25°C (77°F), respectively, over much of the 1980-1981 winter test. It appears that a fairly large number of these units could have been run in series before an appreciable degradation in the performance of the latter units would have occurred. In cases requiring minimal snow-melting capability or involving preferential icing problems, the water temperature could possibly be as low as 10°C (50°F), which means that well water or municipal water supplies would be feasible water sources.

An 11-mile (17.6-km) section of mountainous highway in Colorado is currently scheduled for improvement to Interstate standards. The existing two-lane road is confined by the Colorado River and the scenic but sheer walls of Glenwood Canyon. Roadway ice has been a persistent problem in this canyon because of the lack of direct winter sunlight and the river's proximity, which causes a high local humidity. This icing problem is expected to be magnified on certain segments of the proposed highway because it incorporates several tunnels and a significant length of elevated structures, some of which will be superelevated.

Since the area is endowed with considerable geothermal activity, a feasibility study of incorporating geothermal snow- and ice-melting systems at these critical locations was undertaken. A project panel formed by the Colorado Department of Highways (CDOH) divided this study into three phases. The initial phase included a literature search, identification of known geothermal waters in the area, and a preliminary engineering and cost analysis. The literature search indicated that only one small section of roadway in the United States has been geothermally heated. Even though this system has operated effectively since 1948 in Klamath Falls, Oregon, no useful engineering design data have been developed. The Japanese have also operated several snow-melting systems for roads with "natural thermal water," but they are just beginning to quantify the performance of these systems (1).

The second phase of the feasibility study involved exploratory drilling in the canyon to determine the local thermal gradient and hopefully to discover new geothermal sources near the proposed structures. The preliminary results obtained from these two phases are given in a CDOH report by Swanson (2). This paper will summarize the results obtained from the final phase of the study, which entailed the design, fabrication, instrumentation, and subsequent performance of a prototype geothermal bridge-heating system (3).

EXPERIMENTAL FACILITY

It was predetermined that the geothermal water should not flow through pipes embedded in the deck since the freezing of the water during a system failure could irreparably damage the heating system and fracture the deck. The geothermal water also contains both corrosive and fouling materials, which cause maintenance to be required on the exposed plumbing elements. It was therefore decided to use ammonia-charged gravity-operated heat pipes as intermediate heat exchangers to prevent these problems from occurring within the deck slab itself. Ammonia heat pipes were chosen because of their simplicity and success in similar applications (4-7).

The heat pipes employed on this project are illustrated schematically in Figures 1 and 2. Any time that the flowing water is warmer than the deck, energy from the geothermal water is conducted through the walls of the evaporator pipe and vaporizes a portion of the liquid ammonia within the evaporator. The ammonia vapor rises into the condenser tubes where it condenses to give up the heat of vaporization to the deck; the condensate then returns to the evaporator under the influence of gravity. Since the energy transport is in the form of the latent heat of vaporization, the temperature drop along the heat pipe is extremely small.

The two different heat-pipe designs depicted in Figures 1 and 2 were provided by the SETA Corporation of Laramie, Wyoming, and Energy Engineering, Incorporated (EEI) of Albuquerque, New Mexico. The SETA Corporation provided three manifolds with condenser element spacings of 0.15 m (6 in), 0.30 m (12 in), and 0.46 m (18 in). These three units will be referred to as the SETA 6-in, SETA 12-in, and SETA 18-in modules, respectively. EEI provided heat-pipe manifolds of an alternate design with 0.15-m and 0.20-m (8-in) condenser-pipe spacings (EEI 6-in and EEI 8-in).

To test these heat pipes in situ, a structure that will eventually be used as a parking garage by CDOH was erected in the Glenwood Springs Maintenance Yard from two twin-T slabs placed on abutments 2 m (6.5 ft) high. Longitudinal and transverse layers of reinforcing steel that supported the heat-pipe manifolds were placed on the 15x5-m (50x16-ft) deck formed by the twin-T's. This deck was then overlaid with 0.15 m of concrete with the top of all the condenser elements located approximately 6.4 cm (2.5 in) below the surface. The entire deck was heated with the exception of a 2.5x5-m (8x16-ft) control section located in the center of the deck. The bottom of the deck was insulated with 5 cm (2 in) of urethane foam except under the unheated control.

The geothermal water was obtained from a dammed ditch that drained through the maintenance yard. Some of this water had to be recirculated when the system was operated at the higher flow rates since the spring's output was not adequate.

In order to quantify the performance of each heat-pipe system, a variety of transducers were employed. The water-flow rate through the system was monitored in addition to the water temperature at the entrance and exit of each heat-pipe manifold. An array of thermistors was used in each deck section to trace the thermal responses of the upper and lower deck surfaces, of a few condenser pipes, and of several locations midway between the condenser pipes. In addition, the local environment was quantified in terms of ambient air temperature, wind speed, wind direction, relative humidity, barometric

Figure 1. SETA heat-pipe design for Glenwood Springs geothermally heated bridge.

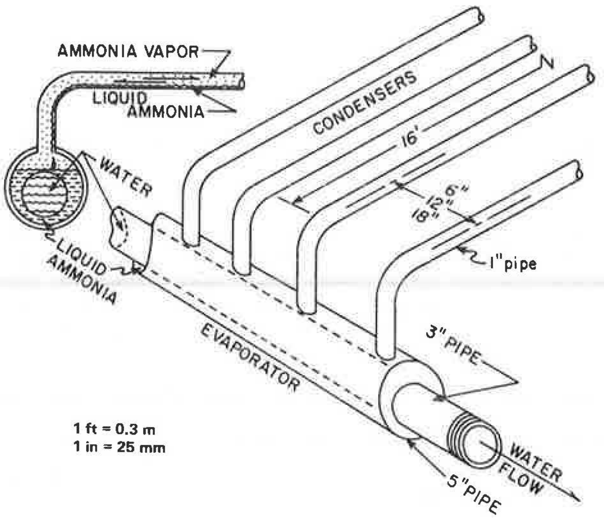
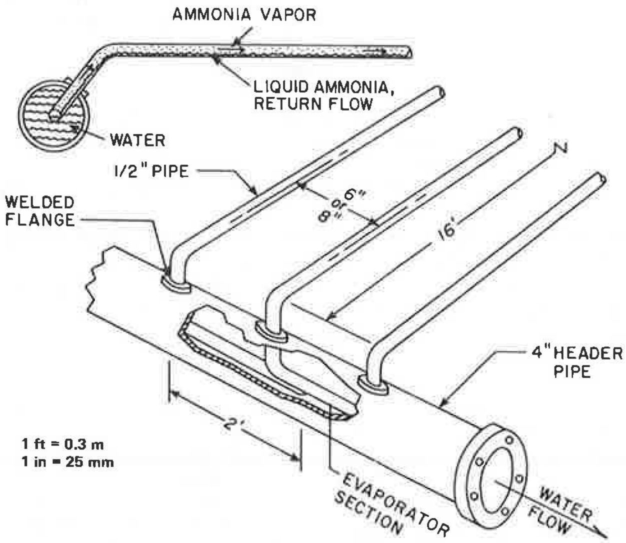


Figure 2. EEI heat-pipe design for Glenwood Springs geothermally heated bridge.



pressure, and incoming solar radiation. These data were recorded by a 100-channel data acquisition supplied by the Department of Mechanical Engineering at the University of Wyoming. The various surface conditions on the deck were also photographed on a 24-h basis by using a time-lapse camera activated at 10-min intervals.

SYSTEM PERFORMANCE

The geothermal heating system was activated on March 18, 1980, shut down on April 11 for the summer, reactivated on September 19, 1980, and permanently disabled in June 1981. The monthly averaged climatic record for the 1980-1981 winter (8) is compared in Table 1 with the long-term climatological averages. Table 1 also tabulates the percentage of each month for which experimental data were obtained. The 1980-1981 winter was relatively mild in that the two traditionally coldest months, December and January, were approximately 4°C warmer than normal and the coldest temperature recorded at the site was only -17.5°C (0°F). Between November 17, 1980, and April 30, 1981, 22 cm (8 in) of snow were reported by the Glenwood newspaper to have fallen, which appears to be about average for that time period.

The monthly averaged geothermal water temperatures and flow rates for April 1980 and the 1980-1981 winter are given in Table 2 along with the corresponding average temperature increases that were induced on the five heated surfaces. Over the three-month period from December through February, when the monthly averaged air temperatures were all near freezing, the following hierarchy in the averaged surface-temperature increases was observed: EEI 6-in [9.3°C (17°F)] > SETA 6-in [6.6°C (12°F)] ~ SETA 12-in [6.4°C (12°F)] > SETA 18-in [5.8°C (10°F)] > EEI 8-in [5.6°C (10°F)]. The monthly averaged flow rates and temperatures of the geothermal water during this period varied between 30 and 50 gal/min (114 and 189 L/min) and 24°-25°C (75°-77°F), respectively. The above hierarchy indicates that the relative performance of the various designs did not completely follow what would have been anticipated, but the severe fouling of the water pipe had a large influence on the performance of these systems. This point will be pursued later.

Table 3 delineates the performance of the heat-pipe systems in terms of various surface-freezing characteristics over the life of the experiment. This table indicates that the heated surfaces were frozen between 1 and 15 percent as long as the unheated control, which was at or below freezing 22 percent of the recorded time. A measure of the severity of the freezes is given by the area (degree days) enclosed between the freeze line and surface temperatures below freezing on a plot of temperature versus time. This freezing factor was reduced between 90 and 99 percent by the various heat-pipe modules, whereas the corresponding number of freeze-thaw cycles was decreased from 66 to 95 percent. The photographic record shows that the unheated control section was covered with snow or ice for approximately 545 h and partly covered with snow for an additional 115 h during the 1980-1981 winter. The heat-pipe modules reduced the duration of the snow and ice cover by at least 96 percent. Figure 3 depicts one of these events where the control section was iced over, as was the adjacent section of Interstate 70, while the ice on the heated surfaces on either side of the control section had melted. The SETA 12-in module can be seen on the left-hand side of the frozen control section in Figure 3, whereas the EEI 6-in module is on the right-hand side.

The SETA 6-in and EEI 8-in evaporator sections were disassembled on June 24, 1980, for examination. Figure 4 shows the 0.6-cm (0.25-in) thick fouling layer that had formed inside the water pipe through the SETA 6-in module. This layer consisted of a sludge deposited on top of a dense corrosion scale that was strongly bonded to the pipe wall. A fouling layer of this magnitude represented a 30 percent reduction in the flow cross-sectional area and would obviously have a significant effect on the system's thermal performance. An attempt was made to clean this heat exchanger with a 3-in (7.62-cm) rotary wire brush on March 19, 1981, but it appears that only the sludge layer was removed. The sludge layer pictured in Figure 4 was therefore deposited in only three months, but it was reported that the sludge layers in the other two modules had essentially the same thicknesses when they were disassembled at a later date.

The corresponding fouling that accumulated inside the water pipe of the EEI 8-in module over the total test period is pictured in Figure 5. It indicates that the fouling deposits had in essence isolated the enclosed heat-pipe evaporator bundle from the geothermal water flow, which would account for the relatively small amount of surface heating that was observed (see Table 2) near the experiment's conclusion. For some unknown reason, the performance of the EEI 8-in module was always below par, whereas Table 2 shows that the EEI 6-in module generally produced the largest surface-temperature increases.

In order to be able to predict the performance of these heat exchangers with various water temperatures, a coefficient of performance θ was defined as the ratio between the observed temperature increase of the heated surface $(T_s - T_c)$ and the maximum possible temperature increase, that is, the temperature difference between the geothermal water (T_w) and the unheated control (T_c). This coefficient of performance θ is a function both of the combined convective and radiative heat-transfer coefficient between the deck surface and the environment and of the system's overall specific heat-transfer conductance u (in watts per square meter per degree centigrade) between the water and the heated surface. The variation in a system's conductance (u) during this experiment was mainly due to the fouling and it was only slightly affected by the varying water-flow rates.

The weekly average coefficient of performance for the SETA experimental modules is plotted versus time in Figure 6. θ for the SETA 6-in module is shown to have decreased from a value near 0.4 at the beginning of the experiment down to a value around 0.29 over the coldest midwinter months and then finished with a value of 0.23 after one year. The effect that fouling had on this pipe is clearly indicated by the 20 percent drop in its θ from March through April after it had been partly cleaned on March 19, 1981, whereas the θ values of the other SETA manifolds remained essentially constant or increased during this same period.

θ for the SETA 12-in manifold decreased from 0.43 to 0.21, and its midwinter average was 0.23. The θ variation for the SETA 18-in module was from 0.29 to 0.13 with a 0.25 midwinter mean. A detailed heat-transfer analysis of these data with the corresponding environmental data indicated that the fouling had reduced the experimental observed conductance of the SETA modules by at least 55 percent. The major effect of fouling on these units appears to have been fairly early in the experiment in that they maintained a reasonably constant conductance over the latter part of the experiment. Figure 6 indicates that the relative effects of the fouling on the SETA modules were such that there was very little difference in their performance after February 1981.

The coefficient of performance for the EEI modules is compared with that for the SETA 6-in module in Figure 7. θ for the EEI 6-in manifold decreased from 0.44 to 0.27 with a midwinter mean of 0.39, whereas the EEI 8-in unit's θ decreased from 0.28 to 0.15 with a midwinter mean of 0.24. The heat-transfer analysis indicated that the conductances of the EEI modules had decreased by approximately 60 percent over the lifetime of the experiment. This analysis also implied that fouling was still causing the two EEI modules to continue to degrade at the conclusion of the experiment, whereas the conductances of the three SETA modules appear to have reached steady-state values.

IMPLEMENTATION AND CONCLUSIONS

Even though the fouling of the experimental heat exchangers proved to be fairly extreme, all the modules reduced their respective snow-cover time by at least 96 percent relative to the unheated control. The corrosion and deposition must in any case be curtailed if this heat-pipe system is to be feasible. There is a good possibility that this problem can be solved with the use of a protective and durable coating or liner since the sludge deposit in the polyvinylchloride supply lines was minimal. A study to investigate and test various alternatives to control the fouling without significantly decreasing the system's thermal conductance is currently being initiated.

A total surface area of 59 m^2 (640 ft^2) was heated by the heat-pipe modules, but this resulted in an insignificant drop in the water temperature even at flow rates as low as 35 gal/min (133 L/min). A much larger series of heating units could have been installed with very little degradation in the performance of the last units. This is demonstrated in Figure 8, which plots the coefficient of performance of the nth SETA 18-in heat exchanger, θ_n, versus the number of modules. This plot implies that the coefficient of performance for the

Table 1. Monthly averaged environmental parameters for Glenwood Springs.

	Climatological Record (1931-1960)		Experimental-Site Data (winter 1980-1981)			
Month	Air Temperature (°C)	Precipitation (cm)	Air Temperature (°C)	Precipitation[a] (cm)	Wind Speed (m/s)	Percentage of Month Recorded
Sept.	16.4	3.6	13.2	–	0.9	37
Oct.	10.6	3.6	10.8	–	0.8	95
Nov.	2.4	3.1	–	–	–	0
Dec.	−2.6	3.7	1.4	4.6	1.0	71
Jan.	−4.0	4.6	0.2	0.5[b]	1.0	93
Feb.	−1.3	4.5	−0.6	2.2	1.2	83
March	3.3	3.9	6.3	8.3	2.1	38
April	8.7	4.8	9.1	6.2	2.1	98

Note: $t°C = (t°F - 32)/1.8$; 1 cm = 0.39 in; 1 m/s = 2.2 mph.

[a] Monthly values as reported in Glenwood Springs newspaper.

[b] Major snowstorm not recorded.

Table 2. Monthly averaged water temperatures and flow rates and corresponding temperature increases of heated surfaces.

	Water			Heated-Surface Temperature Increase (°C)				
Month and Year	Temperature (°C)	Flow (gal/min)	Air Temperature (°C)	SETA 6-in	SETA 12-in	SETA 18-in	EEI 6-in	EEI 8-in
April 1980	26	138	3.4	7.6	6.4	4.8	8.4	4.7
Sept.	29	–	13.2	4.5	3.3	3.1	4.8	2.4
Oct.	28	33	10.8	4.8	3.8	3.3	5.8	3.2
Dec.	25	32	1.4	6.4	6.3	5.5	9.1	5.5
Jan. 1981	24	52	0.2	6.0	6.3	5.3	8.9	5.4
Feb.	24	50	−0.6	7.3	6.7	6.5	9.6	6.0
March	26	98	6.3	5.6	3.7	3.6	4.6	2.4
April	27	92	9.1	4.0	3.3	3.2	4.0	1.9

Note: $t°C = (t°F - 32)/1.8$; 1 gal/min = 3.8 L/min; 1 in = 25 mm.

Table 3. Percentage of reduction in various freezing characteristics of heated sections.

Heated Section	Time Frozen (h)	Time Below Freezing (degree-days)	Freeze-Thaw Cycles	Snow-Cover Duration (h)
SETA 6-in	94	95	73	99
SETA 12-in	91	95	74	99
SETA 18-in	85	90	66	96
EEI 6-in	99	99	95	100
EEI 8-in	89	93	66	97

Note: 1 in = 25 mm.

Figure 3. Typical melting event with ice-covered unheated control and wet heated surfaces.

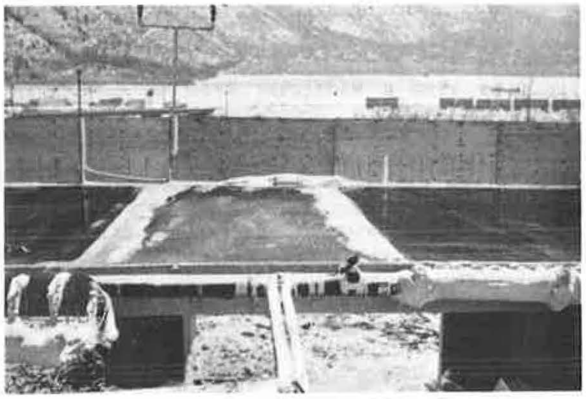


Figure 4. Sludge deposits from geothermal water in SETA 6-in evaporator.

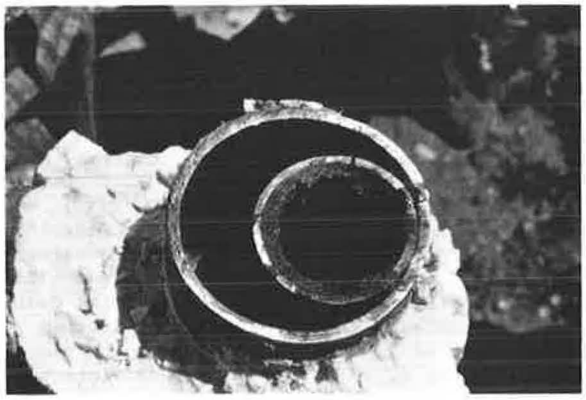


Figure 5. Cross section of EEI 8-in evaporator section showing deposits from geothermal water.

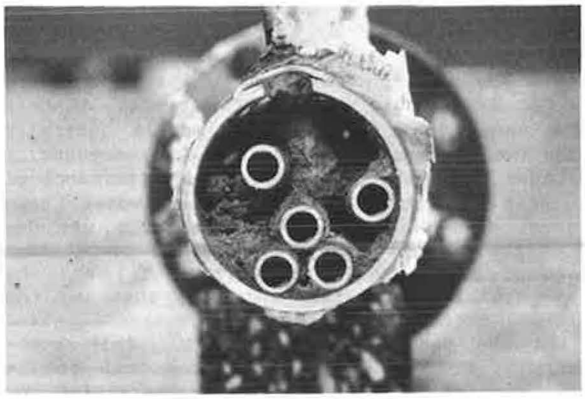


Figure 6. Coefficient of performance θ versus time for SETA heat-pipe modules.

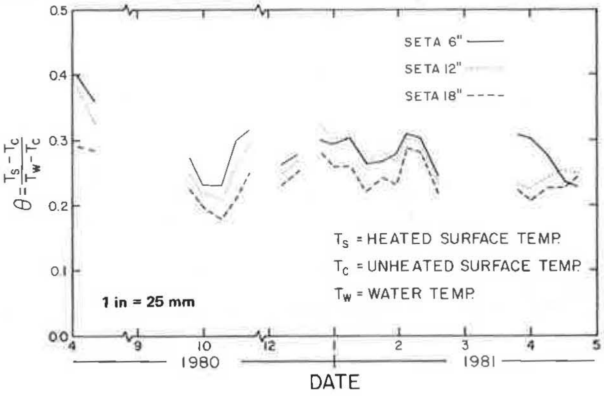
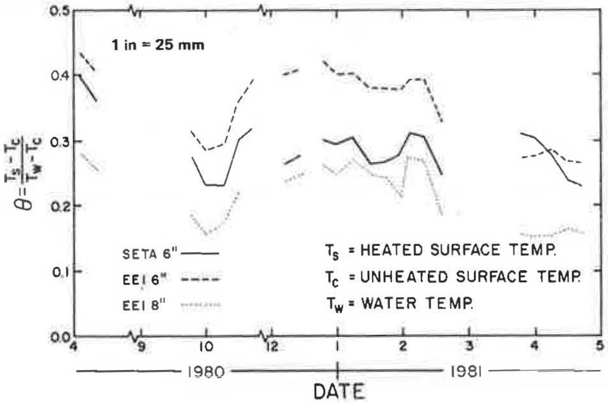


Figure 7. Coefficient of performance θ versus time for EEI heat-pipe modules and SETA 6-in module.



200th unfouled heat exchanger, θ_{200}, would have only dropped 21 percent from the θ_1 value for a 100-gal/min (380-L/min) flow rate and a large combined convective-radiative surface-film coefficient of 15 W/(m^2 · °C). For example, if the control surface is frozen but dry and the water temperature is 38°C (100°F), the surface temperature of the first unfouled module should be around 12°C (54°F), whereas the heated surface 498 m (1600 ft) down the road would be estimated to be around 8°C (46°F). For the same case but with fouling, Figure 8 indicates that the temperature of the first surface should be 7.4°C (45°F), whereas the 200th surface would be at 6°C (42°F). It therefore appears that a large length of highway could be easily handled with the hot springs located in the canyon. One spring, for instance, has a reported flow rate of 3000 gal/min (11 400 L/min) at 43°C and another has one of 2000 gal/min (7600 L/min) at 24°C.

It should be noted that source temperatures much lower than the ones used in this experiment can still be effective. For instance, long heat pipes have been successfully used to prevent preferential

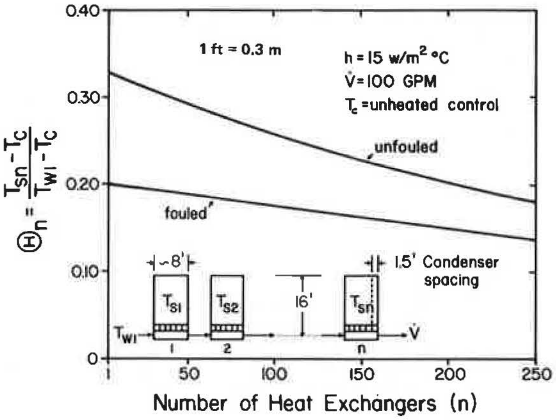


Figure 8. Variation of θ_n with number of unfouled and fouled SETA 18-in heat-pipe modules in series.

freezing and to significantly reduce the duration of snow cover on road (4,7) and bridge (5) surfaces by transferring thermal energy from the ground itself. The undisturbed winter ground temperatures 3 m (10 ft) or more below the surface were only of the order of 6°-10°C at these sites. The performance of a Glenwood-type heating system at these sites with the water temperature matching the local undisturbed ground temperature would have been superior to these ground heat-pipe systems due to the cooling of the earth around the ground heat pipes. Wells, municipal water lines, and waste water such as sewerage may therefore prove to be feasible energy sources for roadway heating systems.

In summary, all Glenwood heat-pipe modules were very effective as snow-melting systems, even when they were severely fouled. This was accomplished essentially with 25°C water at flow rates around 35 gal/min. Even at this low flow rate, the system could have supported a fairly large number of these modules in series without a large degradation in the performance of the last units. In situations requiring just the elimination of preferential icing or only requiring a limited snow-melting capability, this heating system could effectively use water with temperatures as low as 10°C.

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Construction and Benefits of Rubber-Modified Asphalt Pavements

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A paving system was developed in Sweden in the 1960s in which relatively large rubber particles were incorporated into asphalt-concrete pavements. The original purpose was to increase skid resistance and durability. This system, distributed under the trade names Skega Asphalt or Rubit in Scandinavia and PlusRide in the United States, was also found to provide a new form of winter ice control because of the increased flexibility and the action of protruding rubber particles. The Alaska Department of Transportation and Public Facilities installed five experimental pavement sections by using the PlusRide system between 1979 and 1981. Major modifications to normal asphalt pavement aggregate gradations, asphalt contents, and mix design procedures are considered essential to achieve durable nonravelling rubber-asphalt pavements. Laboratory tests of PlusRide paving mixes also indicate a potential for greatly increased pavement fatigue life as a result of the elasticity of this material. The attainment of low voids in the pavement is the primary design and construction objective, and mix design and construction activities are discussed. Observations of the skid-reduction benefits under icy road conditions have been made with a British pendulum tester and a vehicle equipped with a Tapley brake meter. Tests indicate that significant reductions in icy-road stopping distances nearly always resulted from the use of the PlusRide paving system. For 19 testing dates over two winters, stopping distances were reduced by an average of 25 percent; reductions on specific dates ranged from 3 to 50 percent.

In the late 1960s, experimentation was done in Sweden on the effects of mixing rubber particles in asphaltic pavements. A system incorporating 3-4 percent by weight of relatively large (1/16 in to 1/4 in) rubber particles into an asphalt pavement was developed to increase skid resistance and durability and was found to provide a new form of winter ice control as well as a reduced noise level. The ice-control mechanism apparently results from the flexing of the protruding rubber particles and the