THE USE OF HEAT PIPES TO PREVENT ICE FORMATION ON HIGHWAY BRIDGE DECKS

PROJECT 73-05-2

BY

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This Research Conducted Jointly by
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The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Oklahoma Department of Highways.

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Summary

Sufficient heat can be transported from the surrounding ground to a bridge deck by heat pipes to both reduce the number of freeze-thaw cycles and to reduce the time during which the surface is below freezing. In a computer model of the thermal response of a bridge during a sample month, the use of heat pipes spaced six inches apart reduced the number of freeze-thaw cycles by 58% and the time that the surface was below freezing by 87%. While even higher performance is possible, economic and structural constraints will certainly preclude the elimination of all freezing.

A screen covered groove heat pipe using ammonia as a working fluid appears to yield the best performance. Computer models are presented to analyse the performance of such heat pipes and to predict the thermal response of a highway bridge with heat pipes to either idealized or actual meteorological conditions. Recommendations are made for further work.

Introduction

Section 1

This report presents the results of a study of the use of heat pipes to carry heat to a highway bridge deck from the surrounding ground. This heat added to the bridge deck would serve two purposes:

(1) By reducing the number of freeze-thaw cycles that the bridge deck experiences during a winter, the life of the bridge surface might be increased.

(2) By delaying the time for the freezing of the bridge surface, the conditions of "preferential icing" might be reduced. Perferential icing is a highway condition that exists when moisture on the bridge surface freezes before moisture on the adjacent roadway due to the lower thermal inertia of the bridge deck.

Previous attempts have used various methods to provide supplementary heat to bridge decks such as embedded electrical resistance heating[1] and radiant heaters[2] (gas and electric). These methods suffer from several problems, primarily the high, and ever increasing, cost of the electrical or gas energy supply. In addition, a satisfactory method of controlling the heat input has not been devised. Due to the thermal inertia of the bridge deck, the occurance of icing conditions must be anticipated so that heating can actually begin before freezing starts. However, a false initiation of heating is to be avoided due to the relatively high operating cost of the heating system. Thus the control system must be very accurate. Further, it is suspected that the high temperature of the surface of the electrical resistance wiring which is necessary for adequate heat input can result in premature deterioration of the concrete bridge surface. Though radiant heaters do not seem to produce such deterioration due to high temperatures, their efficiency tends to be low. Thus radiant heaters have particularly high operating costs.

Chemical melting agents have also been used to reduce preferential icing[3]. Because of the immediate action of these chemical agents, the control system for the dispensing mechanism does not have to anticipate the icing conditions, thus the control system is simplified. However, most chemical agents tend to be corrosive so that this method of reducing preferential icing often increases deterioration of the bridge surface.

Embedded pipes circulating a heated fluid have also been proposed. Two sources of heat for this fluid have been considered: the heat produced by the decay of radioactive waste and the sensible heat of the surrounding ground. Both of these heat sources have the desirable feature that they do not require any energy from traditional, useable energy sources. The heat of decay of radioactive wastes is currently not useful because of its low energy density, while the sensible heat of ground is not used because it is a very low grade energy which is widely dispersed. Thus both of these heat sources could conceivably be exploited without additionally burdening our nation's already short energy supply. A study of the radioactive waste source proved it to be unfeasible[4]. While the sensible heat of the surrounding ground is a feasible heat source in many locations, the complexity and expense of the pipe and pumping system have discouraged its use.

An alternative method to use the sensible heat of the ground near a bridge is to carry this heat by means of a heat pipe. A heat pipe is a relatively recent invention (whose operation is explained in a subsequent section of this report) which can carry heat very efficiently i.e., with a very small temperature drop. A further advantage of the heat pipe is that it is completely passive in that it is a closed system which requires no supplementary energy to move the heat from the ground to the bridge deck. Thus its operating cost is zero.

The use of heat pipes to carry thermal energy from surrounding ground to a highway surface has been most thoroughly investigated by Dynatherm Corporation[5]. This work has centered on highways rather than bridges, and has included an experimental installation of heat pipes in a concrete test slab. Initial tests appear promising, but data are limited due to the unseasonably warm weather during the reported test period.

This study will analyze the thermal response to a bridge as it might behave in weather typical of Oklahoma when it is equipped with a heat pipe system to conduct earth heat to the deck. A computer program to thermally model a bridge is discussed which can predict the reduction in freeze-thaw cycles resulting from the heat pipe installation. Consideration of the elements of an appropriately designed heat pipe is also made.

Heat Pipe Theory

A heat pipe is a device which can transfer a large amount of heat across a relatively small temperature difference. Thus it can more efficiently transport thermal energy than can such good conductors as aluminum or silver. Such high efficiency is important in this particular application of bridge deck heating because the heat source itself (the ground near the bridge) is at such a low temperature (about 50-60°F) that if significant temperature drop occurred between the heat source and the bridge deck, then the bridge deck could not be kept warm enough to significantly reduce freezing.

A heat pipe is a closed tube which contains a working fluid (Figure 2-1). Thermal energy (heat) is carried from one end (the evaporator) to the other end (the condenser) by the change of phase of the working fluid. In the evaporator end, heat enters the heat pipe and evaporates the working fluid. This evaporation of working fluid at the evaporator results in a higher vapor pressure in the evaporator end causing the vapor to flow to the condenser end. The condenser end is at a slightly lower temperature which causes the working fluid to condense. This evaporation and condensation of the working fluid results in a transport of thermal energy from the evaporator end of the heat pipe to the condenser end.

This is briefly the operational concept behind a heat pipe. However, in order for the heat pipe to continuously transport heat, there must be a mechanism to return the condensed working fluid to the evaporator end so that the evaporator does not dry out. In a heat pipe, this return occurs by capillary flow of the working fluid through a wick. As the working fluid evaporates in the evaporator, the depletion of liquid causes the liquid-vapor interface to retreat into the wick. This produces a

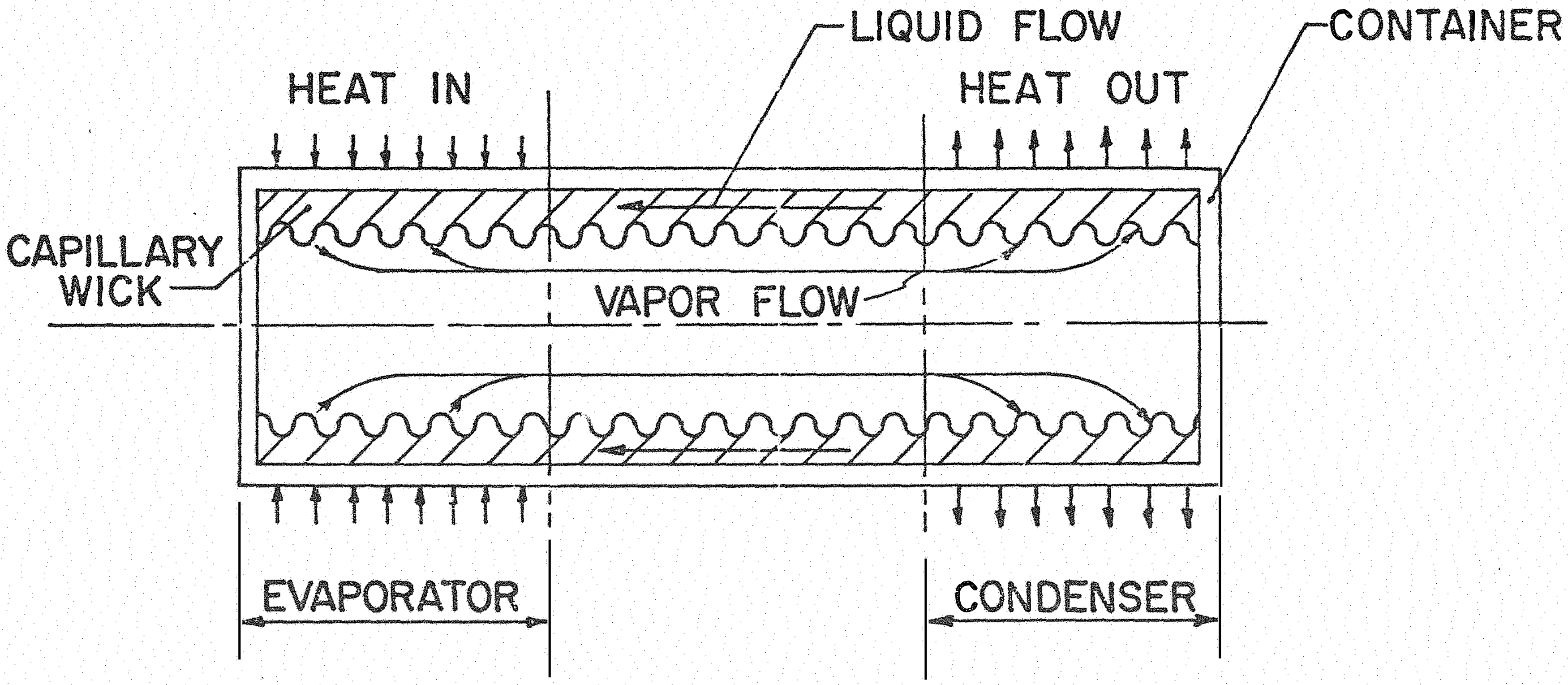


Figure 2-1. Schematic cross section of a heat pipe.

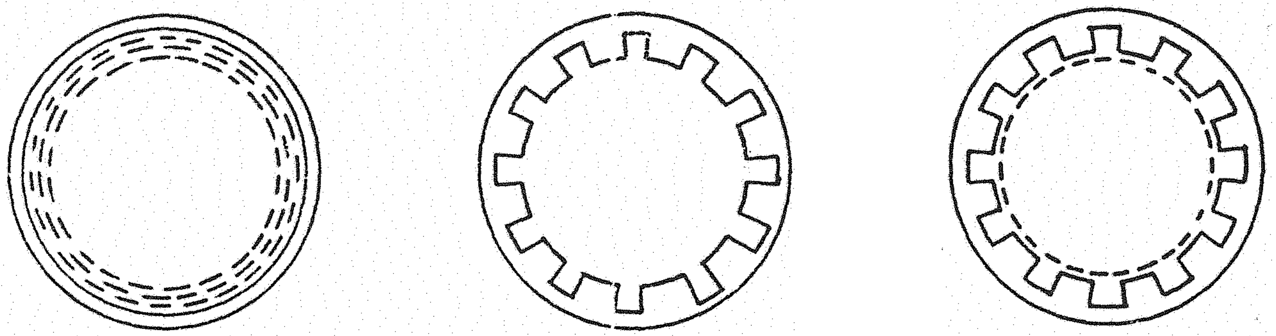
capillary pressure which pumps the condensate back to the evaporator. As long as the capillary pressure thus produced is greater than the sum of pressure drops due to gravitational forces acting on the liquid and pressure drops due to vapor and liquid flow resistance, then the heat pipe will operate without drying out the evaporator.

Considerable work has been done to theoretically analyze the operation of heat pipes. One of the earliest studies was by Cotter[6]. We will only discuss here some of those parameters which are important to the design of a heat pipe for this particular application. More general discussions can be found in the literature following Cotter.

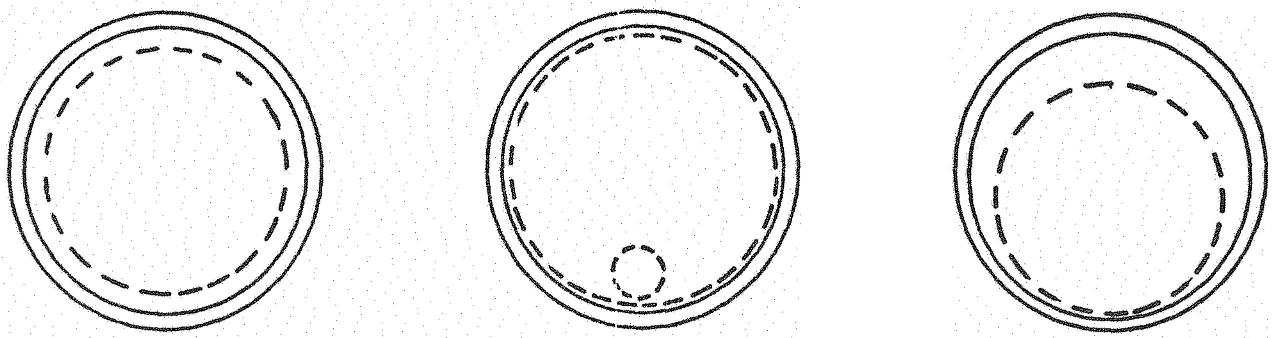
Heat pipes which operate in the temperature range of concern here are commonly referred to as ambient temperature heat pipes. For such heat pipes the maximum amount of heat that can be carried, Q_{max}, is usually limited by the ability of the capillary wick structure to return the liquid from the condenser to the evaporator. (This is in contrast with high temperature heat pipes whose Q_{max} can be limited, for example, by the vapor flowing from the evaporator to the condenser reaching sonic velocity).

For this reason, ambient temperature heat pipes are designed with a wick structure which has a low pressure drop for the fluid which flows through. Of the six wick designs shown in Figure 2-2, the wrapped screen, open groove, and screen covered grooves have proved to be most effective for the ambient temperature heat pipes due to their lower pressure drop.

The wick pumping limitation also has a strong bearing on the selection of the working fluid for a horizontal ambient temperature heat pipe. The Q_{max} of an ambient heat pipe is proportional to $h_{fg}\ \sigma/\nu$ (see, for example Chi[7], p. 34)



Wrapped Screen Open Grooves Screen Covered Grooves



Annulus Artery Crescent Annulus

Figure 2-2. Six heat pipe wick designs.

where h_{fg} = latent heat of vaporization

σ = surface tension

ν = kinematic viscosity

Figure 2-3 shows this figure of merit for various fluids in different temperature ranges. It can be seen that for temperature ranges of interest here, water and ammonia are the best choices. While water is somewhat better from a heat transfer standpoint, it has the disadvantage that, in practice, it may contain dissolved minerals and gases which inhibit its wetting characteristics (thus reducing σ) and lead to the formation of scale. Ammonia is not so sensitive, yet is compatible with most steels and aluminum so that it has found wide acceptance in ambient heat pipe designs. For example, the Dynatherm installation[5] uses ammonia as a working fluid.

Thus, the important consideration in the heat pipe design is that it be sized, and that the wick structure and working fluid are selected, such that it will supply the necessary heat flow at the appropriate temperatures to perform the desired warming of the bridge deck.

The approach taken in this study is to determine the temperature and heat flux of the heat pipe which corresponds to a certain thermal response of the bridge (see next section). With these Q_{max} and temperature, the heat pipe design can be considered. Following traditional analysis of heat pipe performance (e.g. Chi[7]) a computer program has been developed which can be used to design a heat pipe for various sizes and wick types. This program is used to study such design variables as wick type, necessary evaporator length, possible condenser length (thus bridge-span capability), and effect of inclination angle. This program is listed in Appendix A.

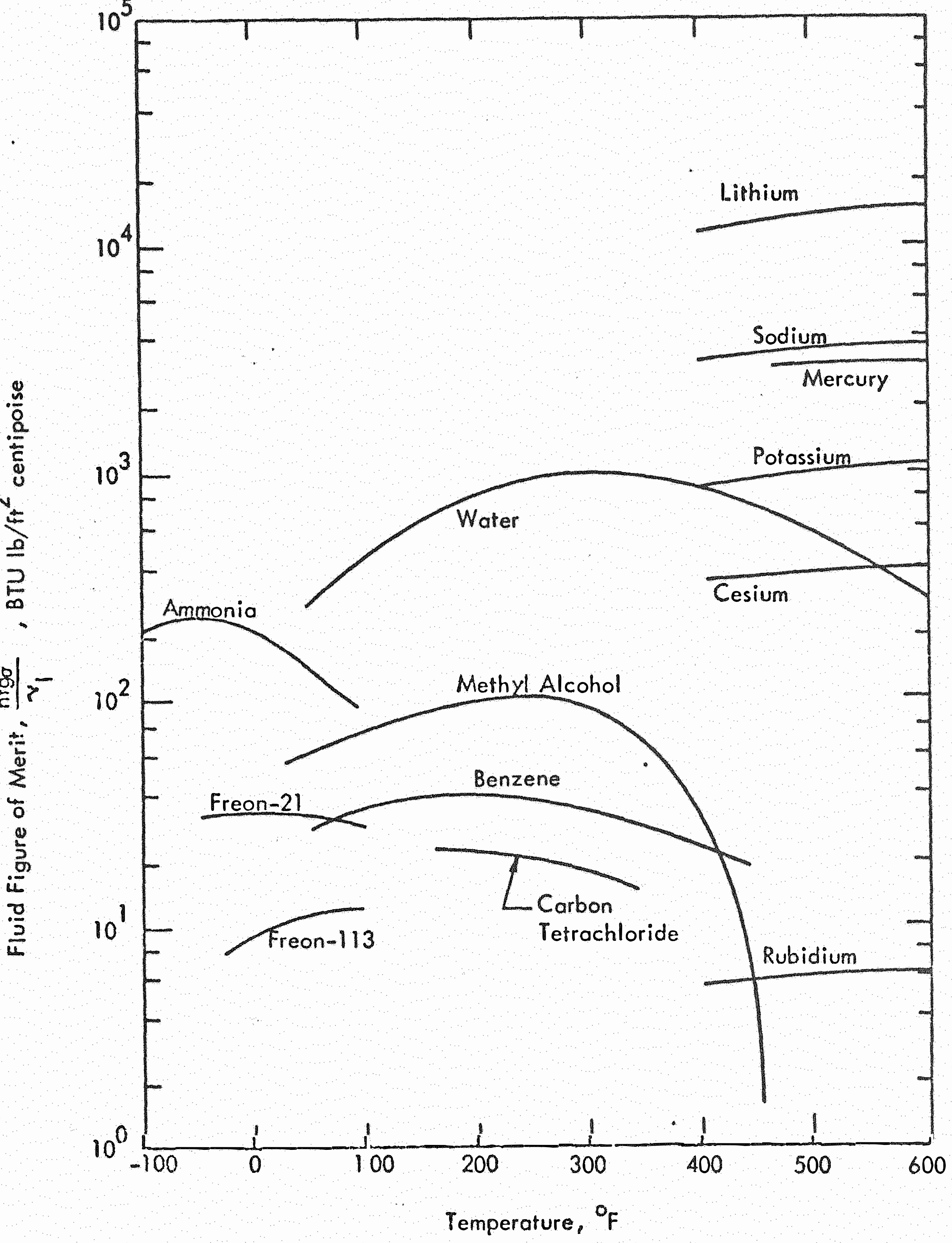


Figure 2-3 HEAT PIPE WORKING FLUID FIGURE OF MERIT FOR CAPILLARY PUMPING

Mathematical Modeling

To date several computer models for heat transfer through a medium with embedded cylindrical heat sources have been used to study the thermal response of bridge decks. Schnurr and Rogers modelled the heat transfer for such a case as steady-state and found design data by which tube heat flux and tube surface temperature were correlated to tube spacing, depth, diameter, and weather conditions.[8] Nydahl and Pell used TOSSA,[9] a transient or steady-state heat transfer computer program, to model the thermal response of a bridge and compared the numerical results to data obtained from an existing bridge.[10] Temperature response data for a bridge with an embedded cable was also given. Manuel Regis L. V. Leal formulated a computer model for the heating of a plane slab with embedded cylindrical sources for the transient or steady-state case.[11] In our case, the bridge was modelled by finite differences and solved using the implicit alternating-direction method.[12] This scheme is stable regardless of the size of time step used in the computation, a clear advantage over the explicit method of solution which restricts maximum time steps. A minimum of computer time could then be used, according to the size of time steps chosen. The implicit alternating-direction method provides a means of solving the grid equations by Gaussian elimination for the special case of a tridiagonal matrix, again providing a savings in computation time. (Appendix B)

Assumptions made in the heat transfer model of a bridge deck with embedded heat pipes are as follows:

1. Temperature variation in the z-direction (i.e. in direction of traffic flow) is small compared with variations through and across the bridge. In other words, the model is two-dimensional.

2. The material surrounding the heat pipe is homogeneous.
3. Heat pipe spacing is uniform.
4. Heat pipes are isothermal.
5. Side losses on the bridge are negligible.
6. Contact resistance between heat pipe and surrounding material is negligible.

Figure 3-1 shows a cross-section of a bridge deck with embedded 1.5 inch OD heat pipes. Traffic flow in this diagram is in the z-direction, perpendicular to the page.

Figure 3-2 shows sections of the model used to numerically solve for the transient temperature distribution of the bridge deck. It can be seen that, because of symmetry, the solution for temperature in one section will be identical to any other section, so that by superimposing solutions, the bridge deck temperature distribution.

The model consists of an isothermal half of a heat pipe. The two sides of the model, not including the heat pipe, are adiabatic, since the thermal gradient normal to these sides is zero.

Heat loss from the bridge's top surface can occur in two ways -- convection and radiation. The convective heat loss is found by the equation

$$Q_c = h_c A(T_{\underset{a}{c}} - T_s)$$

where

Q_c = heat transfer rate (BTU/hr)

h_c = convective conductance (BTU/hrft^{2}F)

A = surface area (ft^2)

T_a = air temperature (F)

T_s = bridge surface temperature (F).

The convective conductance is a function of wind speed, the characteristic bridge length, and the air temperature.

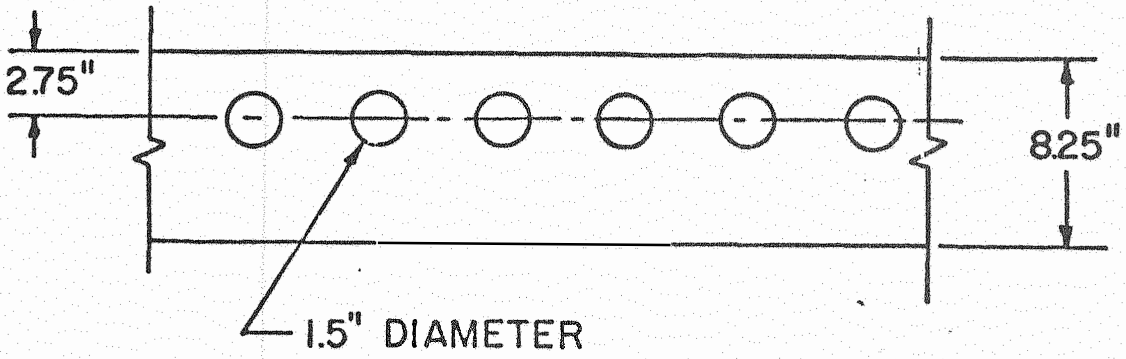


Figure 3-1. Vertical cross section through bridge with heat pipe installation. Section is perpendicular to traffic flow.

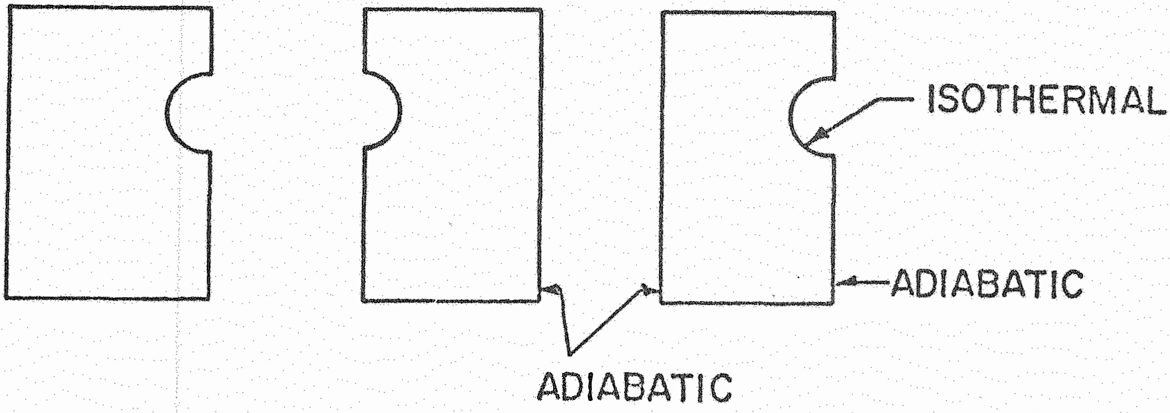


Figure 3-2. Subsections for mathematical model. These subsections can be added together to represent the bridge cross section.

The radiative heat transfer from the bridge surface for a cloudy sky is given by

$$Q_R = \epsilon\sigma(T_a^{4} - T_s^{4})$$

where

ϵ = emissivity of bridge surface

σ = Stefan-Boltzmann constant ($BTU/hrft^2R^4$)

and T_a and T_s are expressed here in degrees Rankine.
For a clear sky, the long-wave radiation emitted by the atmosphere is given by

$$Q_{LW} = - 54.19 + 1.195\ T_a^{4}$$

where T_a is given in degrees Rankine.[13] Thus, the heat transfer by radiation with a clear sky is given by

$$Q_R = \epsilon\sigma(T_E^{4} - T_s^{4})$$

where

T_E = effective air temperature (R).

The effective air temperature is found using

$$T_E = \left(\frac{Q_{LW}}{\sigma\epsilon}\right)^{\frac{1}{4}} .$$

The bottom surface of the bridge transfers heat only by convection. Radiative transfer is negligible because the transfer surroundings have approximately the same temperature as the bridge bottom surface. The convective bottom heat transfer is found as a percentage of the upper surface convective heat transfer. This percentage becomes smaller because the wind speed across the bottom is reduced by means of exposed steel beams under the bridge, hills and the like.

Heat transfer in the bridge deck itself is by conduction and is given by

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \alpha \frac{\partial T}{\partial \theta}$$

where

x,y = coordinates for the two-dimensional problem

α = thermal diffusivity (ft^2/hr)

θ = time (hr).

Our purpose in constructing a computer model was to determine the effect of heat pipe spacing on temperature in the bridge, and to determine the effect of the heat pipes on conditions conducive to ice formation. To do this, we assumed cloudy days and clear nights. This combination of sky cover is most conducive to the formation of ice, thus our model represents the most pessimistic sky conditions. Clear days provide the bridge with added heat via solar flux and long-wave radiation. Cloudy days omit these added heat sources. The effective temperature of a clear night sky is of the order of 430°R (-30°F). A cloudy sky emits approximately as a black body at air temperature, which is of the order of 480°R (20°F). Thus, the clear night is most severe for night sky conditions.

The air temperature variation is modelled as a sine wave. Each computer run was given a minimum air temperature and several maximum air temperatures. In order to establish a reasonable initial condition, a constant initial bridge temperature was first assumed. The model allowed a 24 hour period to find the true transient temperature distribution in the bridge. This distribution then serves as the subsequent initial condition. In order to study response for temperature cycles of several amplitudes, the model was allowed to run through 5 cycles; at the end of each a 5°F increment in maximum air temperature was made.

The heat pipe temperature was assumed to be 50°F. This is less than Oklahoma's integrated average earth temperature to a depth of 10 feet during winter months.[14] The average wind speed for Oklahoma, 15 mph, was selected as a design constant.[15] Larger winds increase the convective heat transfer process. Thus, to increase wind speed as a design parameter would lower temperatures at night and raise temperatures at day, resulting in a greater daily bridge temperature fluctuation. Smaller wind speeds simply decrease the fluctuation of the daily bridge temperature. The wind is assumed in a direction perpendicular to traffic flow across a two lane bridge. Other constants are noted in Table 3-1.

Figures 3-3 and 3-5 show the effects of the heat pipe on the surface temperature of the bridge. The percentage of the 24 hour period that the bridge surface is frozen is plotted against the maximum air temperature. The maximum air temperature is simply the minimum air temperature plus Δt. Each graph is of a constant minimum air temperature. The bridge surface temperature is not uniform but is a maximum directly above the heat pipe center and a minimum halfway between the heat pipes. The surface temperatures sometimes vary by more than 6.3°F for the heat pipes with 8.25" spacing. When the minimum surface temperature reached 32°F, freezing or thawing was assumed. Temperatures at freezing were chosen to the nearest 30 minutes, giving a ± 2% error for the percentage of day the bridge surface is considered frozen. The heat pipe spacing is measured from the center of one heat pipe to the center of the nearby heat pipe. It is seen from the graphs that the heat pipe, at any spacing given, significantly reduces freezing of the bridge surface. The 6" heat pipe spacing reduces the percentage of time the bridge surface is frozen by at least 50% for any temperature variation. The 4.5" spacing never allows freezing of the bridge surface for a

Table 3-1. Parameter values used in theoretical study of bridge thermal response to sinusoidal temperature fluctuations.

Material: concrete
Wind speed: 15 mph
Characteristic bridge length: 26 ft
Bridge depth: 8.25 in
Back loss: 10%

Heat pipe temperature: 50°F
Heat pipe diameter: 1.5 in
Depth of center of heat pipe: 2.75 in
Concrete emissivity: 0.940
Concrete conductivity: 1.0 BTU/hrftF

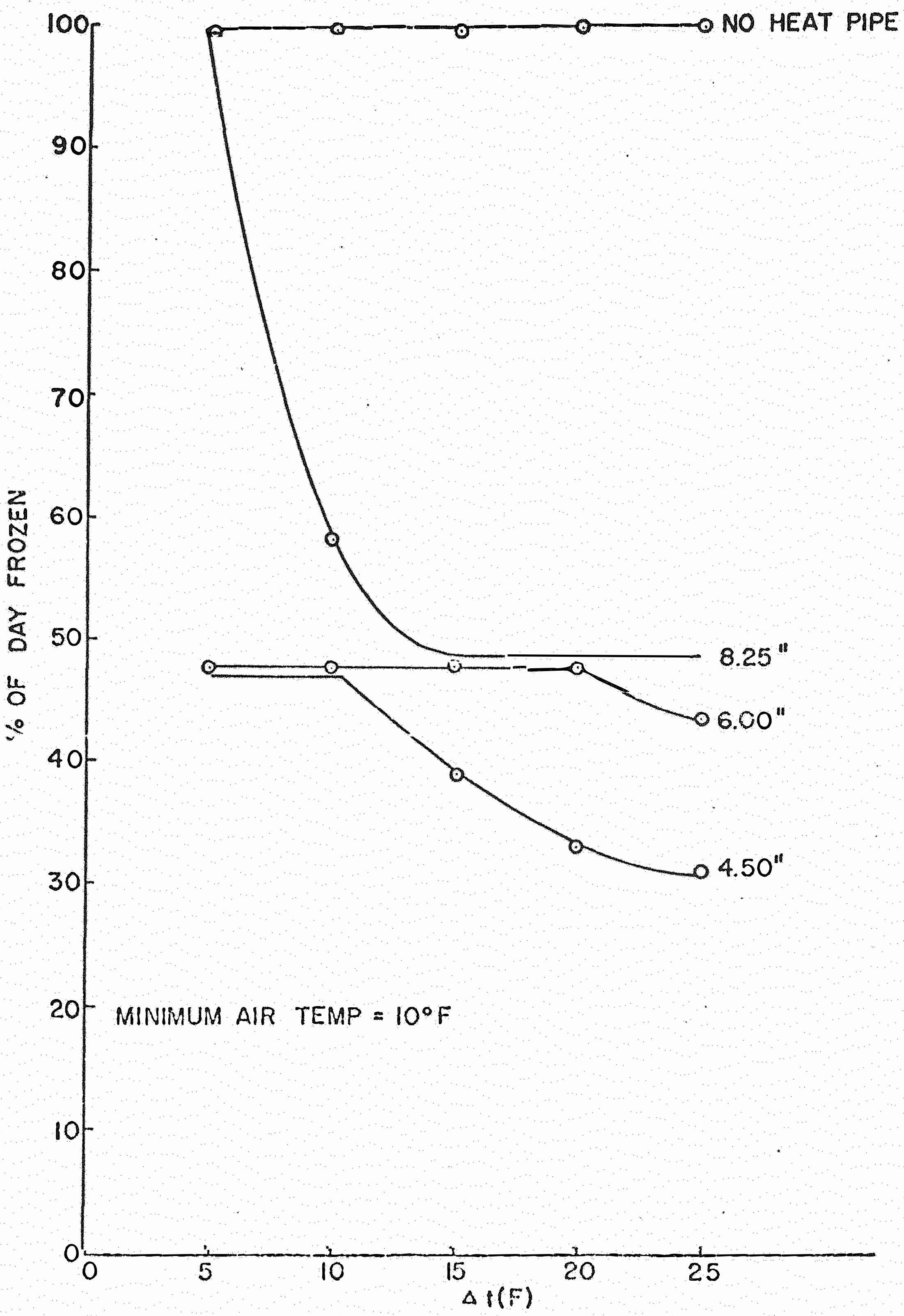


Figure 3-3. Percentage of time below 32°F of the minimum bridge surface temperature as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 10°F.

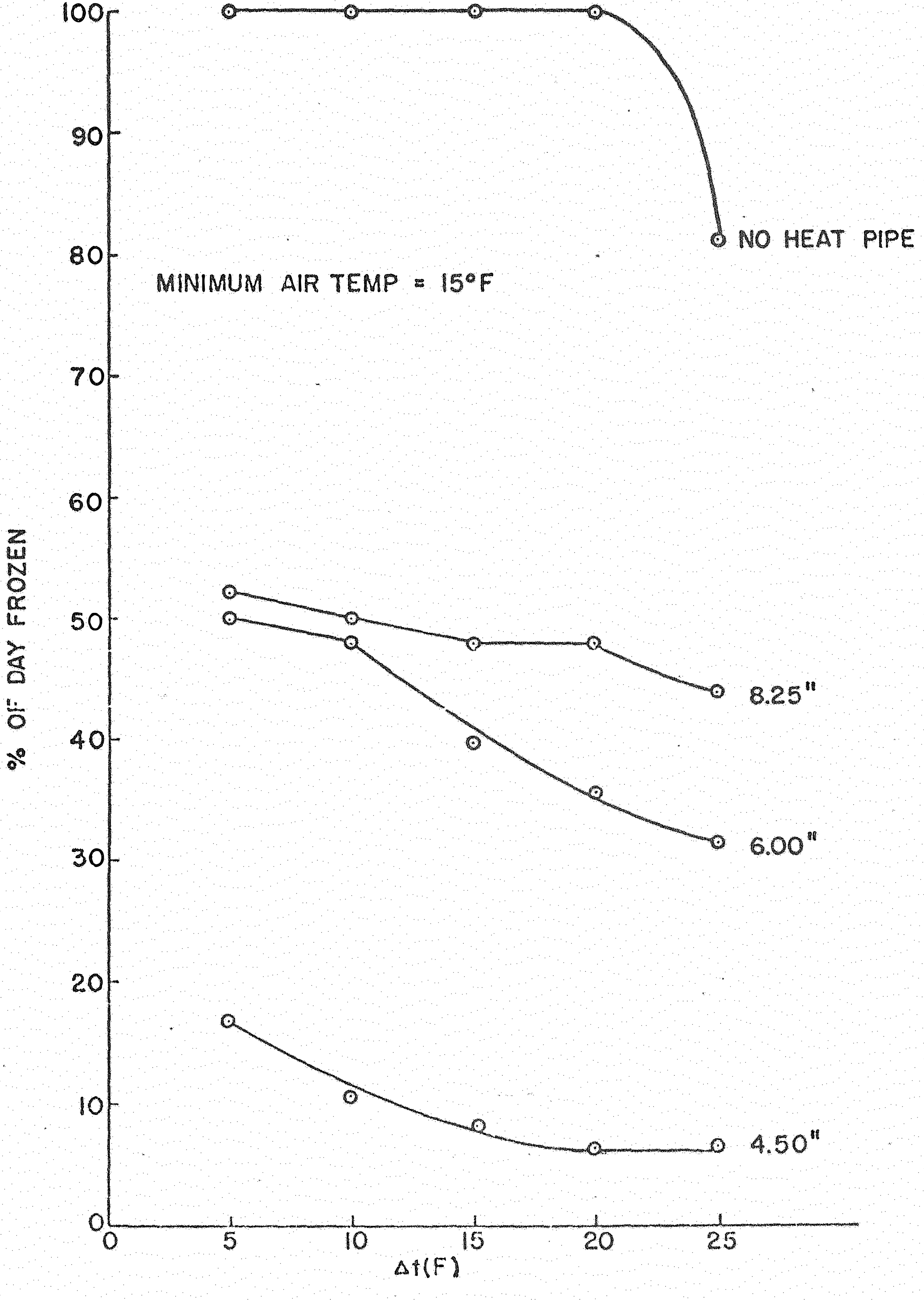


Figure 3-4. Percentage of time below 32°F of the minimum bridge surface temperature as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 15°F.

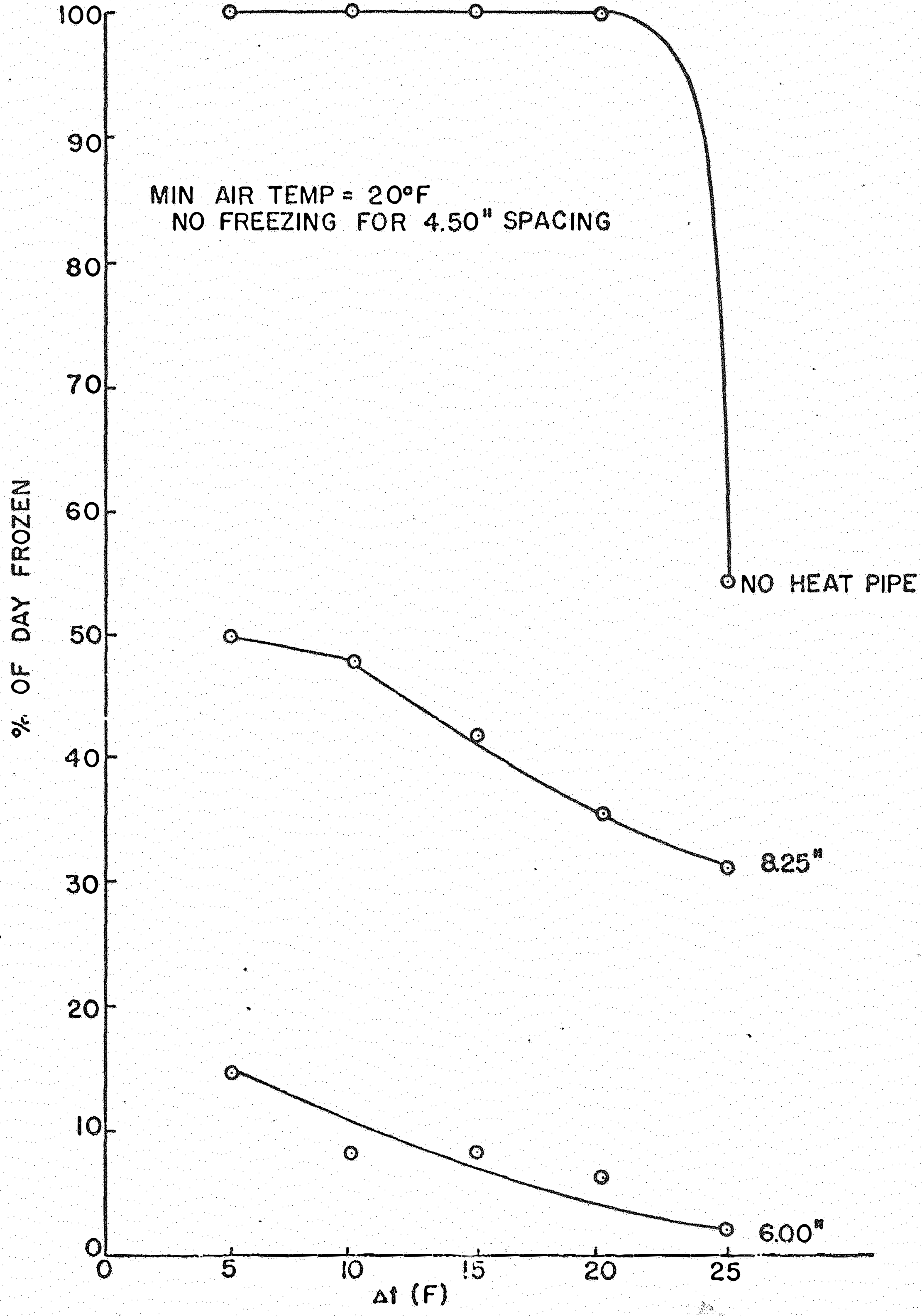


Figure 3-5. Percentage of time below 32°F of the minimum bridge surface temperature as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 20°F.

minimum temperature of 20°F. For a minimum temperature of 15°F, the 4.5" spacing gives an added difference to the 6" spacing of 25% to 30% of a day that the bridge is unfrozen -- quite significant. However, for the 10°F minimum temperature this difference is apprciably less, 0% to 13% of a day. It is expected that the 8.25" spacing will not permit enough heat to appreciably delay icing, as the ice will be an added heat load.

The straight lines at 47.9% of the day, on two of the graphs, can be explained physically. At 12.5 hours, the effects of clear sky night radiation are seen on the bridge surface. The bridge surface temperature drops several degrees Fahrenheit as the sky becomes clear. At this jump in surface condition, extra heat is required to keep the surface from freezing. The straight lines represent this transition.

Figures 3-6 to 3-8 show the effects of the heat pipe on the minimum bridge temperature at a depth of 0.375". The 8.25" heat pipe spacing increases the freeze-thaw cycles as compared with the unheated bridge for each of the air temperature minimums considered. Only for the 10°F air temperature does the 6" spacing initiate freeze-thaw cycles, and there they occur for each variation of air temperature considered. The 4.5" and 6" spacing provide a decrease in freeze-thaw cycles for the 15°F and 20°F minimum air temperature, and no freeze-thaw cycles occur for either the unheated bridge or the 4.5" spacing at the 10°F air temperature minimum. Therefore, the 8.25" spacing hinders the freeze-thaw characteristics for the temperatures considered. However, it is expected that at higher air temperature minimums the 8.25" spacing would aid in prevention of these cycles. The 4.5" spacing benefited the prevention of freeze-thaw cycles for all cases considered, and the 6" spacing benefited all but the 10°F minimum air temperature.

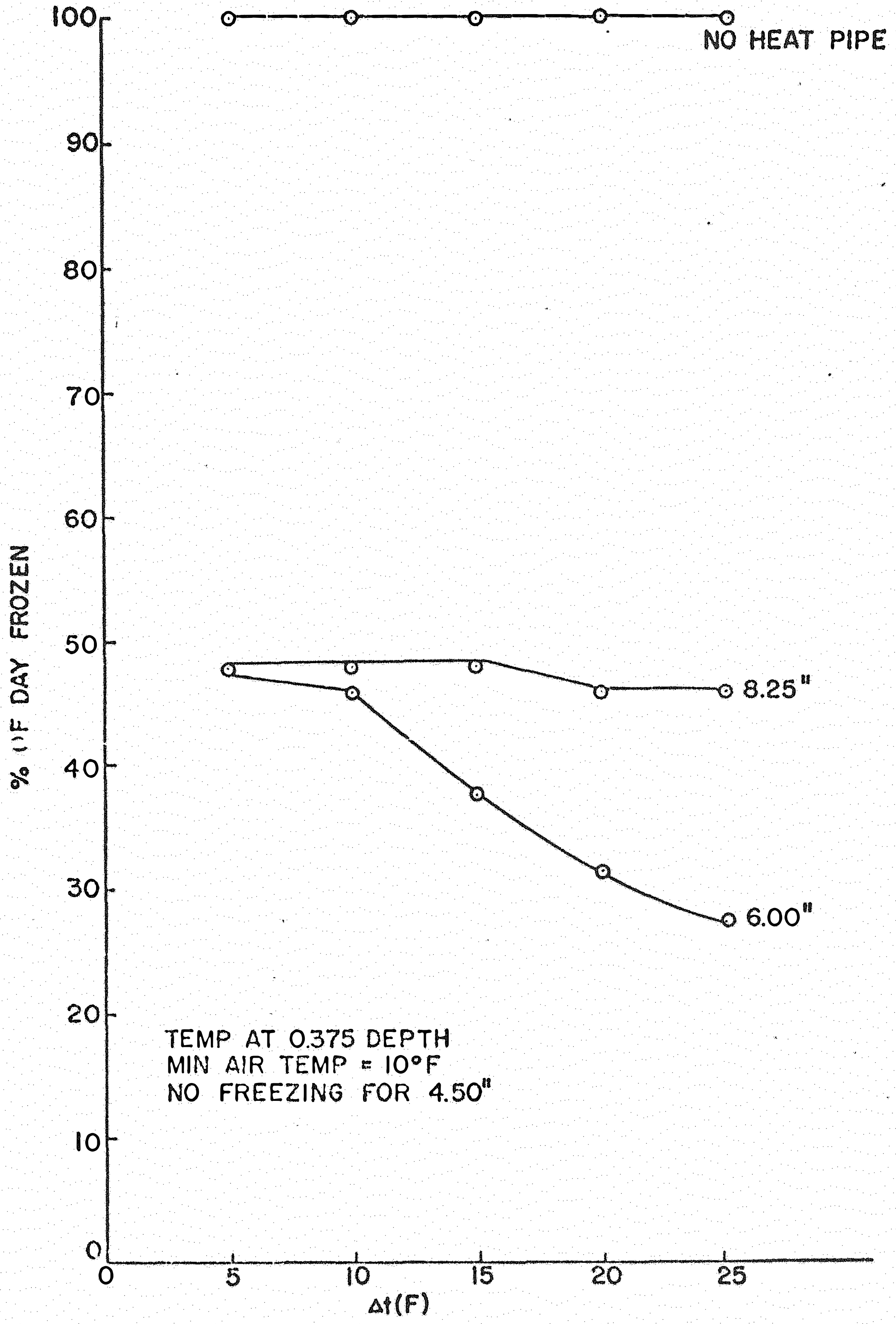


Figure 3-6. Percentage of time below 32°F of the minimum bridge temperature, at a 0.375 inch depth, as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 10°F.

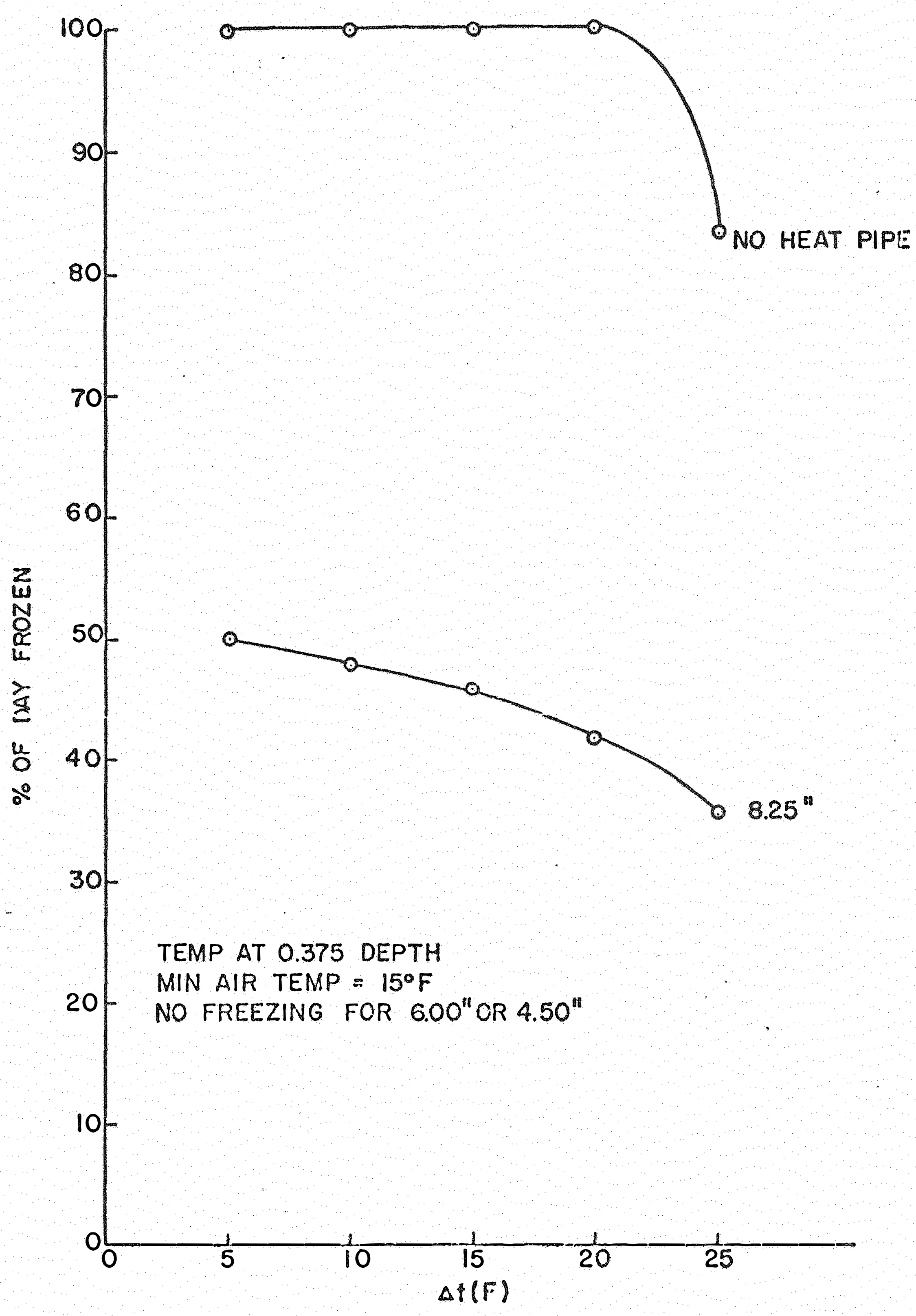


Figure 3-7. Percentage of time below 32°F of the minimum bridge temperature, at a 0.375 inch depth, as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 15°F.

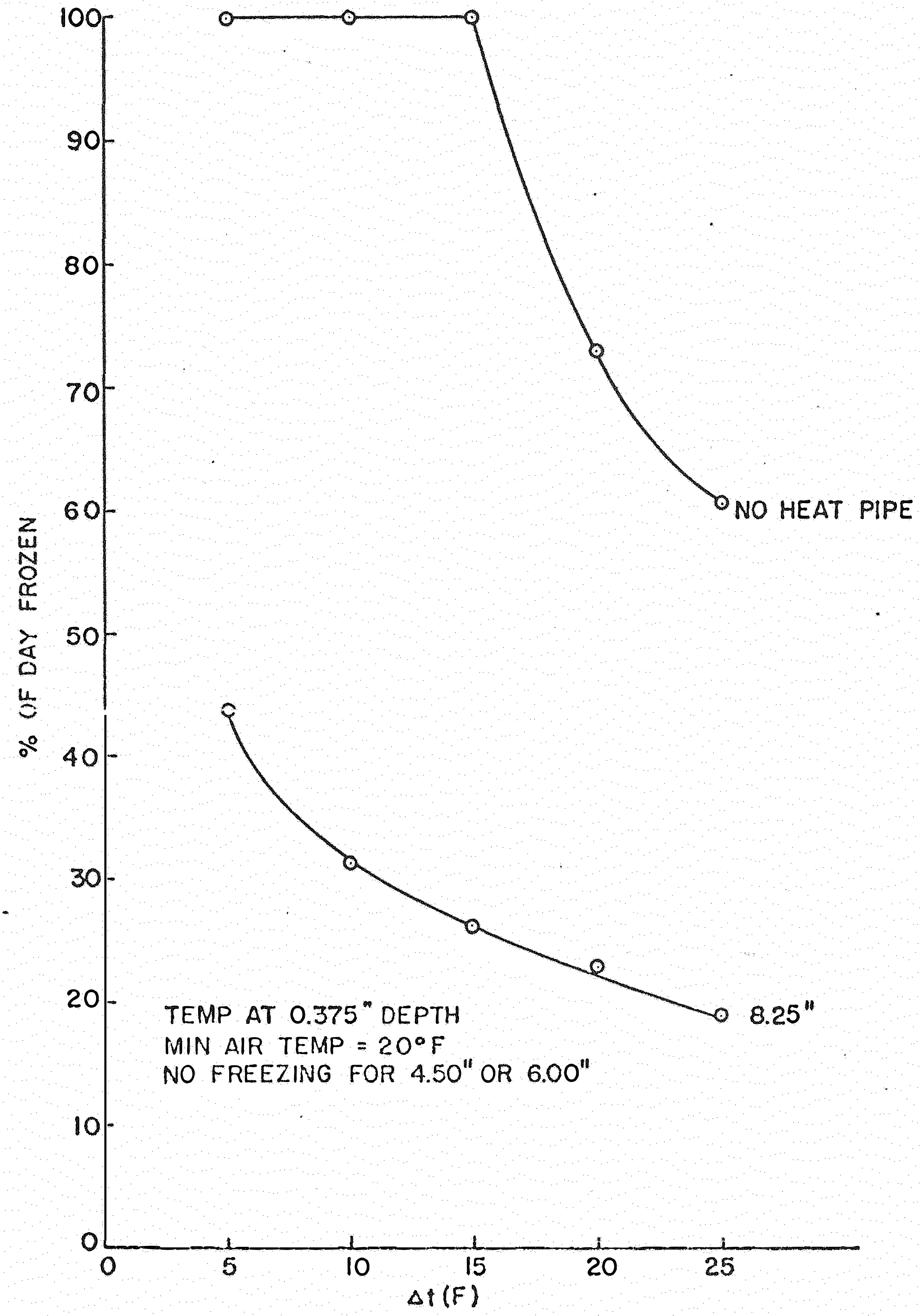


Figure 3-8. Percentage of time below 32°F of the minimum bridge temperature, at a 0.375 inch depth, as a function of amplitude of sinusoidal air temperature fluctuations and heat pipe spacing for a minimum air temperature of 15°F.

Thermal Response of a Bridge for a Sample Month

The preceding theoretical modeling has given some indication of the effect of heat pipe installation on a bridge. This same computer model was next used to represent the thermal response of a bridge with and without heat pipes during a sample month.

The month of January, 1973, was selected as a month with particularly severe weather conditions. The following data were collected by the National Weather Bureau at the Oklahoma City airport and used for this representation: daily maximum and minimum temperature, daily average wind speed, average daily sky cover, and daily incident solar radiation (Table 4-1).

Precipitation data is not used in this model because we have neglected the latent heat of any moisture on the bridge deck. This assumption is somewhat pessimistic from a freeze-thaw cycle viewpoint, because the latent heat of liquid on the bridge deck would tend to retard the dropping of the surface below the freezing point. Of course, it is somewhat optimistic for the case of snow falling on a warmer bridge deck. In addition to the rather complicated mathematical aspects of modeling this precipitation, the necessary data are not available to include accurately these effects. In order to model the precipitation with any degree of relevance it would be necessary to know the distribution of rain (or snow) fall throughout the day as a function of time. These data are not available. It is felt that these latent heat effects will be small and will be best verified with a field experiment.

The instantaneous air temperature was represented by fitting a continuous sine wave between reported maximum and minimum air temperatures.

PRELIMINARY LOCAL CLIMATOLOGICAL DATA

MONTH January
YEAR 1973
LATITUDE 35° 24' N
LONGITUDE 97° 36' W
GROUND ELEVATION (FT) 1285 FT.
STANDARD TIME Central

DAY	TEMPERATURE °F MAXIMUM	MINIMUM	AVERAGE	DEPARTURE FROM NORMAL	DEGREE DAYS (Base 65°)	PRECIPITATION (In.) TOTAL (Water equivalent)	SNOWFALL, ICE PELLETS	SNOW, ICE PELLETS OR ICE ON GROUND AT 6AM	WIND AVERAGE SPEED (m.p.h.)	FASTEST MILE SPEED (m.p.h.)	DIRECTION	SUNSHINE TOTAL (Hrs. and tenths)	PERCENT OF POSSIBLE	SKY COVER SUNRISE TO SUNSET (Tenths)	WEATHER OCCURRENCES	Station Pressure Average 6AM	6PM	Prevailing Direction	Daily Langleys
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	46	24	35	- 4	30	0	0	0	10.6	17	NE	8.2	84	1		28	.975	05	264.5
2	40	27	34	- 4	31	.22	T	0	8.9	14	E	0.2	2	9	1,4	28	.795	07	72.7
3	41	30	36	- 2	29	.83	2.7	T	8.0	19	N	3.1	31	8	1,4,6	28	.453	24	145.2
4	30	20	25	-13	40	0	0	T	14.1	22	N	4.9	50	10		28	.843	36	210.9
5	23	19	21	-16	44	.02	T	0	12.8	17	N	0	0	10	1,6	28	.813	03	29.3
6	24	17	21	-16	44	.15	1.8	T	13.6	19	N	0.1	1	10	6	28	.915	02	87.8
7	21	15	18	-19	47	.24	3.5	5	15.2	19	N	0.6	6	10	1,6	28	.850	36	130.2
8	17	3	10	-27	55	T	T	6	16.3	23	NW	6.4	65	~~8~~ 9	6	29	.030	36	278.3
9	11	0	6	-31	59	T	T	5	12.3	21	N	4.0	40	10	1,6	29	.140	36	175.1
10	16	9	13	-24	52	T	T	5	5.6	14	N	0	0	10	6,8	28	.930	36	100.9
11	20	3	12	-25	53	0	0	5	10.9	22	W	9.1	91	1	6	28	.990	35	318.3
12	27	-1	13	-24	52	0	0	5	8.2	19	SE	9.1	91	6	6	28	.875	18	325.6
13	35	15	25	-12	40	0	0	5	9.1	15	S	9.1	91	4	6	28	.770	20	298.9
14	48	26	37	0	28	0	0	3	7.0	10	SW	9.8	97	8	6	28	.805	21	286.0
15	54	30	42	+ 5	23	0	0	1	4.1	9	S	10.0	100	0	8	28	.915	17	237.3
16	56	35	46	+ 9	19	0	0	T	14.1	25	S	4.7	46	10	1	28	.648	18	195.3
17	66	51	59	+22	6	T	0	0	[illegible]	23	S	1.4	14	9		28	.433	19	144.4
18	61	40	51	+14	14	.02	0	0	13.8	25	NW	9.9	98	0	3	28	.448	31	292.7
19	64	33	49	+12	16	0	0	0	12.3	23	S	4.0	39	10		28	.493	16	230.6
20	59	47	53	+16	12	0	0	0	[illegible]	23	S	0	0	10	2	28	.255	16	92.8
21	48	35	42	+ 4	23	.93	0	0	18.6	33	NW	0	0	10	2,3	27	.940	32	45.6
22	44	34	39	+ 2	26	0	0	0	15.4	33	NW	0.4	4	10		28	.443	34	121.2
23	47	28	38	+ 1	27	0	0	0	[illegible]	29	NW	10.1	100	0		28	.635	34	327.3
24	[illegible]	[illegible]	45	[illegible]	[illegible]	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	100	0		28	.780	24	322.0
25	47	[illegible]	40	+ 3	25	[illegible]	0	0	6.9	13	NW	0	0	10	1	28	.715	04	52.4
26	46	39	43	+ 6	[illegible]	[illegible]	0	0	7.9	14	NW	0	0	10	1	28	.490	26	49.3
27	44	29	37	0	[illegible]	.05	0.3	0	17.4	42	NW	.0	0	10	1,9	28	.433	35	34.3
28	32	23	28	- 9	37	T	T	T	[illegible]	41	NW	10.2	98	0		28	.990	35	350.8
29	41	17	29	- 9	36	0	0	0	6.6	10	N	9.7	93	4		28	.888	20	335.0
30	60	26	43	+5	22	0	0	0	16.1	26	S	7.0	67	5		28	.445	19	320.0
31	58	44	51	+13	14	.15	0	0	17.2	25	S	0.1	1	10	8	28	.163	18	84.0
SUM	1284	779	—	—	—	3.39	8.3	—	3787	—	—	142.3	—	213	—	889	73	-	604.2
AVG	41.4	25.1	—	—	—	—	—	—	12.2	FASTEST	DIRECTION	POSSIBLE	%		—	28	.689	36	194.9
									MISC. →	42	NW	3125	46	6.9	—	28	.693	-	-

TEMPERATURE DATA

AVERAGE MONTHLY 33.3
DEPARTURE FROM NORMAL -3.7
HIGHEST 66 ON 17
LOWEST -1 ON 12
NUMBER OF DAYS WITH -
MAX. 32° OR BELOW 10
MAX. 90° OR ABOVE 0
MIN. 32° OR BELOW 21
MIN. 0° OR BELOW 2
DEGREE DAYS (Base 65°)
TOTAL THIS MONTH 975
DEPARTURE FROM NORMAL +107
SEASONAL TOTAL 2803
DEPARTURE FROM NORMAL +492

PRECIPITATION DATA

TOTAL FOR THE MONTH 3.39 IN.
DEPARTURE FROM NORMAL +2.08 IN.
GREATEST IN 24 HOURS 1.05 ON ~~3-4~~ 2-3

SNOWFALL, SLEET

TOTAL FOR THE MONTH 8.3 IN.
GREATEST IN 24 HOURS 5.3 ON 6&7
GREATEST DEPTH ON GROUND 6 ON 8

BAROMETRIC PRESSURE
(Climatological station elevation)

(H_{pc}) 1214 FT., M.S.L.
MONTHLY AVERAGE STATION 28.791 IN.
HIGHEST SEA-LEVEL 30.72 IN. ON 9
LOWEST SEA-LEVEL 29.16 IN. ON 21

WEATHER

NUMBER OF DAYS -
CLEAR (Scale 0-3) 7
PARTLY CLOUDY (Scale 4-7) 4
CLOUDY (Scale 8-10) 20
WITH 0.01 INCH OR MORE PRECIP. 11
WITH 0.10 INCH OR MORE PRECIP. 8
WITH 0.50 INCH OR MORE PRECIP. 2
WITH 1.00 INCH OR MORE PRECIP. 0

SYMBOLS USED IN COLUMN 16

1 = FOG
2 = FOG WITH VISIBILITY 1/4 MILE OR LESS
3 = THUNDER
4 = ICE PELLETS
5 = HAIL
6 = GLAZE OR RIME
7 = DUSTSTORM
8 = SMOKE OR HAZE
9 = BLOWING SNOW

Wettest January since 1949. The minus 1 temperature was lowest temperature to occur in January since January 12, 1963. Snowfall was largest for January since 1962.

Table 4-1. Meteorological data for the month of January, 1973, recorded by U.S. Weather Bureau at the airport weather station in Oklahoma City.

The time difference between maximum and minimum air temperatures was taken as 12 hours.

Daily wind speeds were assumed constant at the average value reported in the climatological data. The wind was considered to be constant in direction -- perpendicular to traffic flow.

Sky cover was input as either cloudy, for the climatological data scale 8 to 10, or clear, data scale 0 to 7. Mathematical modeling of a partly cloudy sky is extremely difficult, and no data are available to account for its random effects. Therefore, partly cloudy days were included as clear days, thus providing a minimum contribution of long-wave radiative heating of the bridge surface.

Instruments of the Weather Bureau used in measurement of the daily Langleys are insensitive to long-wave radiation. Therefore, the Langleys given in the climatological data account only for short-wave solar radiation. Incident solar radiation was modelled as a half sine wave with a maximum heat flux found from the given day's Langleys. This variation in solar flux occured during a 10 hour interval each day. The sun's heating began when air reached its minimum temperature. Thus, bridge and air responded by lagging the solar heat flux. It should be noted that even cloudy days contributed some short-wave energy, as the sun's rays partially penetrated the cloud cover. After 10 hours, there was no solar heating for the remainder of the day, and only long-wave radiation transfer occured. The concrete's solar absorptivity was 0.65.[16]

The heat pipe's outer diameter, for the study of January, 1973, weather conditions, was changed to 2 inches. There were 3 reasons for doing this. First, the 2 inch pipe's larger surface area exposed more concrete to the heat input, thus providing warmer temperatures through the bridge deck. Second, a larger diameter heat pipe has greater capacity for heat transfer. Finally, a larger node spacing could be used in the computer model of the bridge deck, resulting in a savings in computer time.

Results from the computer model are shown in Figure 4-1 for January 8 through January 13. This period of time represents the most severe weather conditions in January, 1973. Plotted are the air temperature and the bridge surface temperatures with and without heat pipes. The graph of the bridge with heat pipes is for the minimum surface temperature, which occurs at the midpoint between the pipes.

Sudden changes in surface temperature variations are seen to occur at the beginning of each day. This is due to the sudden change in wind speed (in the model) occuring as the day changes. Also, cloud cover changes occurs at this time, as seen for January 11, which effects radiative heat transfer and, therefore, the surface temperature.

It is seen that the bridge with heat pipes drops under 32°F in temperature 5 times, while that without heat pipes passes only one time over this temperature. Thus, based on this period, the bridge without heat pipes has better freeze-thaw characteristics, based on 32°F freezing. This is not the case if 25°F is taken as a reference for freeze-thaw. In this instance there is no freeze-thaw for the bridge with heat pipes and 4 freeze-thaw cycles for the bridge without heat pipes. The bridge with heat pipes has its surface under 32°F for 36 hours during these 6 days, while that without heat pipes amounted to 140 hours. However, for 25°F surface temperature, the bridge with heat pipes had no hours while that without heat pipes amounted to 128 hours. Thus, based on this period, the bridge with heat pipes is far superior in reduction of icing conditions.

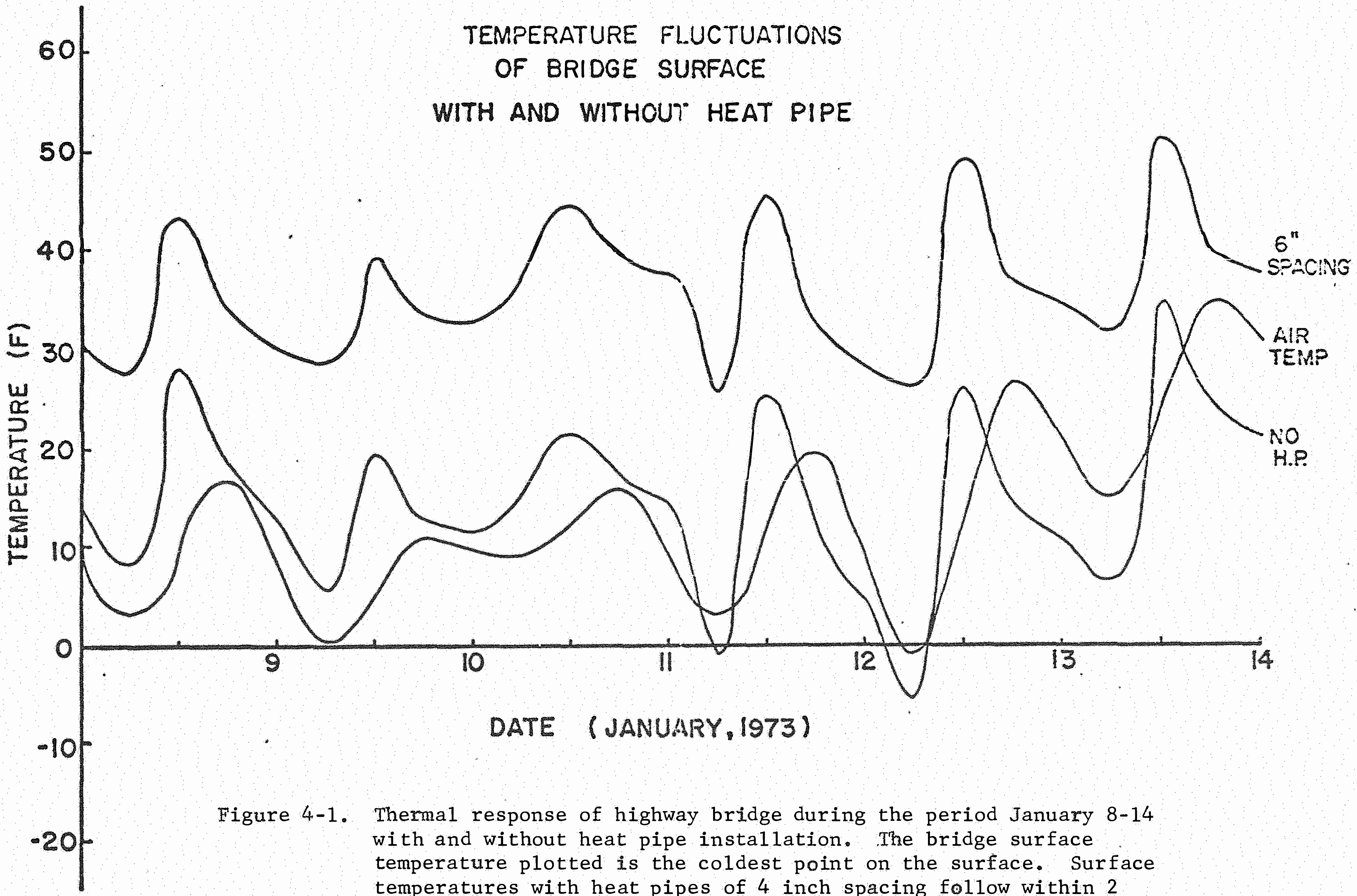


Figure 4-1. Thermal response of highway bridge during the period January 8-14 with and without heat pipe installation. The bridge surface temperature plotted is the coldest point on the surface. Surface temperatures with heat pipes of 4 inch spacing follow within 2 degrees the results shown here for 6 inch spacing, but are omitted for clarity.

Freeze-thaw characteristics for the total month have results summarized in Table 4-2. These results are based on the minimum temperature at the midpoint between the heat pipes. By using heat pipes in the bridge, the surface freeze-thaw cycles based on 32°F have been reduced by 66% for 4 inch spacing when compared to the bridge without heat pipes and by 58% for 6 inch spacing. No surface freeze-thaw cycles based on 25°F occur for the bridge with either of the heat pipe spacings, while 12 occur for the bridge without heat pipes. The freeze-thaw characteristics at 1 inch depth show penetration of cold temperatures in the bridge deck. There were no freeze-thaw cycles occuring at 1 inch or deeper for the bridge with either of the heat pipe spacings. However, without the heat pipe, 11 occur for a freeze based on 32°F, and 9 occur for a freeze based on 25°F. Table 4-2 also shows the time that the surface is below 32°F or 25°F.

Based on the above results, a 6 inch heat pipe spacing is recommended for use in bridges. The small increase of performance in freeze-thaw cycles and surface freezing for the 4 inch heat pipe spacing is not great enough to merit the extra cost for the additional heat pipes required to heat a bridge deck. More detailed examination of a particular installation might result in adjustments in this spacing based on economic considerations, more extensive (or different) meteorological data, and/or particular bridge design characteristics.

FREEZE-THAW CYCLES

	NO HEAT PIPE	4" HEAT PIPE SPACING	6" HEAT PIPE SPACING
SURFACE < 32 F	12	4	5
SURFACE < 25 F	12	0	0
1" DEPTH < 32 F	11	0	0
1" DEPTH < 25 F	9	0	0

HOURS FROZEN

	NO HEAT PIPE	4" HEAT PIPE SPACING	6" HEAT PIPE SPACING
SURFACE < 32 F	298	23	38
SURFACE < 25 F	211	0	0

Table 4-2. Predicted effect of heat pipe installation on number of freeze-thaw cycles and time that bridge surface is below freezing. Values shown are totals for the month of January, 1973.

Heat Pipe Design

In the previously discussed thermal model, it was assumed that the heat pipe was capable of maintaining its condenser end at 50°F. In this section, we will consider the design of a heat pipe which is capable of this performance.

The heat pipe performance will be determined by the physical dimensions of the pipe itself and by the thermophysical properties of the working fluid. As discussed in the earlier section on heat pipe theory, ammonia has been selected as the working fluid for this installation primarily because its wetting characteristics are not as sensitive to contaminants as those of water, the other possible working fluid. Further, in an ammonia heat pipe, the working fluid will be above ambient pressure (89 psi), whereas in a water heat pipe, the working fluid would be below atmospheric pressure (0.18 psi). It is felt that fabrication and maintenance of the pressurized heat pipe will be easier than the sub-atmospheric heat pipe.

Several of the physical dimensions of the heat pipe are set by the assumptions made in the bridge thermal model. The heat pipe has an outside diameter of 2 inches. (The possible effects of a smaller diameter heat pipe will be discussed later). Since the bridge deck surface is nearly horizontal, the heat pipe is assumed to be also horizontal. Any inclination of the heat pipe (e.g. the evaporator end as it goes into the ground) will only tend to increase the heat capacity, thus this is a pessimistic assumption.

For this analysis, we are allowing a 2°F drop in temperature between the evaporator and condenser ends of the heat pipe. Since we previously assumed the condenser was at 50°F, this implies that the evaporator is at 52°F. This should be a very pessimistic representation since the minimum ground temperature should be above 52°F in nearly every location in the state. For example, in Oklahoma City, the average ground temperature at 10 ft depth would be about 60°F. Even allowing for some cooling of the ground and for some contact resistance between the soil and the evaporator, the evaporator should be well above 52°F. Further, it should be mentioned that on warm, sunny days the heat pipe actually reverses its direction and the ground is re-warmed around the buried end of the heat pipe. Thus some of the sensible heat removed from the ground on cold days is restored even during this cold sample month of January,1973, so that ground cooling should not be significant. A more accurate estimation of this temperature for the particular installation being considered would be appropriate: a higher ground temperature (thus a higher temperature difference between evaporator and condenser) would permit a much longer bridge span to be heated. This temperature should be accurately estimated for any proposed bridge installation.

The walls of the heat pipe were assumed to be 1/4 inch thick. Thinner walls would increase the heat capacity of the heat pipe, thus this is a pessimistic estimate. However, thinner walls should only be specified when an analysis which considers the structural role of the heat pipes shows that the thinner walls are structurally sufficient.

With these assumptions about the heat pipe design, the performance of several wick types was analyzed. A heat pipe with screen-covered grooves (Figure 2-2) gave the best performance. Figure 5-1 shows typical performance for such a heat pipe with 50 grooves 1/16 inch wide by 1/16 inch deep covered with one layer of 200 X 200 steel mesh. This graph shows that for this wick, with a 2°F drop between evaporator

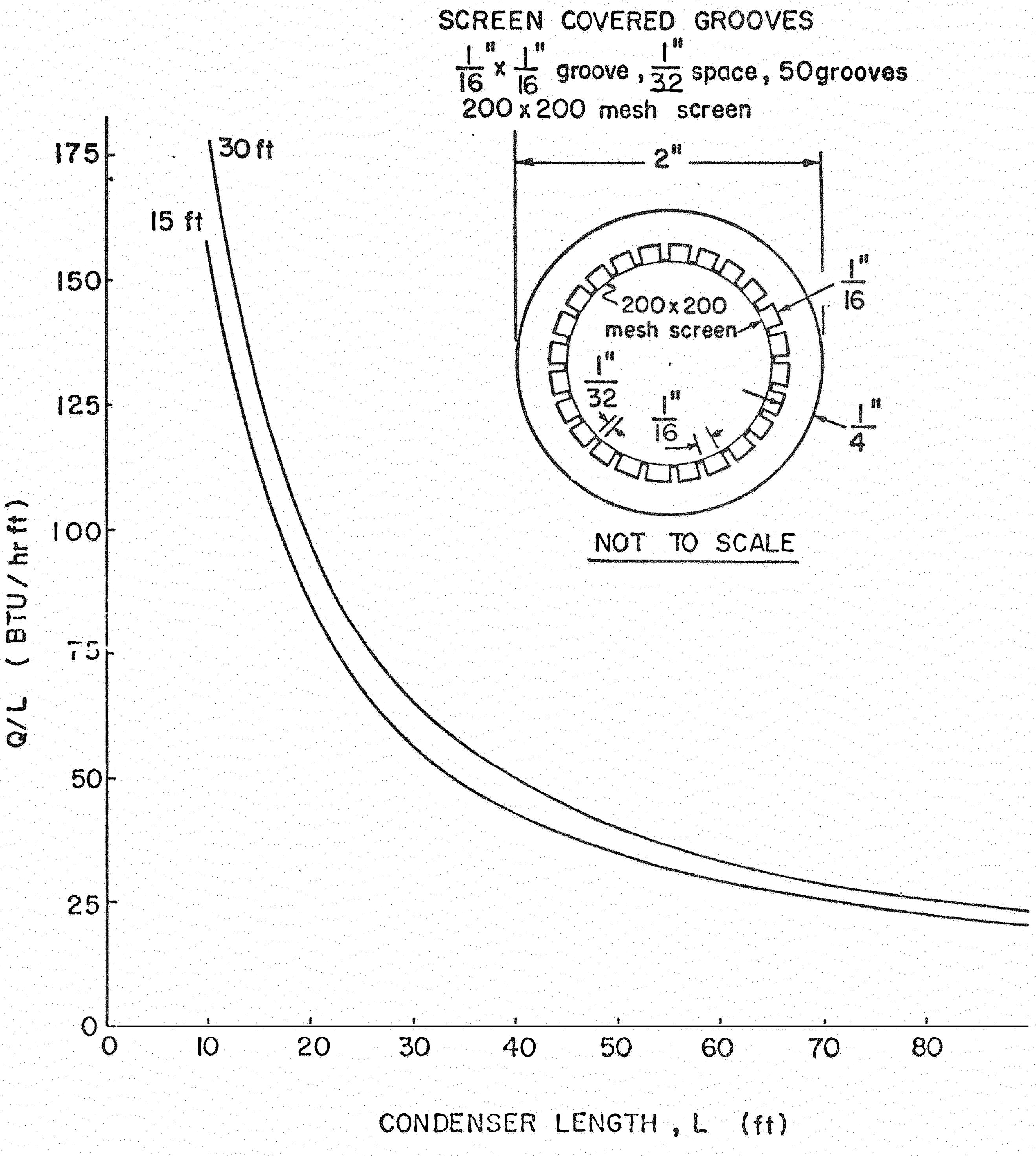


Figure 5-1. Heat delivered per foot of condenser as a function of condenser length for a horizontal, screen covered groove heat pipe with evaporator length of 15 and 30 ft.

and condenser, as the condenser length is increased (i.e. as the bridge span is increased) the heat delivered per foot of condenser falls. This non-linear fall-off in heat delivered per foot is due to the fact that, as the condenser length is increased, the total heat transferred by the heat pipe remains about constant. Thus, the heat delivered per foot of condenser is approximately inversely proportional to the length of the condenser. Figure 5-1 also shows that as the evaporator length is increased from 15 ft to 30 ft, the heat transfer capacity per foot of condenser (again allowing a 2°F drop) increases slightly. The increase in heat transfer with increase in evaporator length is relatively small because all of these pipes are operating well below their maximum capacity anyway.

For very short condensers with a 2°F temperature the open groove heat pipe performs as well as the one with screen covered grooves. However, due to its lower ability to return fluid by capillary action, it reaches its maximum heat capacity with a condenser length of only about 8 feet. Thus the open groove wick design is not practical for bridge installations unless it can be angled such that gravity can assist in the liquid return, thus increasing its maximum heat capacity.

Studies of heat pipes with wrapped screen wicks showed them to have significantly lower heat transfer capability for a given temperature drop. Thus these wicks will not be useful in highway bridge applications, since such a heat pipe would not be capable of warming a bridge of reasonable span. However it should be pointed out that mathematical modeling of a wrapped screen heat pipe can be inaccurate because the performance is very sensitive to the tightness of wick wrap during fabrication. Accurate estimates of the performance of such heat pipes are best made by experiment.

The precise number and geometry of grooves was not optimized in this study. Such optimization can really only be carried out if the economics and technology of fabrication are known. It was observed here that the condenser length (thus span length) was nearly directly proportional to the number of grooves. A larger number of narrow grooves transferred more heat for a given temperature drop than fewer, wider grooves. Thus it would be desirable from a heat transfer standpoint to design the heat pipe with as many narrow grooves as possible.

Length of Bridge Span

The results of the previous bridge thermal model can be combined with the analysis of heat pipe performance to determine the bridge span length which can be accommodated for a particular heat pipe. Table 6-1 shows that during the month of January, 1973, the maximum amount of heat which would flow from a 50°F heat pipe is always less than 60 Btu/hrft with 6 inch spacing. From Figure 5-1, it is seen that for this heat "demand" by the bridge, the screen covered groove heat pipe can have a maximum condenser length of about 25 ft for a 15 ft evaporator and about 30 ft for a 30 ft evaporator. Since this would correspond to one half the distance across the bridge, this result implies that a bridge 50 to 60 ft long could be heated by heat pipes with this spacing.

For heat pipes with 4 inch spacing, the maximum heat demand is always less than 40 Btu/hrft. From Figure 5-1 this corresponds to a condenser length of about 40 feet with a 15 ft evaporator and about 50 ft with a 30 ft evaporator. This yields span lengths of 80 and 100 ft respectively.

There are several methods available to increase this span length. A straightforward design technique for the case of a bridge that is supported in the center would be to bring additional heat pipes up through the center support. In this case the 30 ft condenser would only need to heat 1/4 of the span. Thus with 6 inch spacing a 120 ft bridge would be heated. It would also be possible to bring two sets of 6 inch spaced heat pipes through each end of the bridge. One set would be insulated and remain under the concrete until 30 ft across the bridge at which point it would enter the concrete for 30 ft. The other set of heat pipes would heat the first 30 ft. Thus these two sets would heat a 60 ft half span.

Date →

6" SPACING

Heat flow (Btu/hrft)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		TOTAL
0 - 5	2		2										2	7	1			2	1	6	8	5	1	5	14	13			2	2	4	0-5	77
5 - 10		11	7	4								3	2	2	6	3		4	2		8	8	1	4	6	4	7	2		1	3	5-10	95
10 - 15	6	6	7	3						3	2	2	2	1	3	3		2	3		4	6	6	1	4		5	3	1			10- 15	73
15 - 20	4	7	3	1				1		4	3	1		6	2	3		3	2		4	5	3	1			5	1	7	1		15-20	67
20-25	1			9		6	3	3		7		1	7		5								2	3			7	1	2			20-25	57
25- 30	3			5	19	9	4	2	4	9	2	2	3										4	3				1	1	2		25- 30	73
30 - 35	4			2	5	9	8	1	3	1		8	1										1					7	3	3		30-35	56
35-40							8	7	10		6		3															5	3	2		35 - 40	44
40-45							1	3	2		2		3															4				40-45	15
45-50								4	5		4	3																				45-50	16
50- 55								3			4	4																				50-55	11
55 - 60											1																					55-60	1

Date →

4" SPACING

Heat flow (Btu/hrft)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		TOTAL
0 — 5	3	3	3	2								3	4	8	2	1		3	2	6	12	7	1	7	17	16			2	4	7	0— 5	113
5 — 10	6	14	11	4						3	2	2	2	2	9	4		4	3		7	11	7	3	7	8	11	4	1			5 — 10	125
10 —15	4	7	5	3				3		5	3	2		6	2	3		3	3		5	6	4	2			8	2	8	1		10 —15	85
15 —20	3			12	12	12	6	2	3	15	1		10		4								3	5			5	2	2	1		15 - 20	98
20 - 25	5			3	12	12	10	2	4	1	2	10	1										3					7	4	4		20 - 25	80
25- 30							8	8	10		6		6															5	2	2		25-30	47
30 - 35								5	7		5	3																4				30- 35	24
35 —40								4			5	4																				35- 40	13
40 - 45																																40 -45	
45- 50																																45 - 50	
50 - 55																																50 - 55	
55 - 60																																55 - 60	

Table 6-1. Heat flows from a 50^{o}F condenser to the bridge deck for each day of the sample month. Under each date is indicated the number of hours for each range of heat flow. Data are given for both 6 and 4 inch heat pipe spacing.

A more direct method to supply more heat is simply to increase the temperature difference between the evaporator and condenser. The heat supplied is approximately directly proportional to this temperature difference. Thus if the evaporator temperature in the ground is 54°F instead of 52°F, then the condenser length can be increased to 60 ft (total span increased to 120 ft) with the 6 inch spacing.

Of course this discussion is somewhat misleading because in reality this increase in ΔT is exactly what would happen anyway in an actual installation. For example, let us assume the evaporator is at a constant 52°F and this screen-covered-groove heat pipe is installed with a 50 ft condenser,30 ft evaporator, and 6 inch heat pipe spacing. For our sample month of January, 1973, this heat pipe would supply enough heat (up to 45 Btu/hrft) to keep the condenser at 50°F (or higher) during all but 28 hours (from Figure 6-1). During this time the heat pipe would not transmit enough heat to keep the condenser at 50°F, thus the condenser temperature would drop to 48°F or 49°F until equilibrium is again established between the heat "demand" of the bridge and the heat supplied by the heat pipe. During these hours, the slightly lower heat pipe temperature would have little effect on the surface icing condition or in the number of freeze-thaw cycles since the surface is below 32°F for this time anyway (Figure 4-1).

This discussion simply points out one of the limitations of our model: we have decoupled the heat pipe performance (particularly the temperature drop between evaporator and condenser) from the thermal response of the bridge. In the actual situation these are of course coupled. This is not a serious limitation of this model, however, as long as the heat pipe is operating in a regime well below its maximum capacity. In these models with 6 inch spacing, the assumption that the heat pipe condenser is at 50°F is accurate for condenser lengths up to 30 ft. For a condenser length of up to 50 ft the 50°F assumption would be accurate except for 28 hours during which it will be at most 2°F too high.

Heat pipes with an outside diameter less than 2" might be desirable for economic and/or structural reasons. These studies have suggested that such heat pipes could work. However, of course, they would not deliver as much heat to the bridge as the 2" heat pipe, thus somewhat more freeze-thaw cycles could be expected. The limitation with smaller heat pipes is probably not so much their smaller heat carrying capacity: the studies with the 2" heat pipes suggest that the heat pipe would very seldom operate near its limit in these applications. Furthermore, maximum capacity could be greatly increased by arching the bridge slightly so that the condenser would be inclined at 2-3°. The smaller diameter heat pipes would not perform as well primarily because a smaller surface of the concrete would be being heated to (approximately) 50°F. This could be compensated for by using closer pipe spacing (such as 4 inches). The extent to which this performance would be degraded by the smaller diameter heat pipe can be checked for any specific smaller diameter by using the bridge thermal-response model.

Conclusions and Recommendations

Section 7

The results of this study indicate that heat pipes can be successfully used to both reduce the freeze-thaw cycles of bridges and to reduce the time during which the surface of the bridge deck is below freezing. Though this study was necessarily limited to a general model using limited meteorological data, similar results should be realized in more specific studies.

It appears that heat pipes can be installed in a bridge deck to achieve any desired level of reduction in freeze-thaw cycles and time of surface freezing. There is enough design flexibility through choice of wick, inclination of the condenser, alternate routing paths, and heat pipe diameter and spacing that, technically, any realistic performance level could be achieved. The design choices should be strongly influenced by economic considerations: it will probably not be economical to design to prevent all freezing. Thus the consideration involves weighing the additional cost vs. the additional benefit of incremental heat inputs. The computer models presented here should provide the necessary tools to perform these optimization studies for particular proposed installations once the cost of the installation and benefits of freeze reduction are quantified.

The following are recommendations for future work which, by building on this study, can bring closer to practice the benefits indicated here:

(1) Laboratory verification of the heat pipe performance that was mathematically predicted in this report, including effects of inclination and/or bends, effects of contact resistance at evaporation and condenser, and wick design.

(2) Analysis of the way(s) in which the heat pipes will fit into the structural design of the bridge including structural constraints placed on heat pipe wall thickness, outside diameter, and spacing.

(3) Development of a plan for realistic field fabrication of a heat pipe system for bridge installation.

(4) Assessment of possible corrosion problems with the installed heat pipes.

(5) Selection and analysis, using the computer models of this study, of a specific bridge site which might be used later for field test.

(6) Full-scale test installation of heat pipes in a bridge deck. So that this bridge can serve as its own control, heat pipes might be installed in only one half of the span. The longer that this test installation is monitored, the better correlation that can be made between expense of installation vs. savings in bridge deck maintenance.

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APPENDIX A

A Computer Program for the Analysis of Ambient Temperature Heat Pipes

```
$JOB          ,KP=26
C     PROGRAM HETPIP
   20 FORMAT (///42H PERFORMANCE OF LOW-TEMPERATURE HEAT PIPES
      WRITE (6,20)
    1 FORMAT (I5
   11 FORMAT (E15.6
   12 FORMAT (2E15.6
   13 FORMAT (3E15.6
   14 FORMAT (4E15.6
   15 FORMAT (5E15.6
      READ (5,11) GRF
      READ (5,1) ND
      DO 101 MD = 1,ND
      READ (5,1) NTHP
      READ (5,12) RG,RI
      DG = 2. * RG
      READ (5,14) ZE,ZA,ZC,PSI
      READ (5,12) THETA, CONK
      READ (5,1) NQ
      READ (5,12) QI,DQ
      IF(NTHP-1) 35,31,35
   35 IF(NTHP-2) 33,32,33
   31 READ (5,13) RF,C,EPSIL
      READ (5,12) AREA, PERI
      RE = 2. * AREA/PERI
      GO TO 34
   32 READ (5,13) GRVN,WIDTH,DEPTH
      RE = WIDTH
      GO TO 34
   33 READ(5,13) GRVN,WIDTH,DEPTH
      READ (5,12) AREA, PERI
      RE = 2.*AREA/PERI
   34 READ(5,1) NP
   21 FORMAT (//72H         ZE             ZA              ZC
     1PSI            THETA
      WRITE (6,21)
      WRITE (6,15) ZE,ZA,ZC,PSI,THETA
      DO 102 MP = 1,NP
      READ (5,13) TSAT,PSAT,CPF
      READ (5,14) DENF,VSF,CDF,SFT
      READ (5,13) HFG,DENG,VSG
      DPC = 2.*SFT*COS(THETA)/RE
      DPS = DENF*GRF*(ZE+ZA+ZC)*SIN(PSI)
      IF(NTHP-1) 45,41,45
   45 IF(NTHP-2) 43,42,43
   41 DPF =C*VSF*(ZE+2.*ZA+ZC)/(2.*3.14159*DENF*HFG*EPSIL*RF*RF)
      DPF = DPF/(RI*RI-RG*RG)
      GO TO 44
   42 DPF=9.*VSF*(WIDTH**2+4.*DEPTH**2)*(ZE+2.*ZA+ZC)
      DPF =DPF/(5.*GRVN*DENF*HFG*(WIDTH**3)*(DEPTH**3))
      GO TO 44
   43 DPF=36.*VSF*(WIDTH**2+DEPTH**2)*(ZE+2.*ZA+ZC)
      DPF=DPF/(5.*GRVN*DENF*HFG*(WIDTH**3)*(DEPTH**3))
   44 DPGZ=32./(3.14159*DENG*HFG*HFG*DG**4)
      DPGX=4.*VSG/(3.14159*DENG*HFG*DG**4)
      DO 103 M=1,5
      IF (M-1) 52,51,52
   51 DPG1=DPGX*(21.*ZE+32.*ZA)
      GO TO 53
   52 DNM=EXP(0.8*ALOG(4.7*QWL/(3.14159*HFG*ZE*VSG)))
```

```
      DNM=0.0481 + 0.0494/DNM
      DPG1=DPGX*(ZE/DNM+32.*ZA)
   53 IF(DPS-DPC) 61,60,60
   60 QWL = 0
      GO TO 103
   61 AQ=DPG2
      BQ=(DPF+DPG1)/2.
      CQ=DPS-DPC
  103 QWL=(-BQ+SQRT(BQ*BQ-AQ*CQ))/AQ
      IQ=NQ+1
      DO 104 MQ=1,IQ
      IF(MQ-1) 72,71,72
   71 Q=QWL
      GO TO 73
   72 Q=Q+DQ
   73 DTGE=EXP(0.8*ALOG(4.7*Q/(3.14159*ZE*HFG*VSG)))
      DTGE=2.*Q*ZE*VSG/(3.14159*DENG*(DG**4)*(0.0481+0.0494/DTGE)*HFG)
      DTGA=128.*VSG*Q*ZA/(3.14159*DENG*(DG**4)*HFG)
      DTGC=32.*Q*Q/(3.14159*DENG*HFG*HFG*(DG**4))
      DTGE=TSAT*DTGE/(DENG*HFG)
      DTGA=TSAT*DTGA/(DENG*HFG)
      DTGC=TSAT*DTGC/(DENG*HFG)
      IF(NTHP-1) 82,81,82
   81 CDE=CDF*(CDF+CDWK-(1.-EPSIL)*(CDF-CDWK))/(CDF+CDWK+(1.-EPSIL)*(CDF
     1-CDWK))
      DTWE=Q*(RI-RG)/(3.14159*CDE*ZE*(RI+RG))
      DTWC=Q*(RI-RG)/(3.14159*CDE*ZC*(RI+RG))
      GO TO 83
   82 EPP=GRVN*WIDTH/(3.14159*(RI+RG))
      CDE=EPP*CDF+(1.-EPP)*CDWK
      DTWC=Q*(RI-RG)/(3.14159*CDE*ZC*(RI+RG))
      DTWE=(EXP(5.4*DEPTH/WIDTH)-EXP(-5.4*DEPTH/WIDTH))/(EXP(5.4*DEPTH
     1/WIDTH)+EXP(-5.4*DEPTH/WIDTH))
      DTWE=0.185*Q*DTWE/(GRVN*ZE*CDF)
   83 TE=TSAT-DTGE+DTWE
      TC=TSAT-2.*DTGE-DTGA-DTGC-DTWC
      DTEC=DTGE+DTGA+DTGC+DTWC+DTWE
   22 FORMAT (//69H      TSAT              QMAX              TE              TC
     1              DT
      IF(MQ-1)92,91,92
   23 FORMAT (/53H      Q              TE              TC              DT
   91 WRITE (6,22)
      WRITE (6,15) TSAT,Q,TE,TC,DTEC
      WRITE (6,23)
      Q=QI-DQ
      GO TO 93
   92 WRITE (6,14) Q,TE,TC,DTEC
      IF(DTEC.GE.1.11)GO TO 101
   93 CONTINUE
  104 CONTINUE
  102 CONTINUE
  101 CONTINUE
      CALL EXIT
      STOP
      END

   $EXEC
```

APPENDIX B

A Computer Program to Model The Thermal Response of A Highway Bridge Heat Pipe Installation

```
$JOB            ,KP=29
C
C          TWO-DIMENSIONAL UNSTEADY STATE HEAT CONDUCTION IN A ROAD SLAB
C          WITH EMBEDDED HEAT PIPE AND WITH HEAT CONVECTION & RADIATION
C          FROM IT'S EXPOSED SURFACES.  SOLVED BY THE IMPLICIT ALTERNATING
C          DIFFERENCE (I.A.D.) METHOD.
C
C
C
C VARIABLE AND CONSTANT NAMES FOR THE MAIN PROGRAM ARE.....
C
C          A     -TRAILING COEFFICIENT OF TRIDIAGONAL MATRIX, NON-DIMENSIONAL
C          ABSORP-SOLAR ABSORPTIVITY OF CONCRETE
C          AIRMAX-CURRENT DAY'S MAXIMUM AIR TEMPERATURE (F)
C          AIRMIN(1)-CURRENT DAY'S MINIMUM AIR TEMPERATURE (F)
C          AIRMIN(2)-FOLLOWING DAY'S MINIMUM AIR TEMPERATURE (F)
C          ALPHA -THERMAL DIFFUSIVITY (FT2/HR)
C          AMAX  -MAXIMUM AIR TEMPERATURE FOR THE CURRENT HALF SINE WAVE OF THE
C                 TEMPERATURE VARIATION (F)
C          AMIN  -MINIMUM AIR TEMPERATURE FOR THE CURRENT HALF SINE WAVE OF THE
C                 TEMPERATURE VARIATION (F)
C          B     -CENTER COEFFICIENT OF TRIDIAGONAL MATRIX, NON-DIMENSIONAL
C          BLOSS -BOTTOM HEAT LOSS OF THE BRIDGE AS   OF THE CONVECTIVE HEAT LOSS
C                 OF THE UPPER SURFACE
C          BO    -BIOT NUMBER
C          BOCON -BIOT NUMBER WITH ONLY CONVECTIVE HEAT TRANSFER COEFFICIENT USED
C                 IN ITS DETERMINATION
C          BOLOW -BIOT NUMBER OF BOTTOM BRIDGE DECK SURFACE
C          BORAD -BIOT NUMBER WITH ONLY RADIATIVE HEAT TRANSFER COEFFICIENT USED
C                 IN ITS DETERMINATION
C          C     -LEADING COEFFICIENT OF TRIDIAGONAL MATRIX, NON-DIMENSIONAL
C          CLOCK -TIME ELAPSED (HR)
C          CON   -THERMAL CONDUCTIVITY OF CONCRETE (BTU/HR.FT.F)
C          CONST -A CONSTANT,DETERMINED BY GEOMETRY, ARISING FROM THE NON-UNIFORM
C                 GRID SPACING NEAR THE HEAT PIPE
C          COVER -CLOUD COVER OF SKY = 1 IF CLEAR
C                                    = 0 IF CLOUDY
C          D     -COLUMN MATRIX
C          DALANG-DAILY LANGLEYS OF SOLAR RADIATION
C          DEPTH -THICKNESS OF CONCRETE OF BRIDGE DECK (FT)
C          DEPTH1-THICKNESS OF CONCRETE OF BRIDGE DECK (IN)
C          DTAU  -NON-DIMENSIONAL TIME INCREMENT--FOURIER NUMBER
C          DX    -NON-DIMENSIONAL GRID SPACING
C          EMISS -EMISSIVITY OF CONCRETE
C          F     -NON-DIMENSIONAL CONSTANT = 2(1/RATIO-1)
C          F1    -NON-DIMENSIONAL CONSTANT = 2(1/RATIO+1)
C          FTAIR -AIR TEMPERATURE (F)
C          FTEMP -AVERAGE SURFACE TEMPERATURE USED IN DETERMINING RADIATIVE
C                 TRANSFER COEFFICIENT (F)
C          FTPIPE-HEAT PIPE TEMPERATURE (F)
C          H     -OVERALL HEAT TRANSFER COEFFICIENT FOR CONVECTION AND RADIATION
C                 (BTU/HR.FT2.F)
C          HC    -CONVECTIVE HEAT TRANSFER COEFFICIENT (BTU/HR.FT2.F)
C          HR    -RADIATIVE HEAT TRANSFER COEFFICIENT (BTU/HR.FT2.F)
C          ICOUNT-COUNTER WHICH DETERMINES THE NUMBER OF TIME INCREMENTS BETWEEN
C                 IFREQ TIME STEPS
C          IDAY  -DAY OF THE MONTH ( = 0 FOR PROGRAM TO STOP.
C          IFREQ -NUMBER OF TIME INCREMENTS BETWEEN EACH PRINT OUT
C          IGRID -STARTING SURFACE GRID POINT IN THE X-DIRECTION
C          M     -NUMBER OF GRID POINTS MINUS ONE ALONG Y-AXIS
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```
C          N     -NUMBER OF GRID POINTS ALONG X-AXIS
C          NP1   -NUMBER OF GRID POINTS PLUS ONE ALONG X-AXIS
C          QPIPE -HEAT TRANSFERRED FROM HEAT PIPE TO BRIDGE (BTU/HR.FT)
C          QSKYMX-MAXIMUM INCIDENT RADIATION FROM SKY AND SUN (BTU/HR.FT2)
C          RATIO -FOURIER NUMBER DIVIDED BY NON-DIMENSIONAL GRID SPACING
C          RLGTH -CHARACTERISTIC LENGTH OF THE BRIDGE (FT)
C          SPACE -GRID SPACING (IN)
C          STEMP -AVERAGE BRIDGE SURFACE TEMPERATURE (R)
C          T     -NON-DIMENSIONAL BRIDGE TEMPERATURE AT THE START OF THE FIRST
C                 HALF TIME INCREMENT
C          T1    -INITIAL NON-DIMENSIONAL CONCRETE TEMPERATURE
C          TAIR  -NON-DIMENSIONAL AIR TEMPERATURE
C          TAU   -NON-DIMENSIONAL TIME
C          TEFF  -EFFECTIVE NON-DIMENSIONAL AIR TEMPERATURE FOR A CLEAR SKY
C          TF    -BRIDGE TEMPERATURE (F)
C          TIME  -TIME STEPS OR INCREMENTS (MIN)
C          TPIPE -NON-DIMENSIONAL PIPE TEMPERATURE
C          TPRIME-COLUMN OR ROW OF TEMPERATURES AS FOUND IN SUBROUTINE TRIDAG AND
C                 TRANSFERRED TO MAIN PROGRAM, NON-DIMENSIONAL
C          TRANCO-NAME OF SUBROUTINE USED TO SOLVE FOR TRANSFER COEFFICIENTS AND
C                 EFFECTIVE AIR TEMPERATURE
C          TRIDAG-NAME OF SUBROUTING USED IN SOLVING TRIDIAGONAL MATRIX FOR BRIDGE
C                 DECK TEMPERATURES
C          TSTAR -NON-DIMENSIONAL BRIDGE TEMPERATURE AT THE START OF THE SECOND
C          VEL1  -WIND SPEED (MPH)
C          W     -ANGULAR FREQUENCY OF AIR TEMPERATURE VARIATION (RADIANS/HR)
C          WIDTH -CENTER-TO-CENTER DISTANCE OF HEAT PIPE SPACING (IN)
C          WIDTH1-HALF THE CENTER-TO-CENTER DISTANCE OF THE HEAT PIPE SPACING (IN)
C
C
       DIMENSION A(30),B(30),C(30),D(30),T(30,20),TSTAR(30,20),TPRIME(30)
       DIMENSION TF(30,20), AIRMIN(2)
C
C      .....READ AND CHECK INPUT PARAMETERS.....
       READ(5,100)ALPHA,TIME,N,M,IFREQ
       READ(5,101)FTPIPE
       READ(5,102)CON,EMISS,ABSORP
       READ(5,104)VEL1,RLGTH
       READ(5,105)AIRMAX,AIRMIN(1),AIRMIN(2),DALANG
       READ(5,106)IGRID,COVER
       READ(5,107)PLOSS,SPACE
       READ(5,108)IDAY
       W=0.2618
       TPIPE=1.0
       T1=AIRMAX/FTPIPE
       AMAX=AIRMAX
       NP1=N+1
       DEPTH1=(NP1-IGRID)*SPACE
       WIDTH1=(M-2)*SPACE
       DEPTH=((NP1-IGRID)*SPACE)/12.0
       WIDTH=2.0*WIDTH1
       DX=SPACE/DEPTH1
       DTAU=(ALPHA*TIME)/((DEPTH*DEPTH)*60.0)
       RATIO=DTAU/(DX*DX)
       QSKYMX=0.57929*DALANG
       WRITE(6,200)DTAU,DX,RATIO,N,M,IFREQ
       WRITE(6,203)FTPIPE
       WRITE(6,204)CON
       WRITE(6,208)EMISS,ABSORP
       WRITE(6,212)IGRID,RLGTH
```

```
      WRITE(6,213)BLOSS,SPACE,DEPTH1,WIDTH1
C
C     .....SET INITIAL TEMPERATURE VALUES.....
      DO 2 J=2,M
      DO 2 I=IGRID,NP1
      T(I,J)=T1
    2 TSTAR(I,J)=T1
C
C     .....VARIABLES REQUIRED FOR CALCULATION OF
C               COEFFICIENT ARRAYS A, B, AND C.....
      F=2.0*(1.0/RATIO-1.0)
      F1=2.0*(1.0/RATIO+1.0)
      CONST=(1.0/SPACE)-SQRT(3.0)
C
C     .....PERFORM CALCULATIONS OVER SUCCESSIVE TIME-STEPS.....
      ICOUNT=0
      TAU=0.0
      TAU=TAU+DTAU
      CLOCK=(TAU*DEPTH*DEPTH)/ALPHA
    4 ICOUNT=ICOUNT+1
C
C     .....FIND HEAT TRANSFER COEFFICIENTS AND EFFECTIVE
C               SKY TEMPERATURE.....
      AMIN=AIRMIN(1)
      IF(CLOCK.GT.18.0)AMIN=AIRMIN(2)
      IF(CLOCK.GT.6.0)AMAX=AIRMAX
      FTAIR=(AMAX+AMIN)/2.0-((AMAX-AMIN)/2.0)*SIN(W*CLOCK)
      TAIR=FTAIR/FTPIPE
      TF(IGRID,2)=T(IGRID,2)*FTPIPE
      TF(IGRID,M)=T(IGRID,M)*FTPIPE
      FTEMP=(TF(IGRID,2)+TF(IGRID,M))/2.0
      CALL TRANCO(VEL1,RLGTH,FTAIR,FTEMP,EMISS,H,HC,HR,COVER,TEFF,FTPIPE
     1,ABSORP,CSKYMX,CLOCK)
      IF(ICOUNT.NE.IFREQ)GO TO 66
      WRITE(6,201)CLOCK,FTAIR
      WRITE(6,211)HC,H
   66 BD=(H*SPACE)/(CON*12.0)
      BDCON=(HC*SPACE)/(CON*12.0)
      BDRAD=(HR*SPACE)/(CON*12.0)
      BFLOW=(BLOSS*HC*SPACE)/(CON*12.0)
C
C
C     .....COMPUTE TEMPERATURES AT END OF HALF
C               TIME INCREMENT (IMPLICIT BY COLUMNS).....
      DO 20 J=2,M
      DO 19 I=IGRID,NP1
      IF(I.EQ.IGRID.AND.J.EQ.2)GO TO 50
      IF(I.EQ.IGRID.AND.J.EQ.M)GO TO 51
      IF(I.EQ.IGRID)GO TO 56
      IF(I.EQ.NP1.AND.J.EQ.2)GO TO 53
      IF(I.EQ.NP1.AND.J.EQ.M)GO TO 54
      IF(I.EQ.NP1)GO TO 70
      IF(J.GT.5)GO TO 16
      IF(J.EQ.2)GO TO 5
      GO TO 6
    5 IF(I.EQ.9)GO TO 9
      IF(I.GE.10.AND.I.LE.14)GO TO 10
      IF(I.EQ.15)GO TO 11
      GO TO 16
    6 IF(J.EQ.3)GO TO 7
```

```
      GO TO 6
    7 IF(I.EQ.10)GO TO 12
      IF(I.EQ.14)GO TO 13
      IF(I.GT.10.AND.I.LT.14)GO TO 10
      GO TO 17
    8 IF(J.EQ.4.AND.I.EQ.11)GO TO 14
      IF(J.EQ.4.AND.I.EQ.12)GO TO 10
      IF(J.EQ.4.AND.I.EQ.13)GO TO 15
      IF(J.EQ.5.AND.I.EQ.12)GO TO 44
      GO TO 17
C
C     .....COMPUTE SURFACE COEFFICIENT ARRAYS.....
   50 D(I)=BOCON*TAIR+BORAD*TEFF+T(I,J+1)+(F/2.0)*T(I,J)
      GO TO 52
   51 D(I)=BOCON*TAIR+BORAD*TEFF+T(I,J-1)+(F/2.0)*T(I,J)
   52 A(I)=0.0
      B(I)=F1/2.0+BO
      C(I)=-1.0
      GO TO 19
   53 D(I)=BOLOW*TAIR+T(I,J+1)+(F/2.0)*T(I,J)
      GO TO 71
   54 D(I)=BOLOW*TAIR+T(I,J-1)+(F/2.0)*T(I,J)
      GO TO 71
   70 D(I)=BOLOW*TAIR+0.5*T(I,J+1)+(F/2.0)*T(I,J)+0.5*T(I,J-1)
   71 A(I)=-1.0
      B(I)=F1/2.0+BOLOW
      C(I)=0.0
      GO TO 19
   56 D(I)=BOCON*TAIR+BORAD*TEFF+0.5*T(I,J+1)+(F/2.0)*T(I,J)+0.5*T(I,J-1
     1)
      GO TO 52
C
C     .....COMPUTE COEFFICIENT ARRAYS FOR MATERIAL
C           DIRECTLY SURROUNDING HEAT PIPE.....
    9 D(I)=2.0*T(I,3)+F*T(I,2)+TPIPE
   35 A(I)=-1.0
      B(I)=F1
      C(I)=0.0
      GO TO 19
   14 D(I)=2.0*CONST*T(I,J+1)+2.0*(CONST+1.0)*(CONST/RATIO-1.0)*T(I,J)+
     12.0*TPIPE+CONST*(CONST+1.0)*TPIPE
      A(I)=-CONST*(CONST+1.0)
      B(I)=2.0*CONST*(CONST+1.0)*(1.0/RATIO+1.0)
      C(I)=0.0
      GO TO 19
   10 A(I)=0.0
      B(I)=0.0
      C(I)=0.0
      D(I)=0.0
      GO TO 19
   11 D(I)=2.0*T(I,3)+F*T(I,2)+TPIPE
   36 A(I)=0.0
      B(I)=F1
      C(I)=-1.0
      GO TO 19
   15 D(I)=2.0*CONST*T(I,J+1)+2.0*(CONST+1.0)*(CONST/RATIO-1.0)*T(I,J)+
     12.0*TPIPE+CONST*(CONST+1.0)*TPIPE
      A(I)=0.0
      B(I)=2.0*CONST*(CONST+1.0)*(1.0/RATIO+1.0)
      C(I)=-CONST*(CONST+1.0)
```

```
      GO TO 19
   12 D(I)=CONST*(CONST+1.0)*(0.5*TPIPE+(1.0/RATIO-1.0)*T(I,J)+0.5*T(I,J
     1+1))+TPIPE
      A(I)=-CONST
      B(I)=(CONST+1.0)*(CONST/RATIO+1.0)
      C(I)=0.0
      GO TO 19
   13 D(I)=CONST*(CONST+1.0)*(0.5*TPIPE+(1.0/RATIO-1.0)*T(I,J)+0.5*T(I,J
     1+1))+TPIPE
      A(I)=0.0
      B(I)=(CONST+1.0)*(CONST/RATIO+1.0)
      C(I)=-CONST
      GO TO 19
   44 D(I)=TPIPE+F*T(I,J)+T(I,J+1)
      GO TO 18
C
C     .....COMPUTE COEFFICIENT ARRAYS FOR REMAINING
C              PORTION OF SLAB.....
   16 IF(J.LT.M.AND.J.NE.2)GO TO 17
      IF(J.EQ.2) D(I)=2.0*T(I,3)+F*T(I,2)
      IF(J.EQ.M) D(I)=2.0*T(I,M-1)+F*T(I,M)
      GO TO 18
   17 D(I)=T(I,J-1)+F*T(I,J)+T(I,J+1)
   18 A(I)=-1.0
      B(I)=F1
      C(I)=-1.0
   19 CONTINUE
      CALL TRIDAG(IGRID,NP1,A,B,C,D,TPRIME,TPIPE)
      DO 20 I=IGRID,NP1
   20 TSTAR(I,J)=TPRIME(I)
C
C
C     .....COMPUTE TEMPERATURES AT END OF WHOLE
C              TIME INCREMENT (IMPLICIT BY ROWS).....
      DO 32 I=IGRID,NP1
      DO 31 J=2,M
      IF(I.EQ.IGRID.AND.J.EQ.2)GO TO 57
      IF(I.EQ.IGRID.AND.J.EQ.M)GO TO 59
      IF(I.EQ.NP1.AND.J.EQ.2)GO TO 61
      IF(I.EQ.NP1.AND.J.EQ.M)GO TO 62
      IF(I.EQ.IGRID)GO TO 63
      IF(I.EQ.NP1)GO TO 65
      IF(J.GT.5)GO TO 30
      IF(J.LT.3)GO TO 21
      GO TO 22
   21 IF(I.GE.10.AND.I.LE.14)GO TO 23
      IF(I.EQ.9)GO TO 40
      IF(I.EQ.15)GO TO 41
      GO TO 30
   22 IF(I.EQ.10.AND.J.EQ.3)GO TO 24
      IF(I.EQ.11.AND.J.EQ.3)GO TO 23
      IF(I.EQ.12.AND.J.EQ.3)GO TO 23
      IF(I.EQ.13.AND.J.EQ.3)GO TO 23
      IF(I.EQ.14.AND.J.EQ.3)GO TO 25
      IF(I.EQ.11.AND.J.EQ.4)GO TO 27
      IF(I.EQ.12.AND.J.EQ.4)GO TO 23
      IF(I.EQ.13.AND.J.EQ.4)GO TO 28
      IF(J.EQ.5.AND.I.EQ.12)GO TO 42
      GO TO 30
C
```

```
C     .....COMPUTE SURFACE COEFFICIENT ARRAYS.....
   57 D(J)=2.0*TSTAR(I+1,J)+(F-2.0*BO)*TSTAR(I,J)+2.0*BOCON*TAIR+2.0*BOR
     1AD*TEFF
   58 A(J)=0.0
      B(J)=F1
      C(J)=-2.0
      GO TO 31
   59 D(J)=2.0*TSTAR(I+1,J)+(F-2.0*BO)*TSTAR(I,J)+2.0*BOCON*TAIR+2.0*BOR
     1AD*TEFF
   60 A(J)=-2.0
      B(J)=F1
      C(J)=0.0
      GO TO 31
   61 D(J)=2.0*TSTAR(I-1,J)+(F-2.0*BOLOW)*TSTAR(I,J)+2.0*BOLOW*TAIR
      GO TO 58
   62 D(J)=2.0*TSTAR(I-1,J)+(F-2.0*BOLOW)*TSTAR(I,J)+2.0*BOLOW*TAIR
      GO TO 60
   63 D(J)=2.0*TSTAR(I+1,J)+(F-2.0*BO)*TSTAR(I,J)+2.0*BOCON*TAIR+2.0*BOR
     1AD*TEFF
   64 A(J)=-1.0
      B(J)=F1
      C(J)=-1.0
      GO TO 31
   65 D(J)=2.0*TSTAR(I-1,J)+(F-2.0*BOLOW)*TSTAR(I,J)+2.0*BOLOW*TAIR
      GO TO 64
C
C     .....COMPUTE COEFFICIENT ARRAYS FOR MATERIAL
C             DIRECTLY SURROUNDING HEAT PIPE.....
   23 A(J)=0.0
      B(J)=0.0
      C(J)=0.0
      D(J)=0.0
      GO TO 31
   42 D(J)=TSTAR(I-1,J)+F*TSTAR(I,J)+TSTAR(I+1,J)+TPIPE
   26 A(J)=0.0
      B(J)=F1
      C(J)=-1.0
      GO TO 31
   24 D(J)=2.0*CONST*TSTAR(I-1,J)+2.0*(CONST+1.0)*(CONST/RATIO-1.0)*TSTA
     1R(I,J)+2.0*TPIPE+CONST*(CONST+1.0)*TPIPE
   90 A(J)=0.0
      B(J)=2.0*CONST*(CONST+1.0)*(1.0/RATIO+1.0)
      C(J)=-CONST*(CONST+1.0)
      GO TO 31
   25 D(J)=2.0*CONST*TSTAR(I+1,J)+2.0*(CONST+1.0)*(CONST/RATIO-1.0)*TSTA
     1R(I,J)+2.0*TPIPE+CONST*(CONST+1.0)*TPIPE
      GO TO 90
   27 D(J)=CONST*(CONST+1.0)*(0.5*TSTAR(I-1,J)+(1.0/RATIO-1.0)*TSTAR(I,J
     1)+0.5*TPIPE)+TPIPE
   91 A(J)=0.0
      B(J)=(CONST+1.0)*(CONST/RATIO+1.0)
      C(J)=-CONST
      GO TO 31
   28 D(J)=CONST*(CONST+1.0)*(0.5*TSTAR(I+1,J)+(1.0/RATIO-1.0)*TSTAR(I,J
     1)+0.5*TPIPE)+TPIPE
      GO TO 91
   40 D(J)=TSTAR(I-1,J)+F*TSTAR(I,J)+TPIPE
      GO TO 37
   41 D(J)=TPIPE+F*TSTAR(I,J)+TSTAR(I+1,J)
      GO TO 37
```

```
C
C     .....COMPUTE COEFFICIENT ARRAYS FOR REMAINING
C          PORTION OF SLAB.....
   30 D(J)=TSTAR(I-1,J)+F*TSTAR(I,J)+TSTAR(I+1,J)
      IF(J.EQ.2)GO TO 39
      IF(J.EQ.M)GO TO 38
      A(J)=-1.0
      B(J)=F1
      C(J)=-1.0
      GO TO 31
   38 A(M)=-2.0
      B(M)=F1
      C(M)=0.0
      GO TO 31
   39 IF(I.GE.10.AND.I.LE.14)GO TO 31
   37 A(2)=0.0
      B(2)=F1
      C(2)=-2.0
   31 CONTINUE
      CALL TRIDAG(2,M,A,B,C,D,TPRIME,TPIPE)
      DO 32 J=2,M
   32 T(I,J)=TPRIME(J)
      IF(ICOUNT.NE.IFREQ)GO TO 34
      ICOUNT=0
C
C     .....CHANGE NON-DIMENSIONAL TEMPERATURES TO
C          DEGREES FAHRENHEIT.....
      DO 80 I=IGRID,NP1
      DO 80 J=2,M
   80 TF(I,J)=T(I,J)*FTPIPE
C
C     .....CALCULATE HEAT TRANSFER FROM THE HEAT PIPE.....
      QPIPE=2.0*CON*(0.5*(TF(10,2)-TF(9,2))+2.0*TF(10,3)-TF(9,3)-2.0*TF(
     110,4)+2.0*TF(11,4)-TF(11,5)+TF(12,4)-TF(12,5)+2.0*TF(13,4)-TF(13,5
     2)-2.0*TF(14,4)+2.0*TF(14,3)-TF(15,3)+0.5*(TF(14,2)-TF(15,2)))
      WRITE(6,214)QPIPE
C
C     .....PRINT TEMPERATURES THROUGHOUT THE QUADRANT.....
      WRITE(6,215)
      DO 33 I=IGRID,NP1
   33 WRITE(6,202)(TF(I,J),J=2,M)
C
C     .....CHECK CYCLE TIME.....
   34 TAU=TAU+DTAU
      CLOCK=(TAU*DEPTH*DEPTH)/ALPHA
      IF(CLOCK.GE.24.0)GO TO 72
      GO TO 4
   72 CLOCK=CLOCK-24.0
      TAU=(ALPHA*CLOCK)/(DEPTH*DEPTH)
      ICOUNT=0
      READ(5,100)IDAY,AIRMAX,AIRMIN(1),AIRMIN(2),VEL1,COVER,DALANG
      IF(IDAY.EQ.0)GO TO 300
      QSKYMX=0.57929*DALANG
      WRITE(6,217)IDAY,AIRMAX,AIRMIN(1),AIRMIN(2),VEL1,QSKYMX,COVER
      GO TO 4
C
C     .....FORMATS FOR INPUT AND OUTPUT STATEMENTS.....
  100 FORMAT(8X,F4.2,21X,F5.2,8X,I2,8X,I2,12X,I2)
  101 FORMAT(9X,F7.3)
  102 FORMAT(6X,F5.3,11X,F5.3,12X,F5.3)
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```
  104 FORMAT(7X,F5.2,11X,F6.2)
  105 FORMAT(9X,F6.2,15X,F6.2,15X,F6.2/9X,F6.2)
  106 FORMAT(8X,I1,11X,F3.1)
  107 FORMAT(8X,F4.2,17X,F5.3)
  108 FORMAT(7X,I1)
  109 FORMAT(7X,I2,12X,F6.2,15X,F6.2,15X,F6.2/7X,F6.2,11X,F3.1,12X,F6.2)
  200 FORMAT(115H1    UNSTEADY STATE HEAT CONDUCTION, CONVECTION, $ RADIA
     1TION IN A ROAD SLAB WITH EMBEDDED HEAT PIPE, WITH PARAMETERS/
     212H0    DTAU   = ,F10.5/12H     DX     = ,F10.5/
     312H     RATIO = ,F10.5/
     412H     N      = ,I4/12H     M      = ,I4/12H     IFREQ = ,I4)
  201 FORMAT(//14H0    AT TIME = ,F8.3,30H  HOURS     AIR TEMPERATURE IS ,
     1F6.2,4H  F.)
  202 FORMAT(1H ,13F9.3)
  203 FORMAT(12H     FTPIPE= ,F9.3)
  204 FORMAT(12H     CON    = ,F8.3)
  208 FORMAT(12H     EMISS = ,F9.3/12H     ABSORP= ,F9.3)
  211 FORMAT(10H     HC IS ,F5.3,25H BTU/(HR.SQFT.F)     H IS ,F5.3,16H BT
     1U/(HR.SQFT.F))
  212 FORMAT(12H     IGRID = ,I4/12H     RLGTH = ,F8.2)
  213 FORMAT(12H     BLOSS = ,F7.2/12H     SPACE = ,F8.3/12H     DEPTH = ,F
     19.3/12H     WIDTH = ,F9.3)
  214 FORMAT(38H     HEAT SUPPLIED BY THE HEAT PIPE IS ,F6.2,12H BTU/(HR.
     1FT)/)
  215 FORMAT(43H     FAHRENHEIT TEMPERATURES IN QUADRANT ARE/)
  217 FORMAT(12H1    JANUARY ,I2,6H, 1973/31H     MAXIMUM AIR TEMPERATURE
     1IS ,F5.2,3H F./31H     MINIMUM AIR TEMPERATURE IS ,F5.2,3H F./42H
     2  TOMORROW'S MINIMUM AIR TEMPERATURE IS ,F5.2,3H F./18H     WIND SP
     3EED IS ,F5.2,4H MPH/31H     MAXIMUM SOLAR HEAT FLUX IS ,F6.2,11H BT
     4U/HR.FT2/17H     SKY COVER IS ,F3.1///)
C
  300 STOP
      END

      SUBROUTINE TRIDAG(IF,L,A,B,C,D,V,TPIPE)
C
C         SUBROUTINE FOR SOLVING A SYSTEM OF LINEAR SIMULTANEOUS
C         EQUATIONS HAVING A TRIDIAGONAL COEFFICIENT MATRIX.
C         THE EQUATIONS ARE NUMBERED FROM IF THROUGH L, AND THEIR
C         SUB-DIAGONAL, DIAGONAL, AND SUPER-DIAGONAL COEFFICIENTS
C         ARE STORED IN THE ARRAYS A, B, AND C.  THE COMPUTED
C         SOLUTION VECTOR V(IF)...V(L) IS STORED IN THE ARRAY V.
C
C
C
C VARIABLE AND CONSTANT NAMES IN SUBROUTINE TRIDAG ARE.....
C
C         A, B, C, D, TPIPE -SAME AS MAIN PROGRAM
C         BETA  -VARIABLE USED IN DETERMINATION OF V
C         GAMMA -VARIABLE USED IN DETERMINATION OF V
C         IF    -SUBSCRIPT OF FIRST NODAL POINT IN THE INPUT COLUMN OR ROW MATRIX
C         K     -FIRST APPEARANCE GIVES FIRST SIGNIFICANT POINT OF COLUMN OR ROW
C                MATRIX
C         K     -SECOND APPEARANCE IS A DO LOOP PARAMETER
C         L     -SAME AS NP1 IN MAIN PROGRAM
C         LAST  -CONSTANT USED TO INVERT SEQUENCE OF OPERATION
C         V     -SAME AS TPRIME IN MAIN PROGRAM
C
C
      DIMENSION A(30),B(30),C(30),D(30),V(30),BETA(30),GAMMA(30)
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C
C     .....COMPUTE INTERMEDIATE ARRAYS BETA AND GAMMA.....
      DO 7 I=IF,L
      IF(A(I).EQ.0.0.AND.B(I).EQ.0.0)GO TO 7
      K=I
      GO TO 8
    7 CONTINUE
    8 BETA(K)=B(K)
      GAMMA(K)=D(K)/BETA(K)
      DO 9 I=IF,L
      IF(I.EQ.K)GO TO 9
      IF(C(I).EQ.0.0.AND.A(I).EQ.0.0)GO TO 1
      IF(A(I).EQ.0.0.AND.C(I).NE.0.0)GO TO 2
      GO TO 3
    1 BETA(I)=1.0
      GAMMA(I)=0.0
      GO TO 9
    2 BETA(I)=B(I)
      GO TO 4
    3 BETA(I)=B(I)-A(I)*C(I-1)/BETA(I-1)
    4 GAMMA(I)=(D(I)-A(I)*GAMMA(I-1))/BETA(I)
    9 CONTINUE
C
C     .....COMPUTE FINAL SOLUTION VECTOR V.....
      V(L)=GAMMA(L)
      LAST=L-IF
      DO 6 K=1,LAST
      I=L-K
      V(I)=GAMMA(I)-C(I)*V(I+1)/BETA(I)
      IF(V(I).EQ.0.0)GO TO 5
      GO TO 6
    5 IF(A(I).EQ.0.0.AND.C(I).EQ.0.0)V(I)=TPIPE
    6 CONTINUE
      RETURN
C
      END

      SUBROUTINE TRANCO(VEL1,RLGTH,FTAIR,FTEMP,EMISS,H,HC,HR,COVER,TEFF,
     1FTPIPE,ABSORP,QSKYMX,CLOCK)
C
C           SUBROUTINE FOR FINDING OVERALL, RADIATIVE AND CONVECTIVE HEAT TRANSFER
C           COEFFICIENTS.  THE RADIATIVE CONTRIBUTION DEPENDS ON SKY COVER.
C           EFFECTIVE SKY TEMPERATURE IS ALSO COMPUTED.
C
C
C VARIABLE AND CONSTANT NAMES IN SUBROUTINE TRANCO ARE.....
C
C           ABSORP,CLOCK,COVER,EMISS,FTEMP,FTPIPE,H,HC,HR,QSKYMX,RLGTH,TEFF,VEL1--
C           -SAME AS MAIN PROGRAM
C           ATEMP -AIR TEMPERATURE (R)
C           CONST -A CONSTANT EQUAL TO (0.036)(CON)(PR)**0.33 USED IN DETERMINATION
C                  OF TURBULENT FILM COEFFICIENT (BTU/HR.FT.F)
C           CONST1-A CONSTANT EQUAL TO (0.664)(CON)(PR)**0.33 USED IN DETERMINATION
C                  OF LAMINAR FILM COEFFICIENT (BTU/HR.FT.F)
C           FTAIR -SAME AS FTAIR1 IN MAIN PROGRAM (F)
C           FTEFF -EFFECTIVE SKY TEMPERATURE (F)
C           QCLOUD-LONG-WAVE RADIATIVE HEAT FROM A CLOUDY SKY (BTU/HR.FT2)
C           QLW   -LONG-WAVE RADIATIVE HEAT FROM A CLEAR SKY (BTU/HR.FT2)
C           QLWMAX-MAXIMUM DAILY LONG-WAVE RADIATION FROM A CLEAR SKY (BTU/HR.FT2)
C           QSOLAR-SHORT-WAVE INCIDENT SOLAR RADIATION (BTU/HR.FT2)
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C        RE    -REYNOLD*S NUMBER
C        RTEFF -EFFECTIVE SKY TEMPERATURE (R)
C        SIGMA -PLANCK*S CONSTANT (BTU/HR.FT2.R4)
C        TAV   -AVERAGE TEMPERATURE OF BRIDGE SURFACE AND AIR (R)
C        VEL   -WIND SPEED (FT/SEC)
C        W     -ANGULAR FREQUENCY OF SOLAR HEAT FLUX VARIATION FOR A TEN HOUR
C               DAY (RADIANS/HR)
C
      W=0.31415
      CONST=0.44958E-3
      SIGMA=1714.0E-12
      CONST1=0.8294E-2
      VEL=(VEL1*5280.0)/3600.0
      RE=(VEL*RLGTH)/(1.5E-4)
C
C     .....CONVERT TEMPERATURES TO DEGREES RANKINE.....
      ATEMP=460.0+FTAIR
      STEMP=460.0+FTEMP
      IF(COVER.EQ.1.0)GO TO 1
C
C     .....RADIATIVE COMPONENT FOR CLOUDY SKY.....
      IF(CLOCK.LE.6.0.OR.CLOCK.GE.16.0)GO TO 3
C
C     .....DAYTIME.....
      QSOLAR=QSKYMX*SIN(W*(CLOCK-6.0))
      QCLOUD=SIGMA*(ATEMP**4.0)
      RTEFF=((EMISS*QCLOUD+ABSORP*QSOLAR)/(EMISS*SIGMA))**0.25
      HR=EMISS*SIGMA*(STEMP**3.0+RTEFF*(STEMP**2.0)+(RTEFF**2.0)*STEMP+R
     1TEFF**3.0)
      FTEFF=RTEFF-460.0
      TEFF=FTEFF/FTPIPE
      GO TO 7
C
C     .....NIGHTIME.....
    3 TAV=(ATEMP+STEMP)/2.0
      HR=4.0*SIGMA*EMISS*(TAV**3.0)
      TEFF=FTAIR/FTPIPE
      GO TO 7
C
C     .....LONG-WAVE RADIATION COMPONENT FOR A CLEAR SKY.....
    1 QLW=-54.19+1.195*SIGMA*(ATEMP**4.0)
      IF(CLOCK.LE.6.0.OR.CLOCK.GE.16.0)GO TO 2
C
C     .....DAYTIME.....
      QSOLAR=QSKYMX*SIN(W*(CLOCK-6.0))
      RTEFF=((ABSORP*QSOLAR+EMISS*QLW)/(EMISS*SIGMA))**0.25
      HR=EMISS*SIGMA*(STEMP**3.0+RTEFF*(STEMP**2.0)+STEMP*(RTEFF**2.0)+R
     1TEFF**3.0)
      FTEFF=RTEFF-460.0
      TEFF=FTEFF/FTPIPE
      GO TO 7
C
C     .....NIGHTIME.....
    2 RTEFF=(QLW/SIGMA)**0.25
      HR=EMISS*SIGMA*(STEMP**3.0+STEMP*(RTEFF**2.0)+RTEFF*(STEMP**2.0)+R
     1TEFF**3.0)
      FTEFF=RTEFF-460.0
      TEFF=FTEFF/FTPIPE
C
C     .....TURBULENT CONVECTIVE COMPONENT.....
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      7 IF(RE**0.8.LE.23000.0)GO TO 4
        HC=(CONST/RLGTH)*(RE**0.8-23000.0)
        GO TO 5
C
C       .....LAMINAR CONVECTIVE COMPONENT.....
      4 HC=(CONST1*SQRT(RE))/RLGTH
C
C       .....TOTAL HEAT TRANSFER COEFFICIENT.....
      5 H=HC+HR
        RETURN
C
        END

$EXEC
```