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THERMAL INSULATION AND PREFERENTIAL ICING OF BRIDGE DECKS

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16. Abstract

An evaluation of the ability of insulation to control icing on bridge decks was performed on three bridges in the Colorado mountains. Each bridge was partially insulated. Monitoring of the roadway temperature and meteorology, along with time lapse photography, was used to determine the performance. Insulation was so structured to isolate a cell of air and structural member below the deck from the elements. For the steel I-beam structure, insulation was found to reduce preferential icing. During the test period, temperatures were such that preferential icing was possible 58% of the time for the uninsulated bridge and 50% of the time for the insulated bridge. For the concrete box girder bridge and the steel box girder bridge insulation did not significantly change the preferential icing potential.

The concrete box girder bridge was found to be the least susceptible to preferential icing while the steel I-beam bridge was the most susceptible.

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CONVERSION FACTORS
English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in) or (")	2.54×10^{1}	millimetres (mm)
		2.54×10^{-2}	metres (m)
	feet (ft) or (')	3.048×10^{-1}	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^{2})	6.452×10^{-4}	square metres (m^{2})
	square feet (ft^{2})	9.29×10^{-2}	square metres (m^{2})
	acres	4.047×10^{-1}	hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^{3})	2.832×10^{-2}	cubic metres (m^{3})
	cubic yards (yd^{3})	7.646×10^{-1}	cubic metres (m^{3})
Volume/Time (Flow)	cubic feet per second (ft^{3}/s)	2.832×10^{1}	litres per second (l/s)
	gallons per minute (gal/min)	6.309×10^{-2}	litres per second (l/s)
Mass	pounds (lb)	4.536×10^{-1}	kilograms (kg)
	ounces (oz)	2.835×10^{1}	grams (g)
Velocity	miles per hour (mph)	4.47×10^{-1}	metres per second (m/s)
	feet per second (fps)	3.048×10^{-1}	metres per second (m/s)
Weight/Density	pounds per cubic foot (lb/ft^{3})	1.602×10^{1}	kilograms per cubic metre (kg/m^{3})
Force	pounds (lbs)	4.448	newtons (N)
	kips (1000 lbs)	4.448×10^{3}	newtons (N)
Pressure	pounds per square inch (psi)	6.895×10^{3}	pascals (Pa)
	pounds per square foot (psf)	4.788×10^{1}	pascals (Pa)
Temperature	degrees fahrenheit (F)	$\frac{{}^{o}F - 32}{1.8} = {}^{o}C$	degrees celsius (^{o}C)

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I. BACKGROUND

The phenomena of bridges icing up before adjacent roadways has been both a safety hazard and a maintenance problem for many years. This problem is usually referred to as preferential icing and can present a serious hazard to the unsuspecting motorist. A driver can be traveling along at a speed which is proper for the wet roadway and find himself on a bridge which is preferentially iced. Without sufficient traction the driver may lose control of the vehicle. Accidents of this type have the potential of being serious because of the speed involved and the confinement of the bridge.

The thermal characteristics of bridge decks differ from those of the roadway. Therefore, with certain weather conditions, a bridge deck can become icy before the roadway does. This preferential icing coupled with the usual inherent dangers of bridges (confinement of roadway) causes a substantial hazard to motorists. Once the roadway becomes icy, the ice on the bridges becomes far less hazardous because driving speeds are adjusted to compensate for poor traction.

To compound the problem, bridge designs with significantly different thermal characteristics are used along the same stretch of highway. Consequently, depending upon structural design, different bridge surface conditions may exist under the same environment.

Mitigation of the dangers posed by preferential icing ranges from warning signs, intensified bridge maintenance, insulation of bridge decks, to heating bridge decks.

Both passive and active warning signs have been used to tell drivers of possible dangers. Signs which are activated by ice detector systems have been avoided in recent years due to reliability and performance problems. Despite the vast improvement in ice detection technology, these systems are still prone to error because they can only sense the ice condition at a few small points on the roadway. Even a few false indications can destroy motorist confidence in the system, while failure to indicate all icing events can lead to liability problems. Manually operated signs have been used on a limited basis but tend to be activated and deactivated too late.

Intensive deicing maintenance is practiced extensively. This practice is not without problems. First, it is expensive because it requires special trips by maintenance personnel just to treat the structures. Second, reaction time on this procedure tends to be slow because of lack of information on the condition of the bridge and travel time. This is a serious drawback because preferential icing tends to be most intense for an interim period at the onset of a storm. Finally, the extra deicing chemicals on structures exacerbate the already serious problem of bridge deck support hardware corrosion.

Bridge deck heating is an effective way to control icing on bridge decks but tends to be costly both in the initial construction and in maintenance. Bridge deck heating usually means consumption of fuel to generate the energy to heat the deck. Some innovative systems use heat from the ground or solar energy and can limit the consumption of fossil fuels, but initial costs of these systems tend to be high (20 - 50 dollars per square foot). In a few locations geothermal water is available and can be used as the energy source for the heating.

The use of thermal insulation on the bottom side of bridges has been tested extensively but has not been adopted as a standard procedure for controlling preferential icing. The insulation eliminates the thermal loss (and gain) from the bottom side of the bridge deck. Under certain conditions this loss is significant enough to cause preferential icing.

The performance of insulation is primarily dependent on meteorology and bridge design. In an extreme instance insulation can reduce the temperature of the bridge deck and increase the chances of preferential icing.

Blackburn and others (see Reference 1) concluded that "bridge deck insulation as a counter measure has been shown to be ineffective in controlling localized ice and frost." This conclusion appears to be premature for the following reasons:

(a) Research has only been performed for a limited number of meteorologic regimes, and conclusions as to the effectiveness of the insulation have been mixed. Testing of box girder bridges has been extremely limited.

(b) Insulation is potentially far more economical for controlling bridge icing than any other available alternative.

(c) Insulation is attractive because it is a completely passive measure. Once installed, it requires no operator or maintenance.

(d) A search of HRIS files has revealed that no study has been performed on the new bridge deck design which is standard in Colorado and many other states. (The standard design is a concrete deck covered with a waterproofing membrane and a 2-inch asphalt overlay.) Thermal characteristics of this type of deck are different from those previously studied. The most significant difference is a black surface which has a greater capacity to absorb and radiate heat.

(e) Even if insulation cannot significantly reduce preferential icing, it could be used to modify the thermal behavior of steel beam or box girder bridges to more closely match that of concrete box girder bridges.

The investigation of the effect of insulation on various types of bridge design is the subject of this report.

II. INTRODUCTION

Three bridges near Vail, Colorado were partially insulated with mats of fiber glass insulation. Two of the bridges are located on Vail Pass, and the third bridge is located at Dowd Junction. The bridges on Vail Pass are less than one-half mile apart, while the bridge at Dowd Junction is approximately fifteen miles west (see Figure 1). All three bridges are on I-70.

The most easterly bridge (F-12-AT) traverses Polk Creek on Vail Pass for westbound I-70 traffic. The structure is composed of twin steel box girders and a 7-inch concrete deck with a waterproofing membrane and a 2-inch asphalt overlay. Total length of this structure is 732 feet.

Four tenths of a mile west is a 518-foot concrete box girder bridge (F-11-AL) which traverses Miller Creek. This west bound structure has a 7-inch concrete deck with a waterproofing membrane and a 2-inch asphalt overlay.

Approximately five miles west of the Town of Vail is the open steel girder bridge (F-11-AD) which passes over the Eagle River, a railroad track, and S.H. 24. Total length of this structure is 402 feet. Since this structure is part of the Dowd Junction Interchange, it will be referred to as the Dowd Junction Bridge.

For a quick cross reference for the reader, Table 2 has been prepared as a cross reference for each bridge under study. Also included on this table is the abbreviation scheme used to identify each temperature.

Figure 1

Map of Study Area

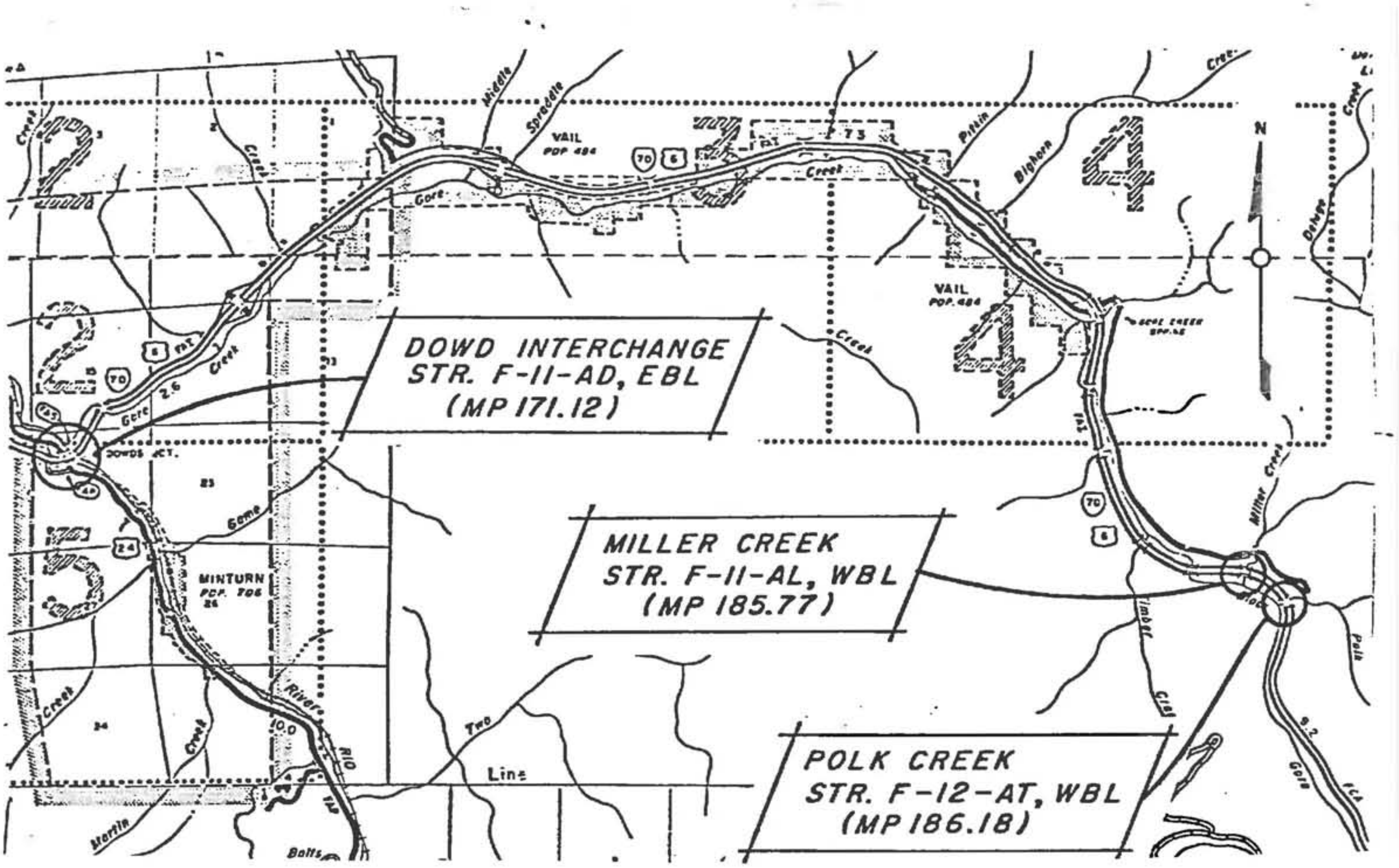


TABLE 2

SUMMARY OF BRIDGES UNDER STUDY
(from East to West)

Name	Structure	Type	Location	Elevation (ft)
Polk Creek	F-12-AT	Twin Steel Box Gerder	Vail Pass	9,550
Miller Creek	F-11-AL	Concrete Box Gerder	Vail Pass	9,420
Dowd Junction	F-11-AD	Steel I-beam	Dowd	7,780

TEMPERATURE ABBREVIATION SCHEME

Three letters are used to depict each temperature sensor. The first letter denotes the Bridge, the second letter denotes the section of the bridge, and the third letter denotes the top or bottom of the slab. The meaning of the second two letters is given below.

A - Approach

I - Insulated Bridge Deck Section

S - Standard or Uninsulated Bridge Deck Section

T - Top of Slab

B - Bottom of Slab

III. CONSTRUCTION

It was decided to insulate one span of each of the three structures to determine the affect of insulation. By not insulating the entire deck a side-by-side comparison is available to analyze the performance of the insulation. By stopping the insulation at the end of the span, a natural barrier (the bulkhead) was provided to separate the insulated section from the non-insulated section.

The major difference between this insulating system and others that were tested by various agencies was that the insulation was placed at the bottom of the structure rather than just below the deck. This method provided the added benefit of containing the heat stored in the air and structural members between the bottom of the deck and bottom of the bridge. Some special support members had to be used to accomplish this for all except the box girder Miller Creek Bridge. The planking was primarily composed of a 2x2 wood frame sandwiched between two sheets of plywood. Insulation was then glued to the top of these panels (see Figure 3).

For the Polk Creek Bridge steel I-beams spanning between the twin steel box girders provided support for these plywood plates (see Figure 4). Insulation was also glued to the inside of the steel boxes on the far sides and bottom (see Figure 5). The insulation contained the thermal storage of the inside sides of the twin box while eliminating the thermal storage from the outside sides and the bottom of the twin box. Ideally, the insulation should be placed on the outside of the box, but no insulating material is available that is sufficiently light weight and can withstand the elements.

For the Miller Creek Bridge, insulation was glued to the inside of the concrete box on the sides and bottom. Although this prevents heat transfer from the bottom of the bridge, it also isolates the thermal heat sink of the concrete box (see Figure 6).

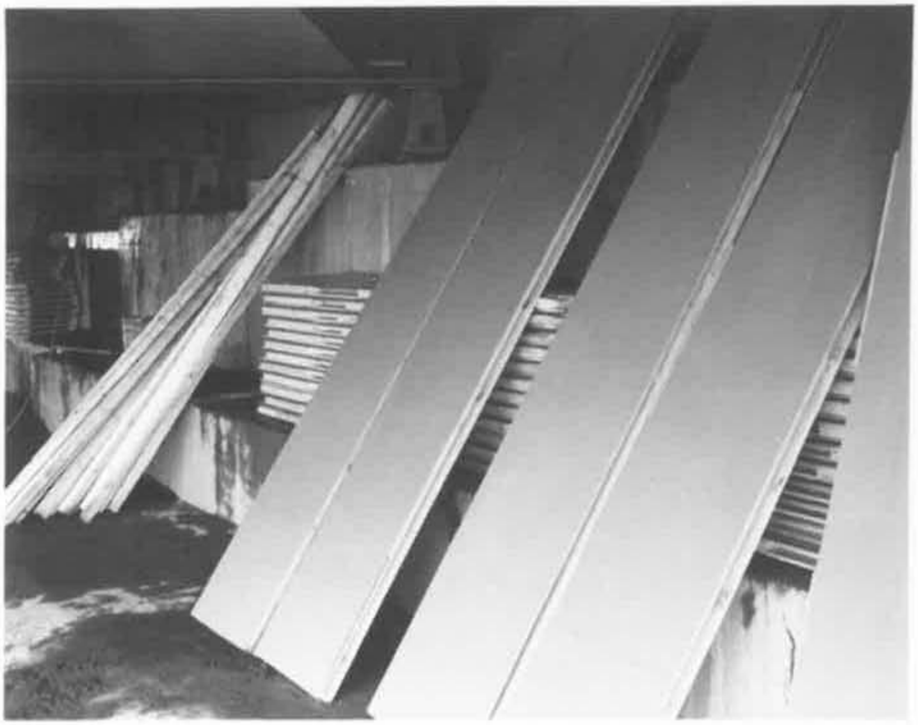


Figure 3

Insulation Support Panels

Figure 4

Structural Support at Polk Creek

Figure 5

Cross Section of Polk Creek Bridge
Twin Steel Box Girder

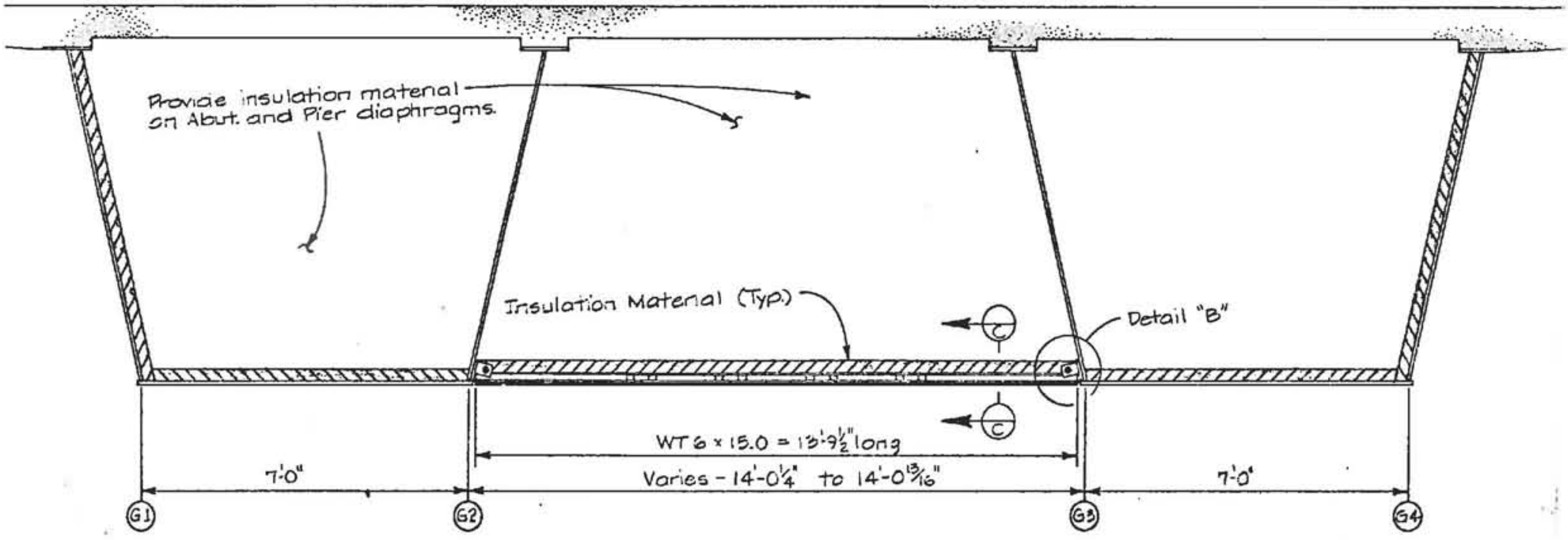
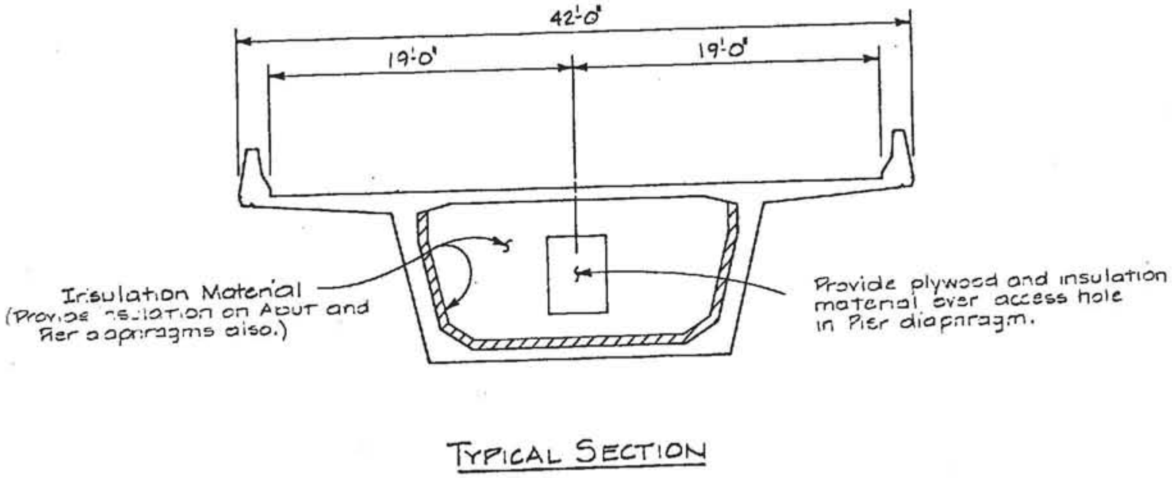


Figure 6

Cross Section of Miller Creek Bridge
Concrete Box Girder



For the Dowd Junction Bridge, the plywood panels were supported by the lower flanges of the steel I-beams (see Figure 7). The insulation system contained the thermal storage of the webs of the I-beams plus any cross members. A slight heat leak in the insulation system is realized since the heat can be conducted through the bottom of the web into the uninsulated bottom flange.

The entire cost of insulating one span of these three bridges was $47,219. which was below the engineer's estimate of $60,545.

Figure 7

Dowd Junction Insulation System

Figure 8

Time Lapse Camera Mounted In Box

IV. MONITORING

The study consisted of continuous monitoring of roadway temperatures and time lapse photography at each bridge. In addition meteorological data was collected at Dowd Junction. The data was recorded on cassette tapes and later transferred to the computer for editing and analysis.

A. Equipment

Seven thermistors were installed at each bridge to detect temperatures. Thermistors were installed at the top and bottom of the bridge deck that was not insulated (standard), top and bottom of the bridge deck that was insulated, and top and bottom of the approach slab. Finally, the seventh thermistor was used to measure ambient temperature below each bridge. These termistors were connected to Cambell Scientific Microloggers. The Micrologger is a microprocessor based data acquisition system which samples the thermistor once every minute. The signal from the thermistor is converted to an actual temperature by a program which is designed to follow the non-linear response curve of the thermistor. Thirty one-minute readings are averaged together and recorded every half-hour on casette tape for every sensor.

Thermistors were installed in top of the bridge deck by drilling a 1/2-inch hole clear through the decks. The leads of the thermistors were fed through the hole and the thermistor was positioned just below the surface of the deck. Duracal (a concrete patch compound) was used to patch the hole and hold the thermistor in place. Connections to the micrologger were made from the bottom side of the deck. For the temperatures at the bottom of the deck thermistors were glued to the bottom of the deck near the location where the corresponding top probe was located. For the approaches, thermistors and their leads were installed in slots cut by a concrete saw. All sensors were located in the center of the right driving lane, and their leads were routed to the insulated cell of each bridge where the microloggers were located.

A fourth micrologger was used to collect meteorological data at Dowd Junction. This included wind speed, wind direction, humidity, and solar radiation. All this data was also averaged over 30 minutes before it was recorded on cassette tape. A special vector averaging program in the micrologger was used to compute the average wind direction, thus, avoiding the dilemma of averaging a 355-degree wind with a 5-degree wind and getting a 180-degree wind.

A visual record of the condition of the bridge deck and approaches was obtained using an 8-mm movie camera. The three cameras were each mounted in an army surplus ammo can (see Figure 8). Holes were cut in each box for the view finder, the lens and the usage indicator. A special electronic circuit was built to turn the camera on and take a single frame once every 8 minutes. Four D-cell alkaline batteries were used for power and could operate this system for about ten days, while a 50-foot roll of film would last for 20 days.

Each camera was mounted to view the corresponding approach, insulated section, and standard section of each bridge. For Polk Creek a tree was available at the appropriate spot to mount the camera (see Figure 9). At Miller Creek a steel pole had to be installed for the camera (see Figure 10). At Dowd Junction the camera was mounted on a deer fence uphill from the bridge (see Figure 11). The cameras provided a visual record of the condition of the bridges and approaches during the daytime.

B. Data Processing

Monitoring began in late September of 1981, but due to various problems the data was not considered complete and accurate until October 15, 1982.

Figure 9

Polk Creek Camera Mount

Figure 10

Miller Creek Camera Mount

Figure 11

Dowd Junction Camera Mount

The bridges were visited approximately once every ten days. Cameras and microloggers were checked, and batteries and cassette tapes were changed. The data tapes were read and interpreted using a special translator box and a standard ASCII interactive terminal. This data was put on disk storage on the Cyber 70 CDC computer for later editing and statistical analysis.

An alternate method used for loading the data on the Cyber computer was first to copy the data onto an Apple microcomputer using the translator box. Once the Apple memory was filled with data, the Apple could be connected to the Cyber 70 via a modem and phone lines, and the data could then be transferred to disk.

Once the data was put on disk it was edited and reformatted into a data bank structure. The new structure was composed of one line of data for each half-hour during the monitoring period. Program BLDFL created a blank data bank file with only the Julian date and the time in the first two fields of each line. Program DATBLD loaded the micrologger data onto this data bank by matching dates and times. If the time on the micrologger did not correspond to the exact half-hour interval, DATBLD assigned the data to the closest half-hour. Four of these data bank files were created as follows:

DOWDALL - Containing all the temperature and meteorological data at Dowd Junction for 1981.

VAIL81 - Containing all the temperature data for both Miller and Polk Creeks for 1981.

DWD1982 - Containing all the temperature and meteorological data at Dowd Junction for 1982.

VAIL82 - Containing all the temperature data for the Miller and Polk Creek bridges for 1982.

The data was split up into these four files for three reasons. (1) One file with all the data would be unwieldy and too costly to manipulate in the computer. (The entire data set was composed of over one-quarter of a million data points.) (2) Because of the distance between Dowd Junction and Vail Pass data between the two sites is somewhat unrelated. Having this data on a common file would be of little value. (3) The end of the year is the time when the ground is going from the gradual cooling-off trend of the fall to the stable ground temperature of the winter. Preferential icing is more likely in the late fall and early winter because of the warmer ground and approach temperatures. It makes sense to look at the fall and winter data separately because of this phenomenon.

C. Calibration

Calibration of the thermistors for the most part was performed before they were installed and after they were removed. Unfortunately the thermistors in the approaches were not able to be removed. However, an in-situ calibration was performed on the top thermistor in the approaches. Four of the approach thermistors failed during the test period. They were the top approach at Miller Creek (MAT), the bottom approach at Polk Creek (PAB) and both approach thermistors at Dowd Junction (see Table 2 for abbreviation scheme). An error in the top sensor on the uninsulated section at Miller Creek was suspected. Other than these specific spots the thermistors calibrated to within plus or minus one degree F (.6 deg. C) of each other (see Table 12). There was an average offset of .76 deg. F (.42 deg. C) between the thermistors and the mercury thermometer used for calibration. This offset was not considered significant because only differences are important to this study. Also, the accuracy of the reference thermometer used may be off by this much.

Table 12

Final Thermistor Calibration

Near Freezing

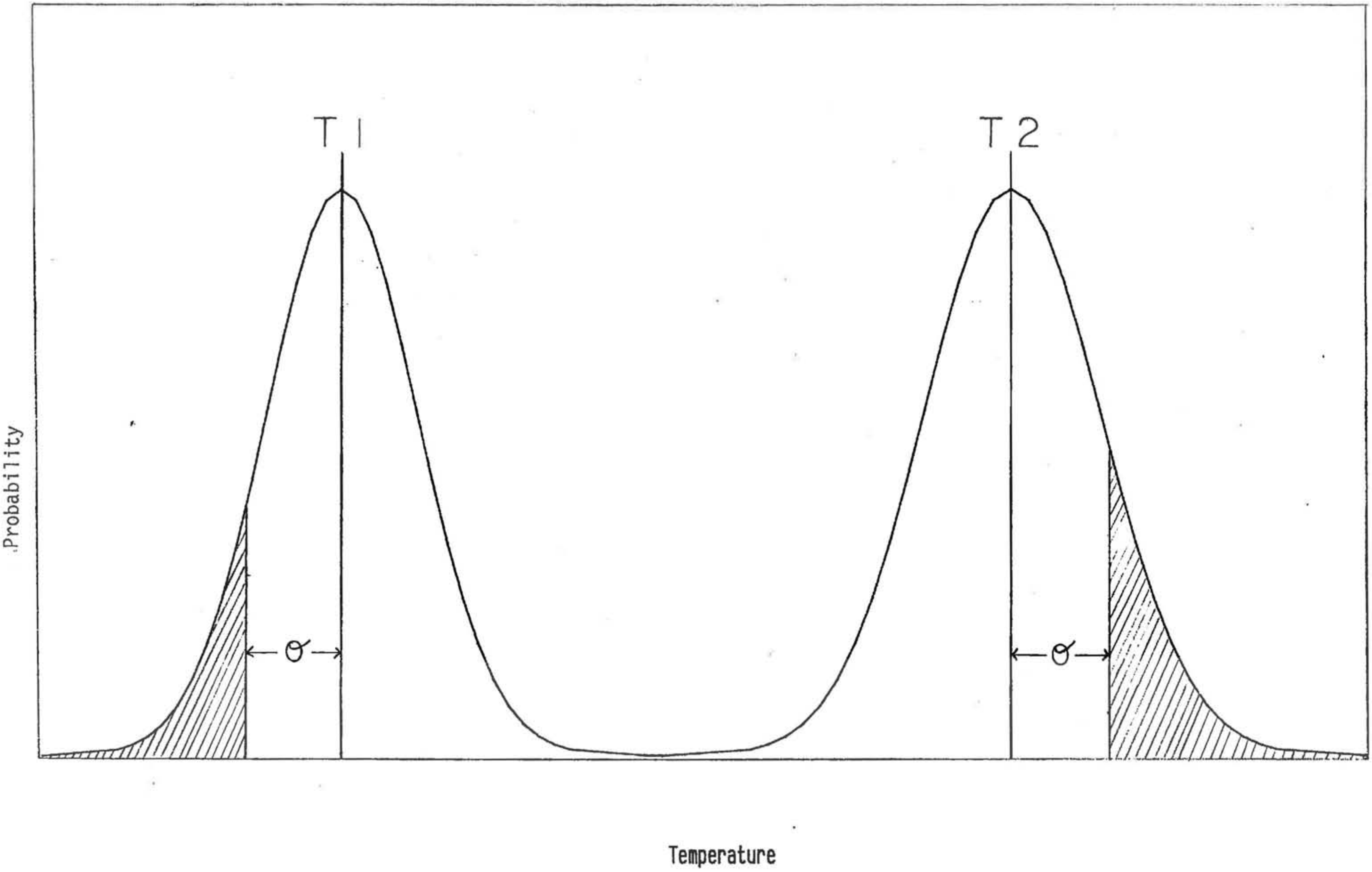
Thermistor Number	Reading (Deg.C)	Mercury Thermometer (Deg. C)	Difference
1	.21	.5	.29
2	.29	.5	.21
3	.63	.5	-.13
4	.56	.5	-.06
5	.02	.6	.58
6	.25	.6	.35
7	.274	.6	.426
8	.012	.6	.479
9	.75	.5	-.25
10	.059	.6	.001
11	.059	.6	.001
13	.17	.8	.63
14	.06	.8	.74
15	1.92	1.4	.52
Average	.23	.65	.28
0	—	—	.30

Since this study deals mostly with differences, it is important to consider the error that would result when the difference between two temperatures is computed. Assuming the error of two temperatures is normally distributed with a standard deviation (σ) of 0.5 deg. F (0.3 deg. C), the distribution curve for these temperatures is depicted on Figure 13. The probability of temperature T1 being σ or greater below the mean is given by the shaded area on the left. Similarly, the probability of T2 being σ or larger above the mean is given by the shaded area on the right. Assuming that the error in each thermistor is independent, the probability of both events happening simultaneously and causing the error of the difference to be 2 σ will be the product of these two probabilities. Based on the normal curve of error the area of each tail is 16%. The probability, therefore, of a 2 σ error of the difference is: 16% x 16% = 2 1/2%. Since σ is .5 deg. F, the accuracy of the differences is plus or minus 1 deg. 97 1/2% of the time.

An error in the top sensor on the standard section of Miller Creek was suspected. Because of the critical nature of the sensor to the study, its data could not just be discarded. An effort was undertaken to determine the error in this sensor and to correct for it. Figure 14 is a graph of the average bridge deck temperatures at Miller and Polk Creek during monitoring in 1981. It is apparent that 1.8 deg. F must be subtracted from the Miller Standard Top (MST) in order for it to fit into the pattern; that is, 0.6 deg. F below the insulated section. The relationship of the bottom temperatures for both structures is the same, so the out of place MST temperature is not due to a different response of the two bridges. Figure 15 is a similar chart for the 1982 data which shows that an adjustment of 3 deg. F of MST must be made. Here again the temperature relationship of the bottom deck does not show a significant difference of thermal response

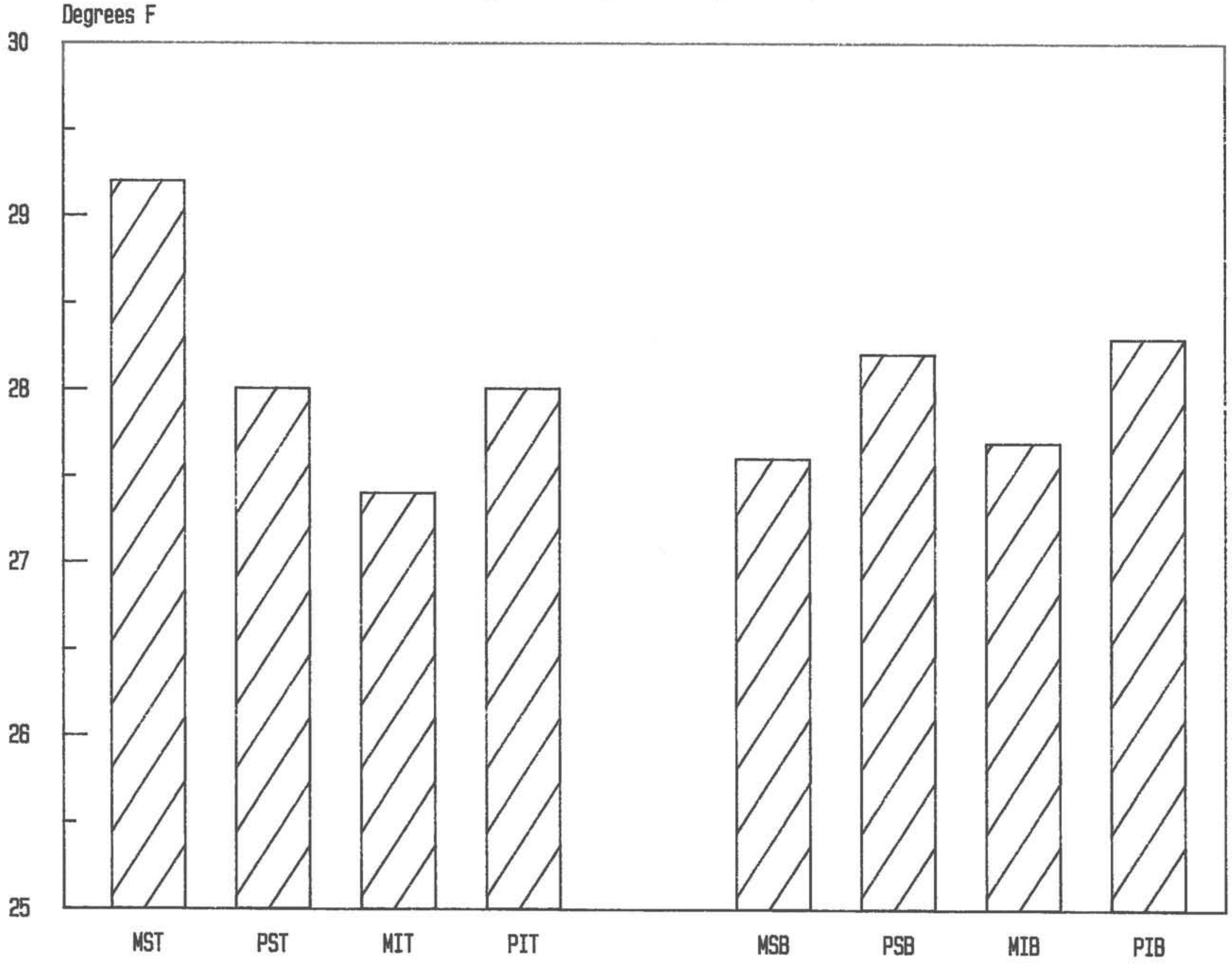
Probability Curve

FIGURE 13



AVERAGE TEMPERATURES

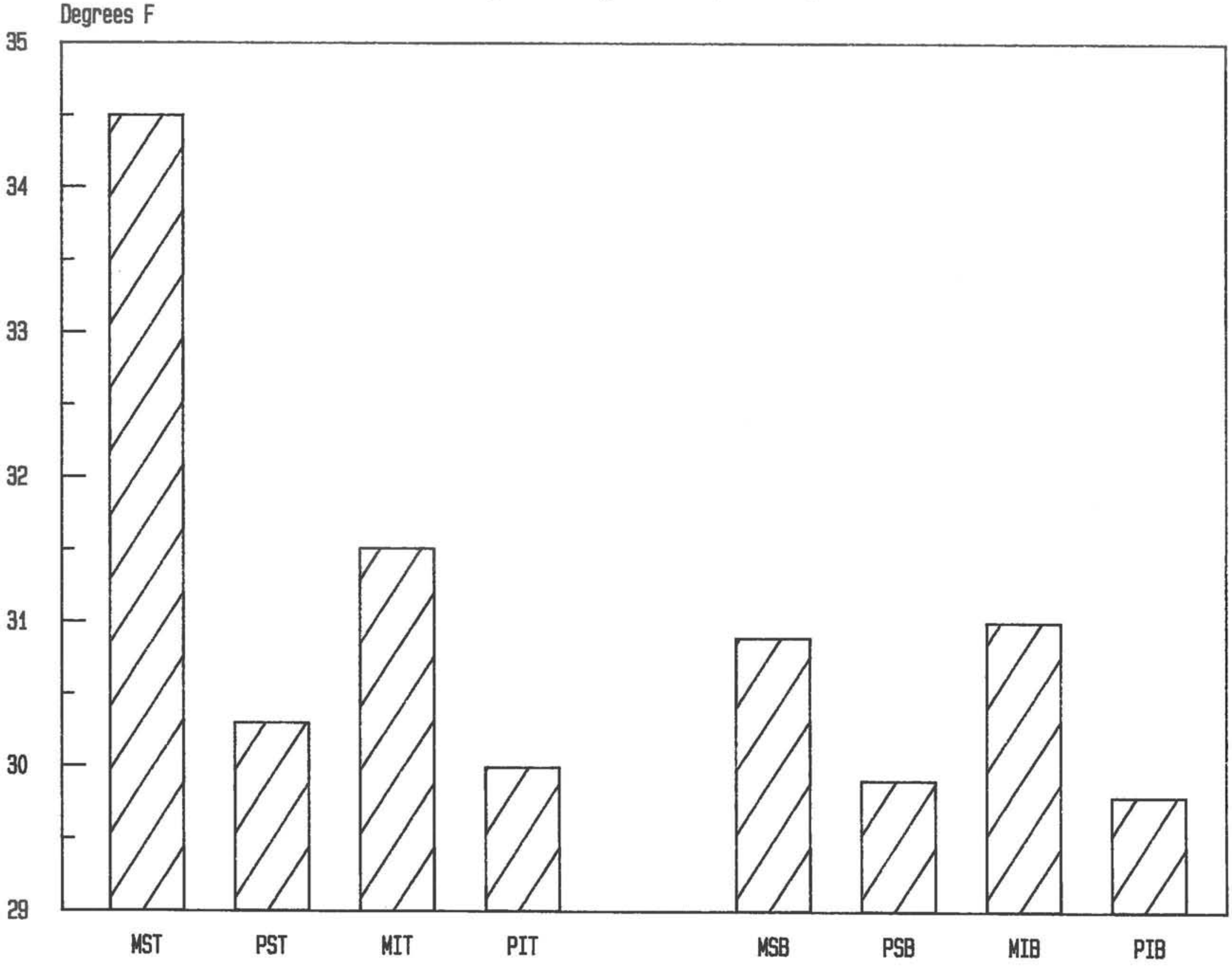
Figure 14 (Avg. 1981 Temperatures)



See Table 2 for abbreviation scheme.

AVERAGE TEMPERATURES

Figure 15 (Avg. 1982 Temperatures)



See Table 2 for abbreviation scheme.

between the two bridges. The offset is, therefore, due to an error in the thermistor itself. During final calibration in June, the error in this thermistor was 5 deg. F. Apparently the calibration of this thermistor was slipping from no error before the test period to 2 deg. F during 1981 testing, to 3 deg F. during 1982 testing, and to 5 deg. F at the final calibration. Based on this discussion, the MST temperatures will be reduced by 2 deg. F for the 1981 analysis and by 3 deg. F for the 1982 analysis.

V. PERFORMANCE ANALYSIS

In order to evaluate the performance of the insulation systems, several methods were employed. First, averages were computed for every hour of the day and plotted. This provided the average diurnal temperature cycle for each sensor. Second, histograms were created based on key temperature differences. This aided in determining the percent of time that the insulation could reduce preferential icing. Third, time lapse films were reviewed, and events where preferential icing occurred were selected and analyzed in detail. Finally, based on performance statistics and accident statistics an estimate of the benefit-cost of bridge deck insulation was computed.

A. Diurnal Averages

Hourly averages for each day of the monitoring were computed to provide a diurnal pattern for each temperature probe and meteorologic data item. These graphs are presented in Appendix A. Averages were paired up (two on each graph) in such a manner as to demonstrate the difference in the thermal response of the approaches, insulated, and standard sections of each bridge deck.

For the Polk Creek structure (Figures A-1 through A-4) the insulated and standard temperatures tend to track fairly close especially for 1981. For late winter and early spring the solar influence is stronger, and separation occurs during late morning and early afternoon. This close tracking indicates that insulating this type of structure is mostly ineffective.

For the Miller Creek Structure (Figures A-5 and A-6) the insulated top (MIT) (see Table 2 for abbreviation scheme) section tends to get significantly warmer in the early afternoon than the standard section. This could be explained by the fact that the insulated section does not lose heat from the bottom like the standard section. Since the bottom temperatures (Figures A-6 and A-7) track so closely, however, this explanation is not likely. It could be that the MIT thermistor itself did not make good thermal contact with the bridge deck and was extra sensitive to the effect of the sun.

The only two available approach temperatures were plotted on Figure A-9 and A-10. Both the top and bottom approach temperatures are more stable than their corresponding bridge temperatures. This is expected because of the thermal mass of the earth below. Herein is the basic cause of preferential icing.

For Dowd Junction (Figures A-11 through A-22) the 1981 average temperatures are running lower than the 1982 temperatures. This is due to a lot of missing data in 1981 during the warmer periods. After reviewing Figures A-11 and A-12, it can be noted that the insulated temperatures tend to run higher than the standard temperatures during the nighttime. This indicates the capacity of the insulation system to reduce preferential icing. A similar temperature difference is reflected in the 1981 bottom temperatures (Figures A-13 and A-15). For 1982 the nighttime difference for bottom temperatures is only slight (Figures A-14 and A-16). Figures A-17 and A-18 show the diurnal approach temperatures as related to the standard deck. Figure A-18 indicates the mode of failure of the approach thermistor. The seal on the thermistor failed, and water contaminated the thermistor. Whenever the water thaws out, a substantial error results. The final three diurnal graphs show ambient temperature, solar radiation, and wind patterns.

B. Histogram Discussion

Numerous histograms were developed based on the difference between three groups of two temperatures. Those histograms are only for data below 35 deg. F. Figure 16 is a typical example. The first difference is the top

```
BMD05D GENERAL PLOT - INCLUDING HISTOGRAM - VERSION OF AUG. 18, 1964
HEALTH SCIENCES COMPUTING FACILITY,UCLA
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Figure 16 Sample Histogram

```
                    TOP INSULATED TEMPERATURE MINUS TOP STANDARD TEMPERATURE AT DOWD JCT.
                    WHEN SURFACE TEMPERATURE IS LESS THAN 35 DEG. F. for 1982.
MIN =     -9.000000                                                                   MAX =        8.040000
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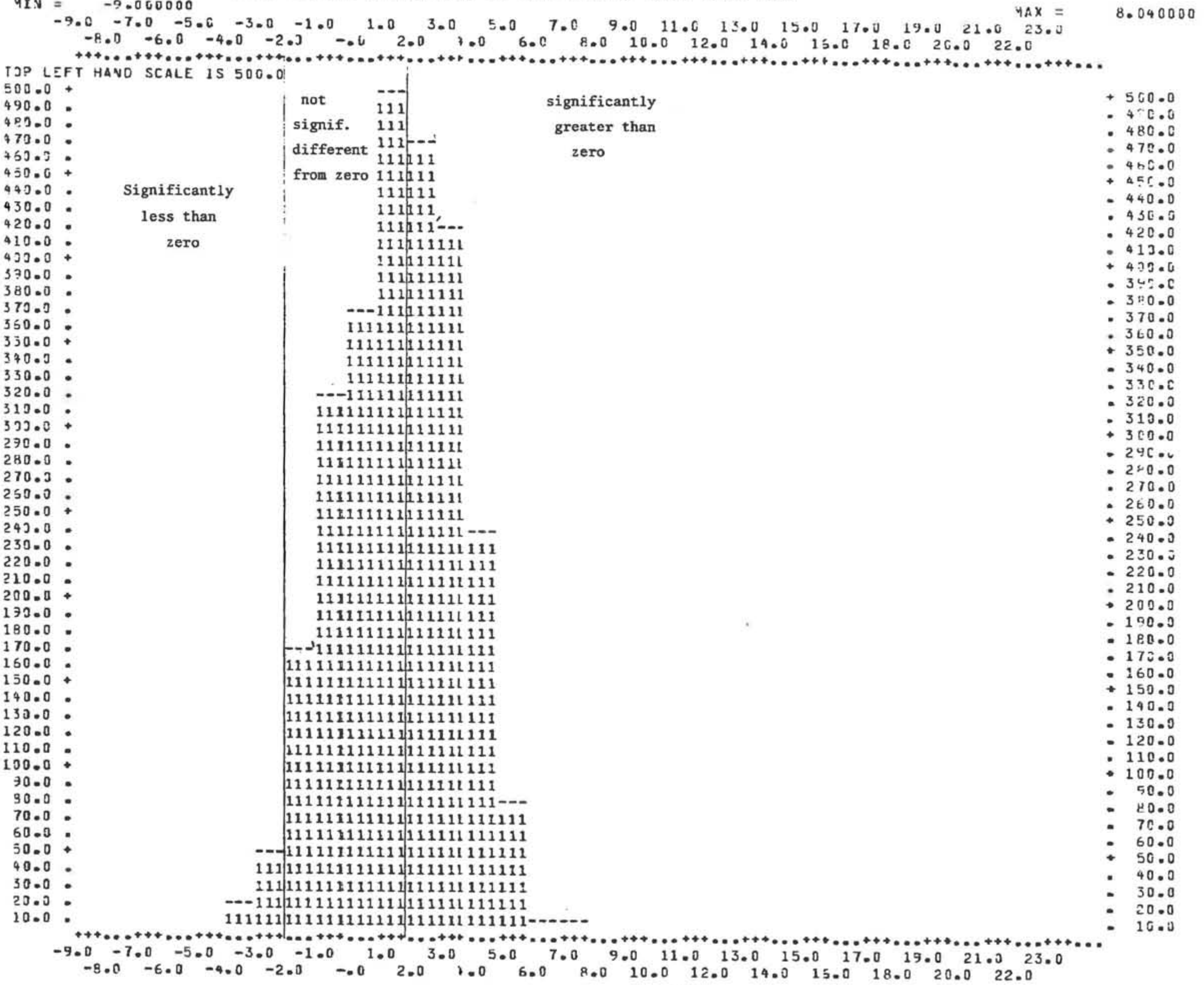


insulated temperatures minus the top standard temperatures for each bridge. The more time this difference is positive, the better the insulation is doing. The second difference is the top approach temperatures minus the top insulated temperatures. The more time this is positive, the more chance there will be of preferential icing over the insulation. The third difference is the top approach temperatures minus the top standard temperatures. The more time this is positive, the more chance of preferential icing over the standard section of the bridge. Similarly, histograms based on the difference between bottom insulated and bottom standard temperatures were generated. These histograms should show similar results to their corresponding top histograms and reinforce the conclusions reached from the top surface histograms. Statistics were derived from these histograms which demonstrated the likelihood of preferential icing and the statistical performance of the insulation systems. These results are discussed in the next section.

Even more selective histograms were created in order to examine the impact that wind speed and direction has on preferential icing at Dowd Junction. Histograms for the same three differences discussed above were created for the case of high winds, low winds, winds parallel to the bridge, and winds perpendicular to the bridge. Low winds were defined as one standard deviation or more below the average (the lower 16 percentile of the wind speeds). Conversely, high winds were defined as one standard deviation or more above the average wind speed (the upper 16 percentile of the wind speeds). Parallel wind was defined as any direction plus or minus 30 degrees parallel to the bridge, and perpendicular wind was defined as any wind within 30 degrees from perpendicular. Discussion as to the effect of wind on preferential icing is in the next section.

In order to investigate the thermal response of different bridge designs, two additional difference histograms were developed for the Vail Pass bridges. They are (1) the Miller Standard Top temperatures (MST) minus the Polk Standard Top temperatures (PST) and (2) the Miller Insulated Top temperatures (MIT) minus the Polk Insulated Top (PIT). The distribution for the insulated difference is narrower than that for the standard difference. This indicates the ability of the insulation to help different bridge designs to behave (thermally) similarly.

C. Performance Statistics

In order to evaluate the performance of the insulation, statistics were derived from the histogram. This data is shown on Tables 17 through 20. The abbreviation scheme is shown in Appendix B.

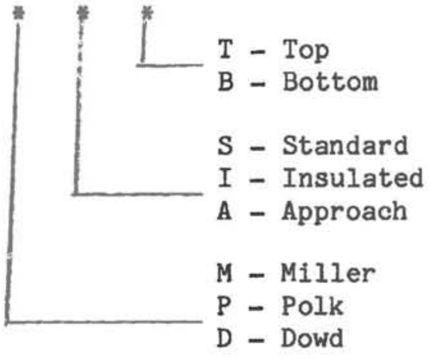
In order to derive these statistics each histogram was divided into three sections (see Figure 16). The first section corresponds to the time the difference is significantly less than zero which was decided to be 2 deg. F or more below zero. The second section corresponds to the time the difference is not significantly different from zero (within 2 deg. F of zero). Finally, the last section corresponds to the time the difference is significantly greater than zero (2 deg. F or more above zero). For each of the categories, the total number of half-hour intervals in each category was recorded, and the percentage in each category was computed. In most cases the most significant entry in these tables will be in the last column.

1. Miller Creek. For the overall performance of the insulation at Miller Creek during 1981, lines 1-4 of Table 17 can be referenced. Because of the failure of the top approach sensor at Miller Creek (MAT), the corresponding temperature data at Polk Creek was used (PAT). Because of the close proximity of the two structures no significant error should

Table 17

Miller Creek
Histogram Statistics
For Data Below 35 Degrees F

Variable	Significantly Less Than Zero		Not Significantly Different from Zero		Significantly More Than Zero	
For 1981	Count	Percentage	Count	Percentage	Count	Percentage
1. MIT-MST	270	10	2412	87	72	3
2. PAT-MIT	65	3	1963	77	520	20
3. PAT-MST	486	20	1305	55	585	25
4. MIB-MSB	0	0	2790	100	0	0
For 1982						
5. MIT-MST	495	24	1467	72	90	4
6. PAT-MIT	759	35	1267	59	121	6
7. PAT-MST	924	51	784	43	98	3
8. MIB-MSB	650	22	2028	67	338	11



result. Based on lines 2 and 3, the insulation reduced the chance of preferential icing during the testing in 1981; i.e., for 1981 the untreated bridge deck was colder than the approach 25% of the time, while the insulated deck reduced this to 20% of the time. This positive benefit of insulation is not supported by the statistics from line 1 or 4. Line 1 indicates that the insulated section is warmer than the standard less often than it is colder (3 versus 10%). Line 4 indicates that the insulated and standard bottom temperatures are never significantly different.

For the performance of the insulation during the 1982 portion, lines 5-8 of Table 17 can be referenced. Lines 6 and 7 indicate that the likelihood of preferential icing is small (3-6%) with a slightly higher possibility for preferential icing over the insulated deck. This is supported by the results of lines 5 and 8. Line 5 indicates that the top standard is warmer than the top insulated six times longer than it is colder (24 to 4%). Additionally, line 8 indicates that the <u>bottom standard</u> is warmer than the <u>bottom insulated</u> twice as long as the other way around (22 to 11%).

Based on this analysis, it can be concluded that insulating this concrete box girder bridge does not reduce preferential icing but can slightly increase this hazardous situation.

2. <u>Polk Creek</u>. Performance of the insulation at Polk Creek in 1981 is shown on lines 1-4 of Table 18. Based on lines 2 and 3, the insulation increases the chance of perferential icing just slightly (38 to 40%). This conclusion is not supported by line 1, but is supported by line 4. Line 1 indicates that the top insulated section is warmer than the top standard about twice as often (2 to 4%) although most of the time (94%) no difference is experienced. Conversely, line 4 indicates that the bottom standard is warmer than the bottom insulated about twice as often as the

reverse (9 to 5). The times the insulated and standard are different are so small that it should not be considered significant.

For 1982 performance lines 5-8 of Table 18 should be referenced. Based on lines 6 and 7 the insulation has a slight edge (16 to 14%) over the standard. Line 5 indicates that 87% of the time the top insulated and standard temperatures are the same, and one is above the other as often as the reverse.

Overall, the results are too close to call and it can be concluded that insulating a steel box girder bridge does not significantly affect the preferential icing potential of the bridge.

3. Miller-Polk Comparison. Table 19 was created to compare the thermal behavior of the two Vail Pass bridges. For both 1981 and 1982 the insulation caused the temperatures between Polk Creek and Miller Creek to be the same more often. Despite the fact the insulation does not significantly reduce the preferential icing for these types of structures, it can still be used to help them behave similarly.

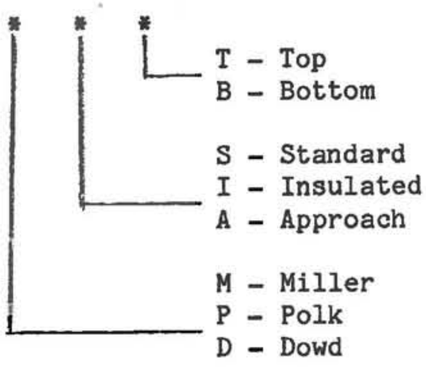
4. Dowd Junction. For the overall performance of insulation at Dowd Junction during 1981 lines 1-4 of Table 20 can be referenced. Based on lines 2 and 3, the insulation reduced the chance of preferential icing by reducing the time the deck temperature was below the approach from 83% of the time to 73% of the time. This conclusion is supported by the statistics on lines 1 and 4. Line 1 indicates that the insulated deck remained at a higher temperature than the standard 23% of the time while dropping below the standard only 1% of the time. Similarly the bottom temperature of the insulation remained higher than the bottom standard five times as long (25% to 5%) than the reverse.

For the performance of the insulation during the 1982 testing, lines 11-14 of Table 20 should be referenced. Similarly to the 1981 statistics, lines 12 and 13 indicate that the insulation decreases the chance of

Table 18

Polk Creek
Histogram Statistics
For Data Below 35 Degrees F

Difference	Significantly Less Than Zero		Not Significantly Different From Zero		Significantly More Than Zero	
For 1981	Count	Percentage	Count	Percentage	Count	Percentage
1. PIT-PST	44	2	2486	94	110	4
2. PAT-PIT	0	0	1680	63	1008	38
3. PAT-PST	14	1	1582	59	1064	40
4. PIB-PSB	240	9	2288	86	144	5
For 1982						
5. PIT-PST	220	7	2706	87	198	6
6. PAT-PIT	420	13	2198	70	504	16
7. PAT-PST	480	15	2192	70	448	14
8. PIB-PSB	sensor failure					



* * *

T - Top
B - Bottom

S - Standard
I - Insulated
A - Approach

M - Miller
P - Polk
D - Dowd

Table 19

Miller-Polk Comparison
Histogram Statistics
For Data Below 35 Degrees F

Variable	Significantly Less Than Zero		Not Significantly Different From Zero		Significantly More Than Zero	
For 1981	Count	Percentage	Count	Percentage	Count	Percentage
1. PIT-MIT	576	23	1920	76	32	1
2. PST-MST*	297	13	1573	66	506	21
For 1982						
3. PIT-MIT	720	34	1272	61	108	5
4. PST-MST	960	54	666	38	150	8

* * *

T - Top
B - Bottom

S - Standard
I - Insulated
A - Approach

M - Miller
P - Polk
D - Dowd

Table 20

Dowd Junction
Histogram Statistics
For Data Below 35 Degrees F

Variable	Significantly Less Than Zero		Not Significantly Different From Zero		Significantly More Than Zero	
For 1981	Count	Percentage	Count	Percentage	Count	Percentage
1. DIT-DST	18	1	1089	76	324	23
2. DAT-DIT	153	12	183	15	894	73
3. DAT-DST	144	12	68	5	1028	83
4. DIB-DSB	72	5	981	70	342	25
low winds						
5. DIT-DST	0	0	60	88	8	12
6. DAT-DIT	6	11	4	7	47	82
7. DAT-DST	5	9	3	5	49	86
high winds						
8. DIT-DST	24	11	178	83	14	6
9. DAT-DIT	11	6	15	8	164	86
10. DAT-DST	11	6	18	9	160	85
For 1982						
11. DIT-DST	70	3	1360	51	1230	46
12. DAT-DIT	945	39	539	22	959	39
13. DAT-DST	783	29	639	24	1251	47
14. DIB-DSB	84	3	2541	91	168	6
low winds						
15. DIT-DST	3	2	83	62	49	36
16. DAT-DIT	39	33	23	19	57	48
17. DAT-DST	41	31	30	22	62	47
high winds						
18. DIT-DST	6	2	196	70	78	28
19. DAT-DIT	95	36	61	23	106	41
20. DAT-DST	94	34	81	29	103	37
parallel wind						
21. DIT-DST	24	7	218	63	104	30
22. DAT-DIT	92	28	58	18	180	54
23. DAT-DST	98	29	74	22	169	49
perpendicular wind						
24. DIT-DST	18	1	612	43	798	56
25. DAT-DIT	590	45	312	23	424	32
26. DAT-DST	420	29	372	26	654	45

preferential icing by reducing the time when the deck temperature is below the approach from 47 to 39% of the time. This is supported by the statistics on lines 11 and 14. Line 11 indicates that the top insulated deck is warmer than the standard 46% of the time. Similarly line 14 indicates that the bottom insulated and standard temperatures are not significantly different 91% of the time. During the 9% of the time they are different, the insulated temperature is higher 6% of the time.

Reduction of preferential icing potential by insulating was realized both for 1981 and 1982 data. The data can be combined for an overall reduction from 58.2% to 50.4%. This ability of the insulation system to reduce preferential icing is further verified by the time lapse filming which recorded several episodes where the insulated deck remained ice free while the standard did not.

Additional statistics were generated for various wind configurations to determine the effect wind had on preferential icing. These statistics were based on low winds, high winds, parallel winds, and perpendicular winds. During both low winds and high winds there is a notable increase in preferential icing potential for the insulated deck for both 1981 and 1982 data (see lines 5-10 and lines 15-20). For the standard deck the difference is not so prominent. All in all the insulation becomes less effective during extreme wind conditions (the low 16% and upper 16% of the wind speeds). Physically this can be explained as follows. During low winds the heat transfer is dominated by radiation effects on the top of the deck, and heat transfer from the bottom becomes negligible. During high winds the heat transfer between the top surface of the deck and the air is so strong that the deck temperature approaches the air temperature. The effect of insulation again becomes negligible. For parallel and perpendicular wind categories, the statistics (lines 21-26) show that insulation is effective when wind is perpendicular to to the structure and counter productive when wind is parallel. For the parallel wind category, there is a 5% increase in preferential icing due to insulation, while for perpendicular wind there is a 13% decrease in preferential icing potential. The confidence in this conclusion is not strong because line 25 does not support the conclusion that the insulation makes the deck cooler during parallel wind. Also the sample size for the parallel wind condition is small. The conclusion is also contrary to the results (Reference 1) where the effects of insulation on a Mississippi Avenue bridge in Denver, Colorado were investigated. The conclusion in that study was that perpendicular winds reverse the benefit of insulation. Both the statistical analysis used and the meteorology encountered were different from Dowd Junction. However, this points out that the effect of wind direction on insulation performance is not universally consistent and that a simple cause-effect relationship does not exist due to air circulation characteristics around the bridge.

D. Individual Event Analysis

Several events were recorded on time lapse film during the test period where preferential icing actually occurred. No time lapse data was collected at Polk Creek due to numerous equipment problems. At Miller Creek only one episode of preferential icing was found on the time lapse film, and no evidence of the insulation's making any difference was found. This is consistent with the statistics based on the temperature data at Miller Creek. At Dowd Junction numerous episodes of preferential ice were recorded on film, and during many of these the insulation reduced the time the bridge deck was iced up or snow covered.

January 10, 1982 at Miller Creek. Figure 21 is an enlargement up of the 8-mm time film for this day at Miller Creek when preferential icing occurred. The approach is wet, and the deck is snow packed; but there is no visual evidence of the insulation's making any difference. Temperature data during this event is not available.

November 6, 1981 at Dowd Junction. Figure 22 shows three levels of snow cover for the roadway at Dowd Junction. The standard section (over the river) has the most snow cover; the insulated section (over the railroad tracks) has less snow cover, and the approach is almost completely clear. Temperatures below the photo are consistent with the visual conclusions.

December 29, 1982 at Dowd Junction. Figure 23 shows a wet approach and a snow covered bridge with only a very slight difference between the insulated and standard sections. The temperature data also reflect the visual situation.

March 3, 1982 at Dowd Junction. Figure 24 shows an unusual situation where the insulated section is actually clearer than the approach.

April 3, 1982 at Dowd Junction. Figure 25 gives a very clear picture of how the insulation can make the bridge deck behave like the approach even when the rest of the deck is snow covered.

E. Benefit-Cost Analysis

For the three year period beginning February 1, 1979 the following icy bridge accidents were reported.

Polk Creek - None

Miller Creek - 1 accident with 2 injuries and a total economic loss of $7,680. No fatalities.

Dowd Junction - 16 accidents; 7 people injuried in 4 of the accidents; total economic loss of $62,370. No fatalities.

Figure 21

January 10, 1982 Preferential
Icing Event at Miller Creek

Figure 22

Preferential Icing Event at Dowd Junction

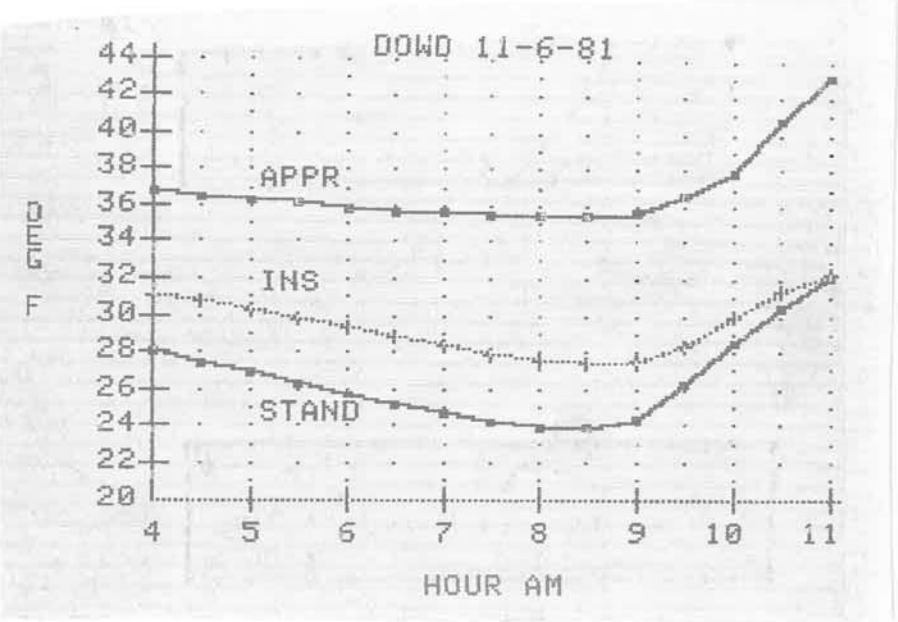


Figure 23

Preferential Icing Event at Dowd Junction

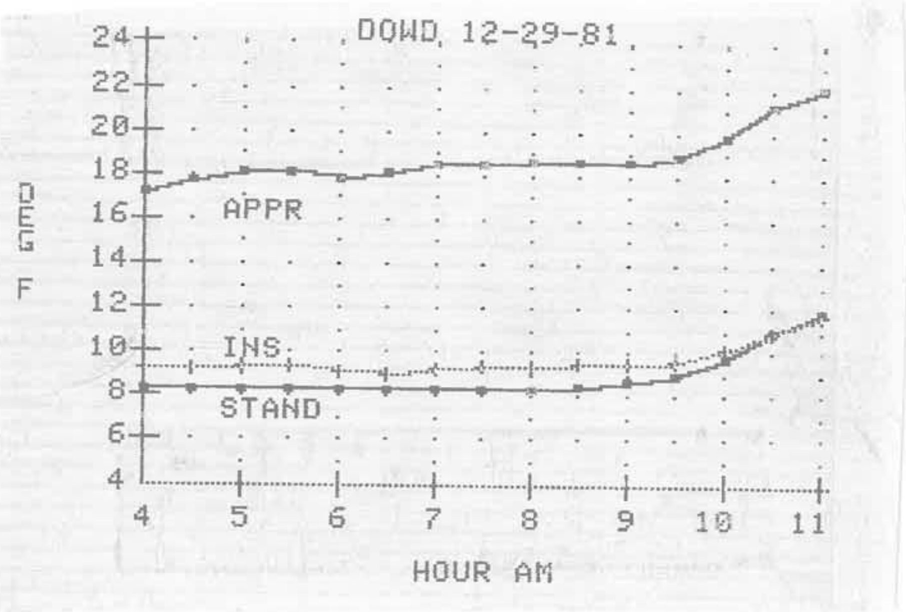


Figure 24

Preferential Icing Event at Dowd Junction

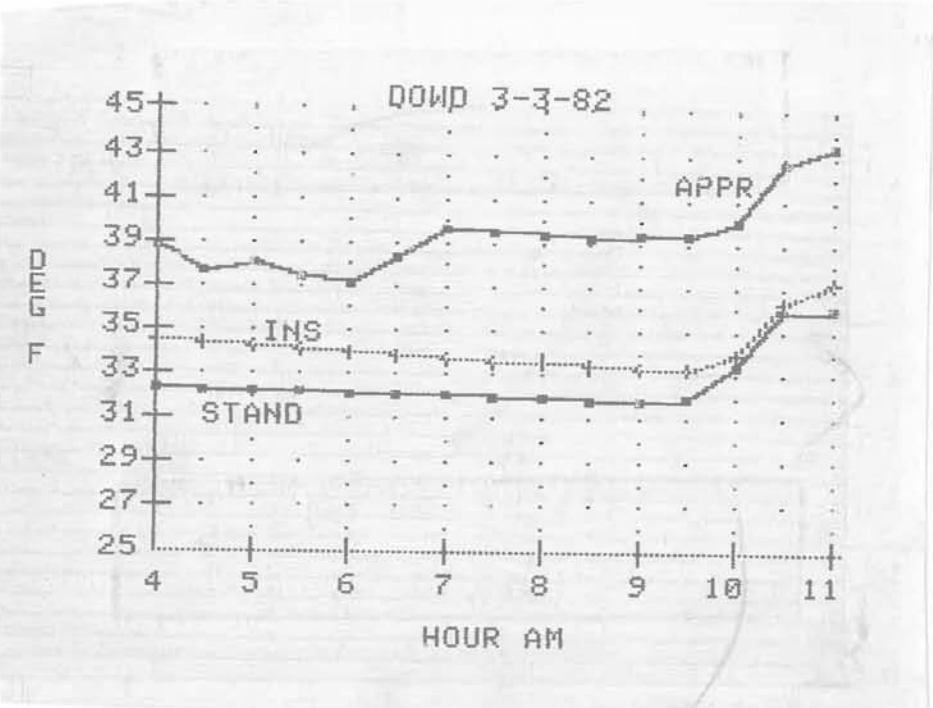
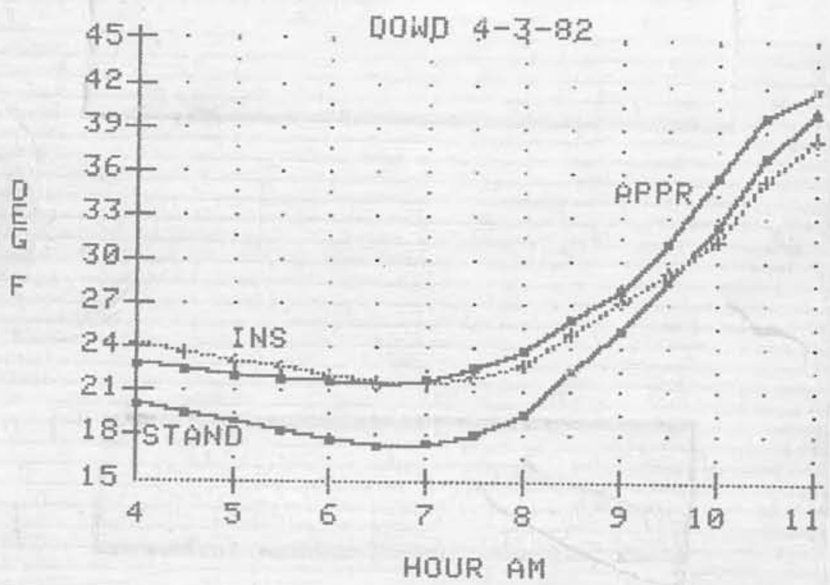


Figure 25

Preferential Icing Event at Dowd Junction



Polk Creek and Miller Creek. Since the effect of insulation on the Miller Creek and the Polk Creek structures was insignificant, the benefit/cost ratio of insulation will be zero. The fact that only one icy bridge accident happened on these two structures over three years indicates that preferential icing is not a serious problem here.

Dowd Junction. For Dowd Junction the insulation reduced the potential for preferential icing from 83% to 73% in 1981 and from 47 to 39% in 1982. Overall this corresponds to a reduction in preferential icing potential from 58.2% to 50.4%. For this analysis it is assumed that the lower temperature of the bridge was the predominant cause of the accident; i.e. if the bridge temperature was as warm or warmer than the approach, the accidents would not have happened. This assumption will result in calculating the upper limit of benefit/cost of the insulation. Since the economic loss due to icy bridge accidents for three years was $62,370, the average cost for one year (1980) should be one-third of this or $20,790. Based on the 1980 Traffic Volume Study (Reference 3), the year 2000 traffic will be 18 times 1980 traffic. Similarly, the accidents and costs will increase at the same rate which is $875 per year. By the end of 1983 (the earliest date bridge insulation could be complete), annual accident costs will have increased $875 per year to $23,415. If we assume a 4% interest rate over and above inflation* and a life expectancy of the insulation system for 20 years, present value of these accident costs can be computed as follows:

$875 x (Gradient Present Worth Factor -20 at 4%) = $97,619
plus
$23,415 x (Present Value of Annuity Factor 20 at 4%) = $318,217
Total $415,836

Total present value cost of icy bridge accidents from 1984 to 2004 is $425,836.

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*This analysis is based on constant dollars. For an 8% inflation rate, the 4% return on constant dollars would correspond to a market interest rate of 12%.

This cost exceeds the benefits by 76% (benefit/cost ratio of .57). It seems unlikely that in actuality the cost of this insulation would be less than the benefits since this represents the upper limit of the performance of insulation. One item that would change the statistics is a fatality occurring

Continuing, if the accidents are assumed to be reduced by the same portion of the time the potential for preferential icing is reduced, the economic loss due to accidents that can be eliminated by insulating the Dowd Junction structure is given as follows:

$$(415{,}836) \quad \frac{58.2\% - 50.4\%}{58.2\%} \quad = \quad \$55{,}731$$

It will require 18,000 square feet of panels and 23,000 square feet of insulation in order to insulate the eastbound Dowd Junction structure. Based on the average of the five law bidders, the cost will be as follows:

18,000 square feet of panel at $4.24	= $76,320
23,000 square feet of insulation at $.74	= $17,020
Mobilization	= $ 5,000
	$98,340

This cost exceeds the benefits by 76% (benefit/cost ratio of .57). It seems unlikely that in actuality the cost of this insulation would be less than the benefits since this represents the upper limit of the performance of insulation. One item that would change the statistics is a fatality occurring due to ice on this bridge. Fortulately no fatal accidents have occurred, but the probability of one occurring is not insignificant because four injury accidents have already occurred.

Because of the high cost of panels, significant saving could be realized by applying foam insulation directly to the bottom of the bridge deck. Cost for that type of system would be approximately $28,000. The performance of this type of system would be less than that tested because the heat capacity of the air and steel below the deck would be isolated. Even if the performance were reduced to half as much, the benefit/cost ratio would be close to one. This is still the upper limit of insulation performance because all the icy bridge accidents were assumed to be eliminated whenever the bridge deck temperature was at or above the approach.

VI. CONCLUSIONS AND IMPLEMENTATION

Among the three types of bridges studied, test results of insulation performance was varied. For the Polk Creek and Miller Creek Bridges (steel box girder and concrete box girder) the insulation did not significantly decrease or increase the potential of preferential icing. For the Dowd Junction Structure (steel I-beams), however, results of insulation was favorable.

For Dowd Junction during the entire test period temperatures were such that preferential icing was possible 58.2% of the time for the uninsulated section and 50.4% of the time for the insulated section. Despite the high accident rate at this location, the benefit/cost ratio for this system is expected to be 75% less than one. This is primarily due to relatively high cost of the panels which must stretch between the I-beams to support the insulation at the bottom of the beams. If foam insulation is sprayed on the bottom of the deck instead of the system tested, the benefit/cost would be larger than one, provided the performance is not reduced more than 50%. This cost analysis, however, assumes the icy accidents will never happen when the bridge deck is at or above the approach temperature.

By comparing the statistics from each bridge it is apparent that the I-beam bridges are most susceptible to preferential icing. The steel box girder bridge is less susceptible than the steel I-beam but more than the concrete box girder bridge.

All other factors being equal, concrete box girder bridges should be chosen over other types of structures studied because of their superior thermal performance. When severe weather and numerous icy bridge accidents are expected on a steel I-beam bridge, insulation should be considered.

REFERENCES

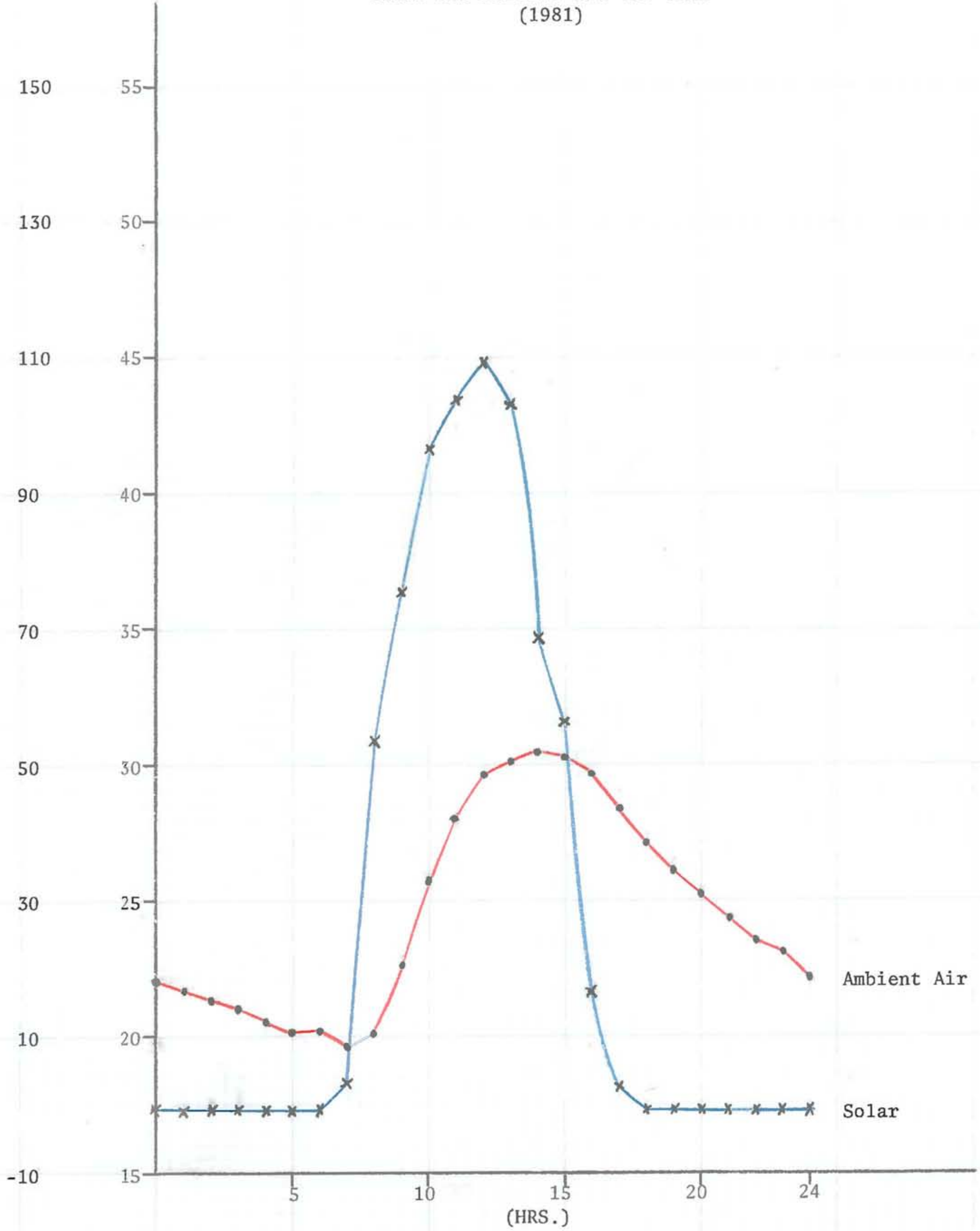
1. Blackburn, R.R., Glennon, J.C., Glautz, W.D., and St. Johns, A.D.; Economic Evaluation of Ice and Frost on Bridge Decks; NCHRP Report No. 182.

2. Griffin, Richard G., Jr., "Infrared Heating to Prevent Preferential Icing of Concrete Box Girder Bridges," Colorado Division of Highways, Report No. CDOH-P&R-R&SS-75-3, Final Report, June 1975.

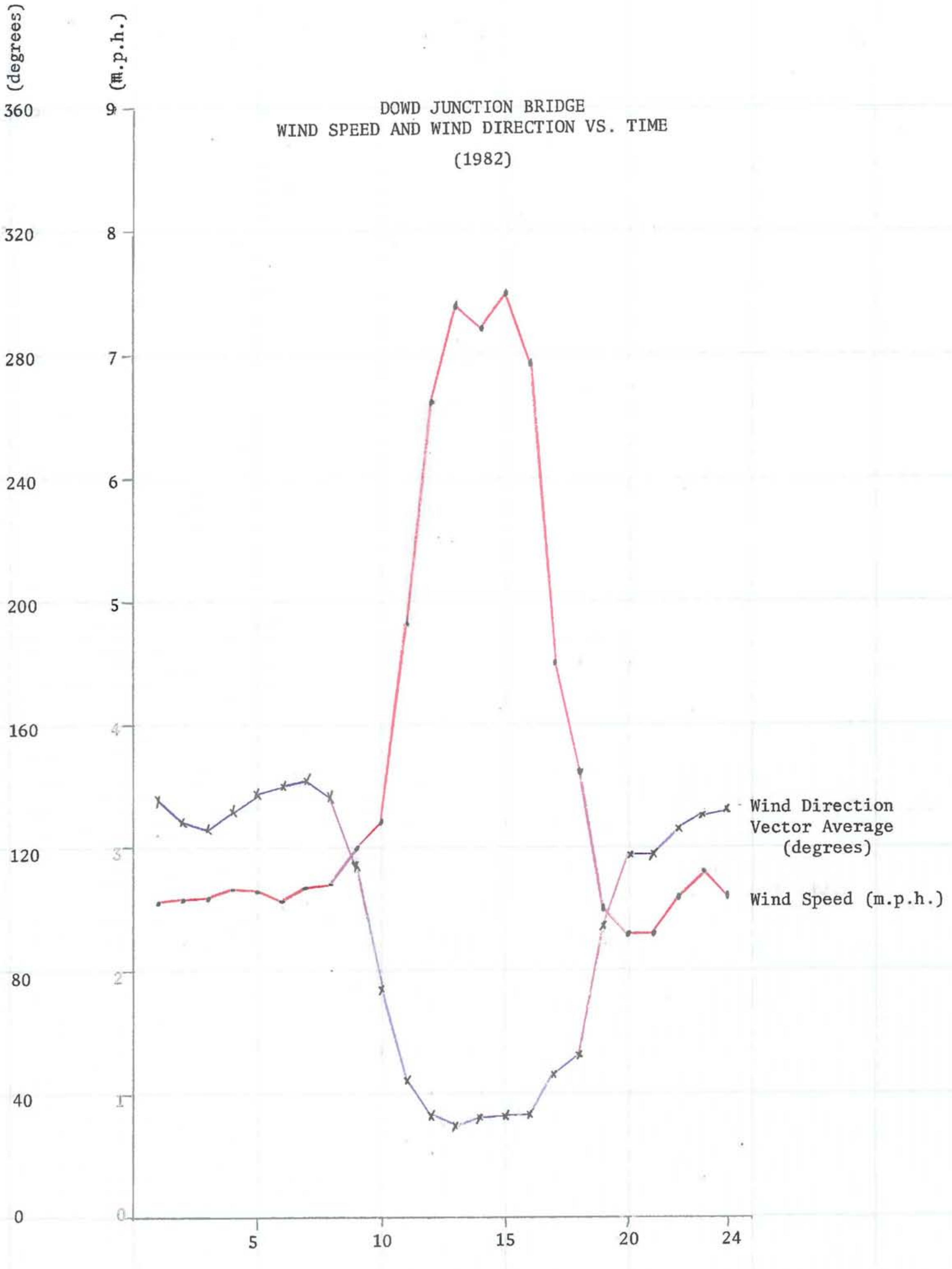
3. Colorado Traffic Volume Study - 1980, Colorado Department of Highways, 4201 E. Arkansas, Denver, Colorado 80222.

APPENDIX

Diurnal Data Plots

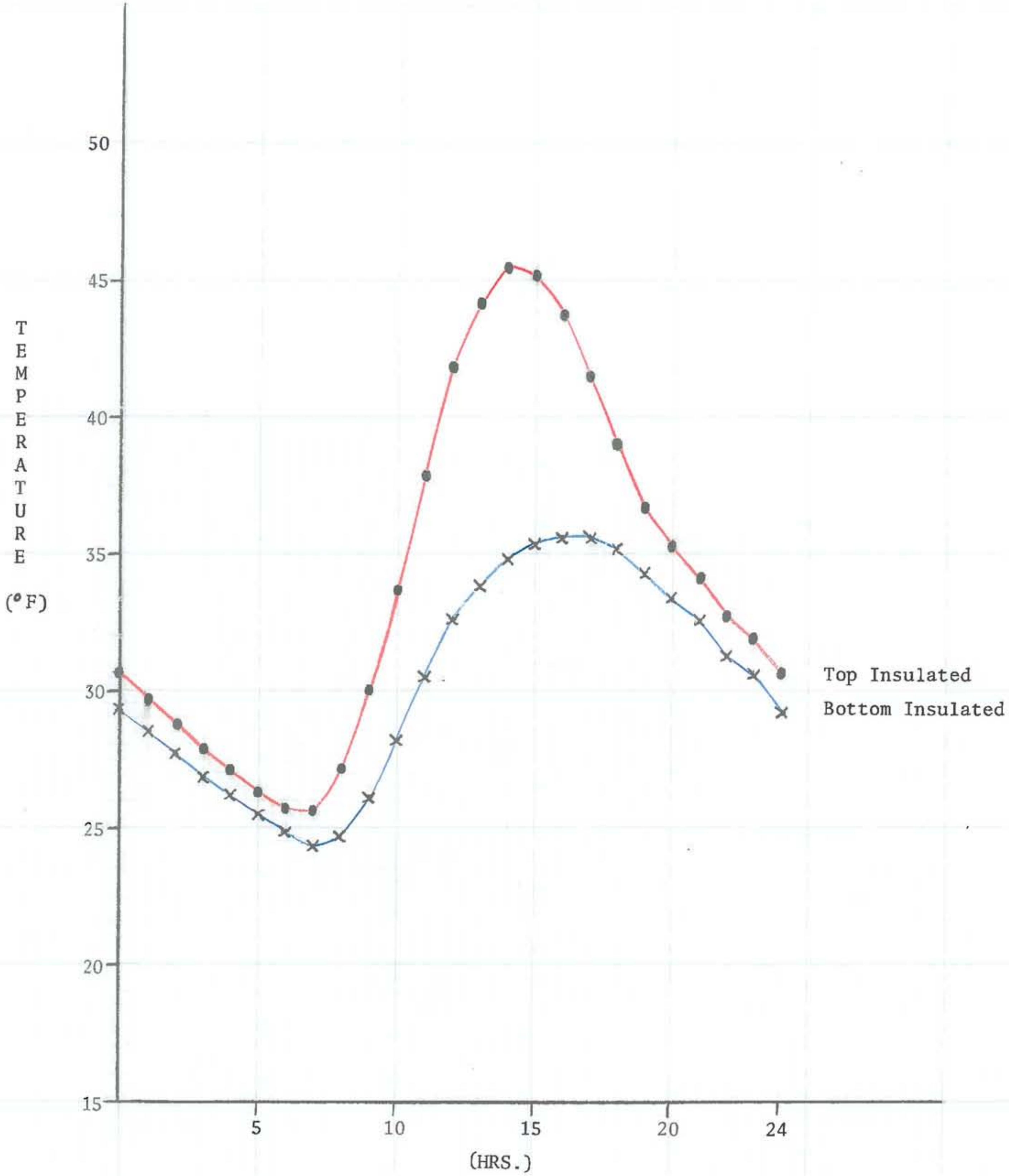


DOWD JUNCTION BRIDGE
SOLAR AND AMBIENT AIR VS. TIME
(1981)



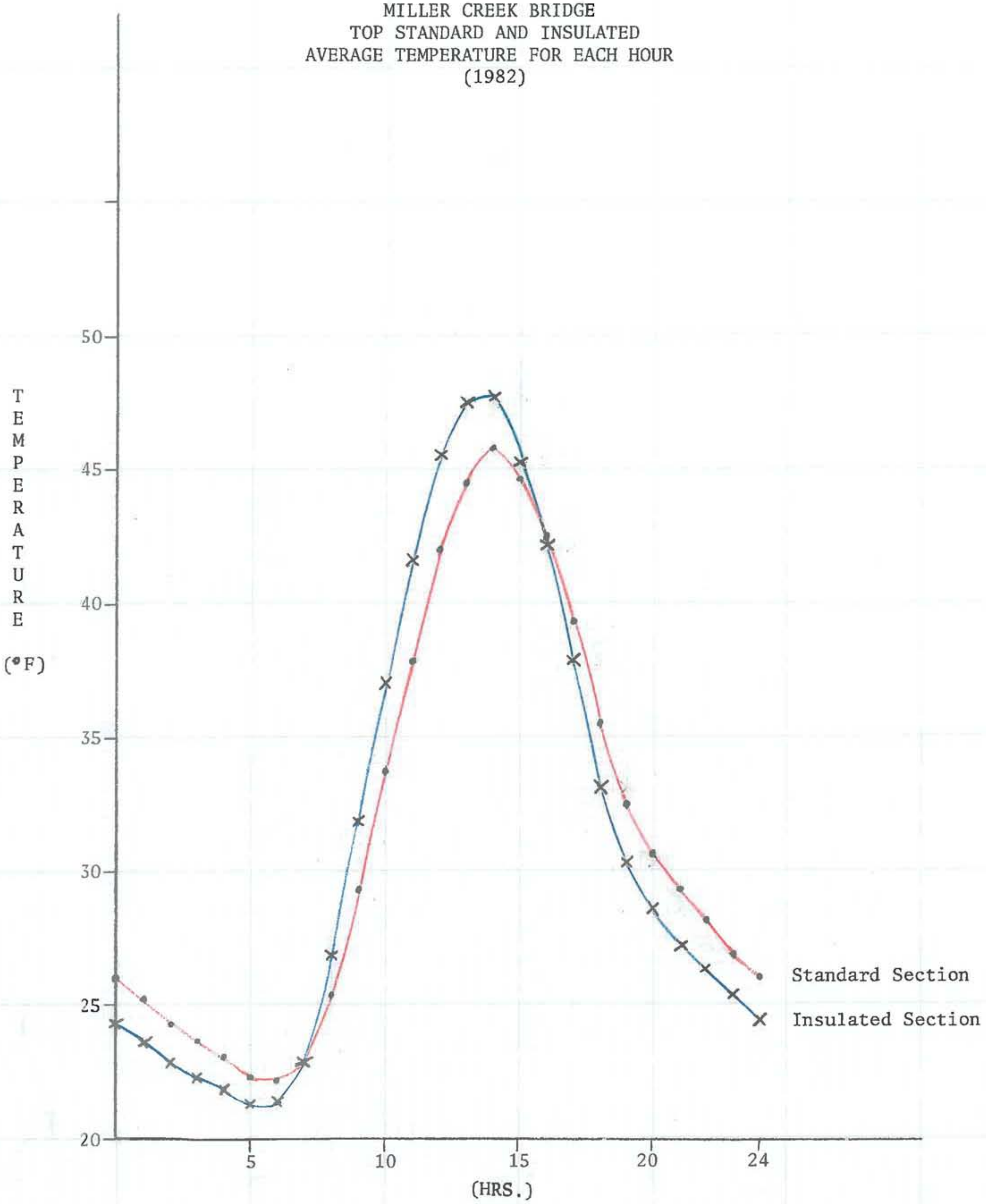
(degrees)
(m.p.h.)
DOWD JUNCTION BRIDGE
WIND SPEED AND WIND DIRECTION VS. TIME
(1982)
360
320
280
240
200
160
120
80
40
0
9
8
7
6
5
4
3
2
1
0
5
10
15
20
24
Wind Direction
Vector Average
(degrees)
Wind Speed (m.p.h.)

DOWD JUNCTION BRIDGE
TOP INSULATED AND BOTTOM INSULATED
AVERAGE TEMPERATURE FOR HOUR
(1982)

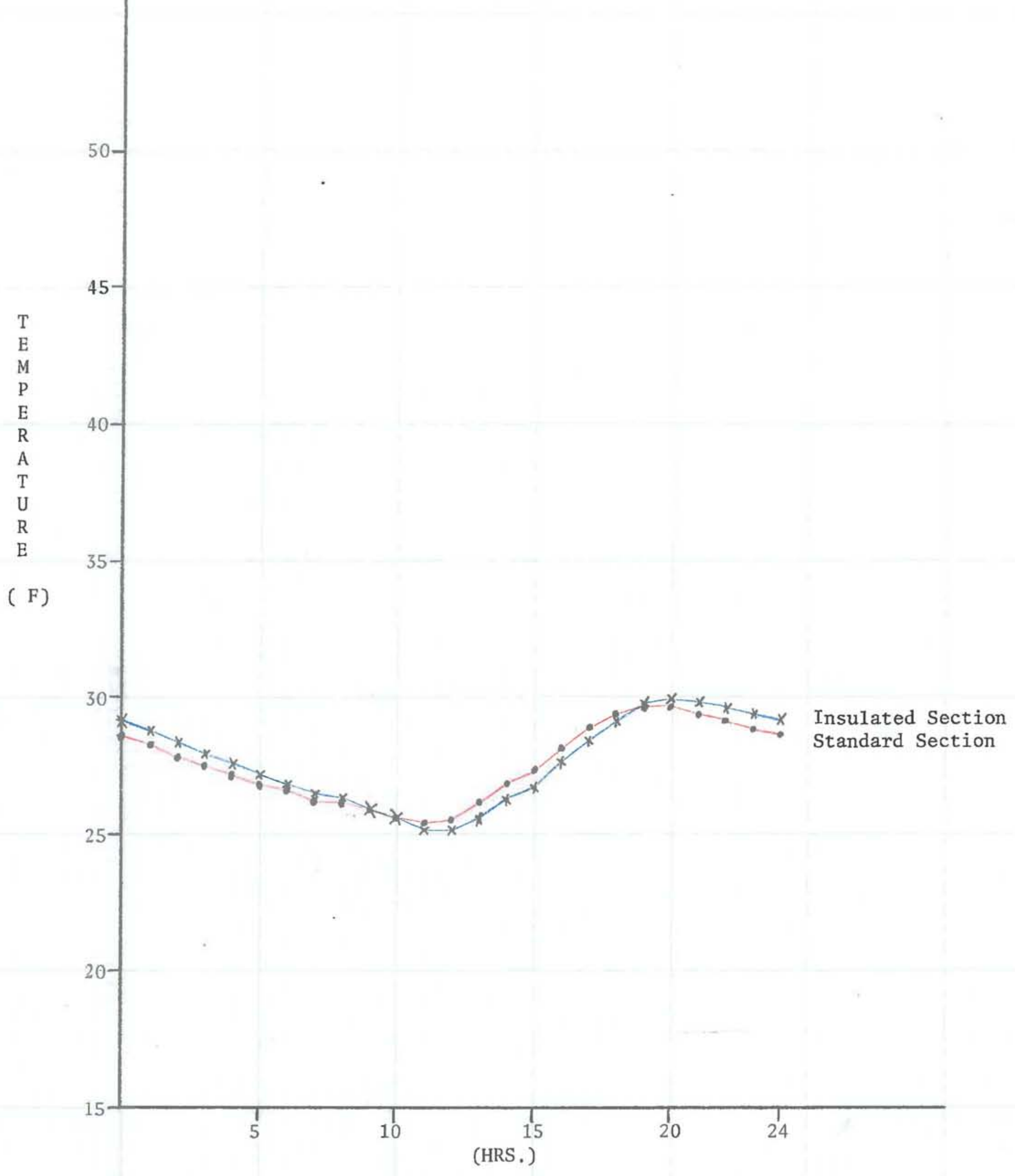


-3° on standard
section temp.

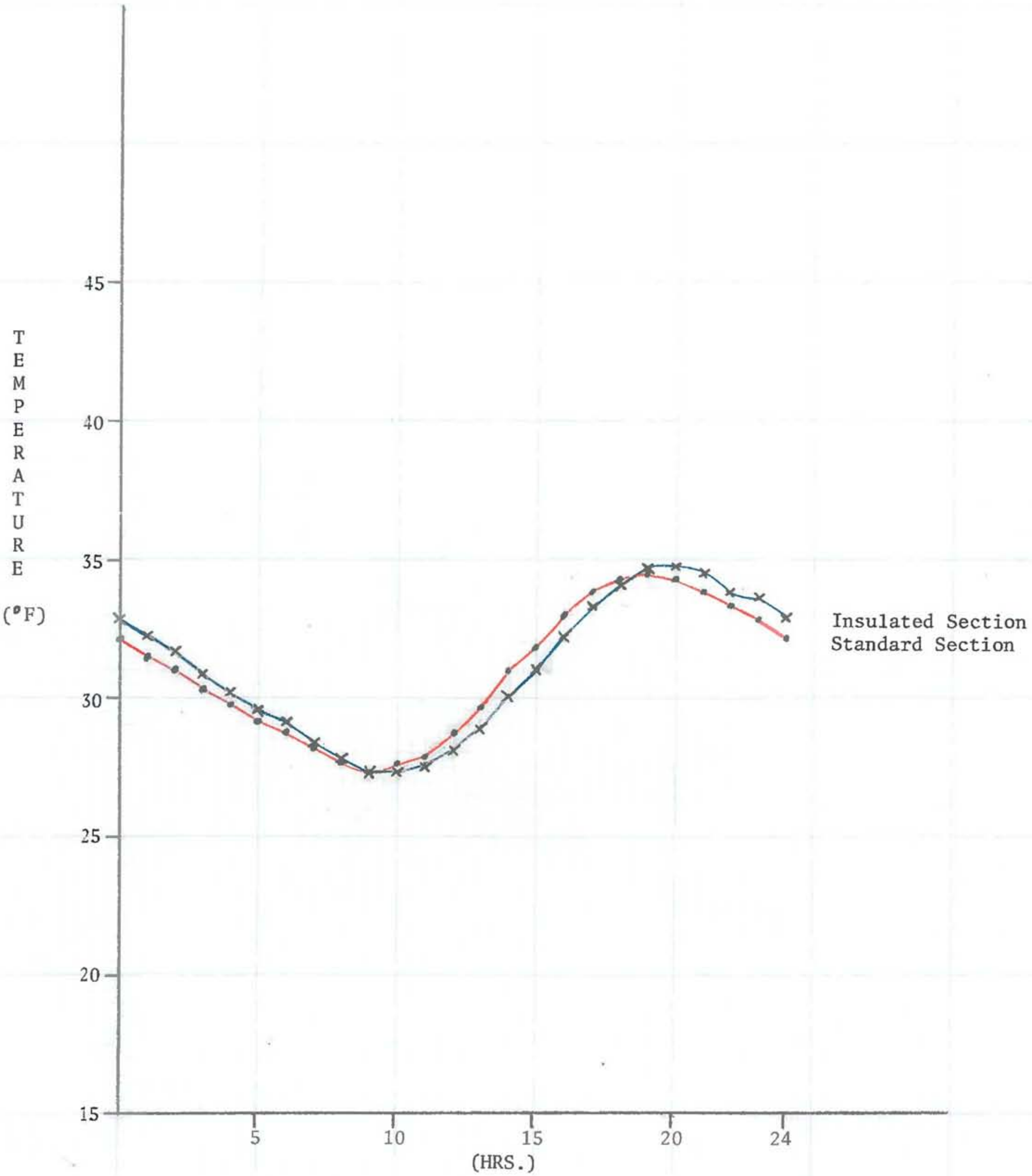
MILLER CREEK BRIDGE
TOP STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1982)



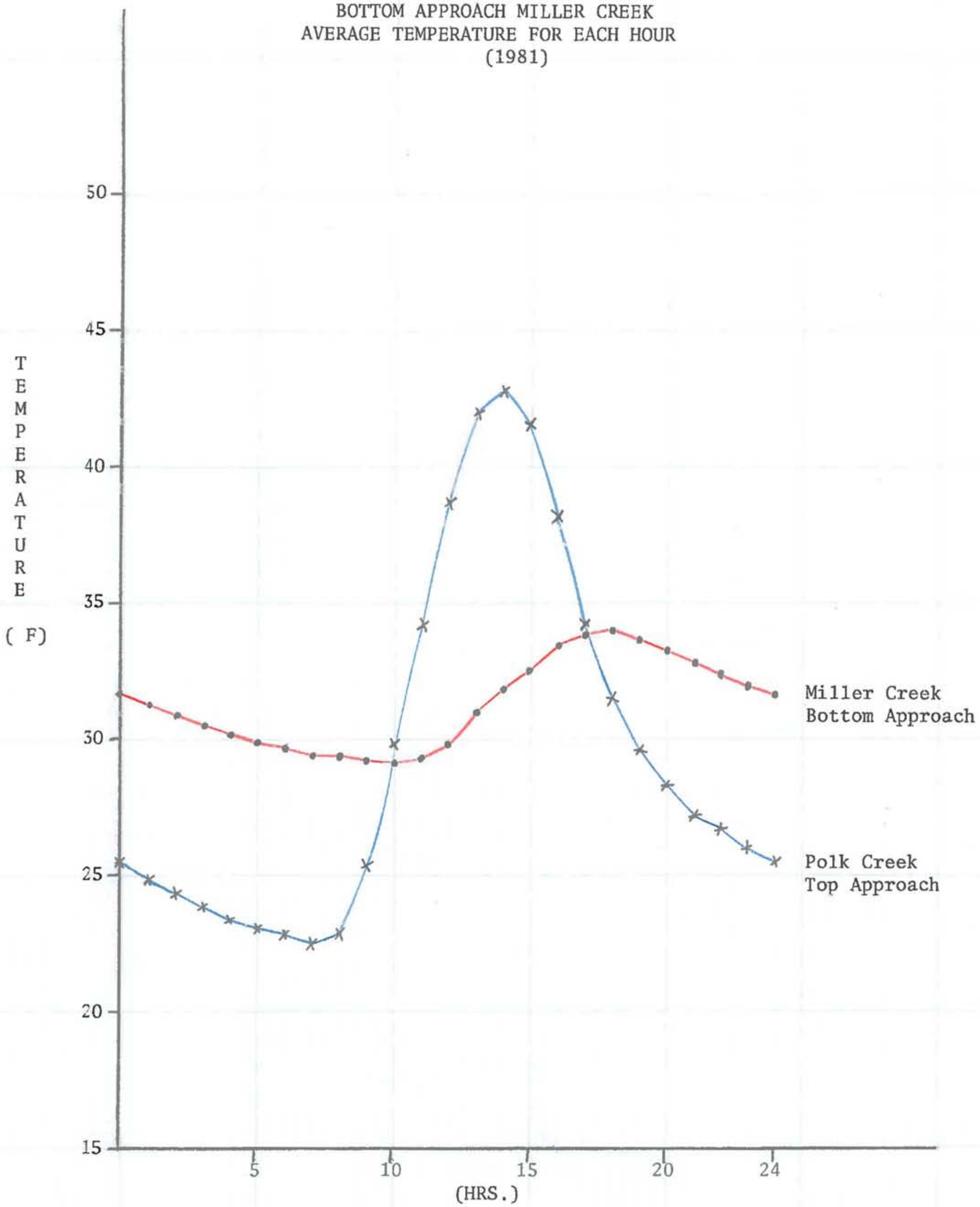
MILLER CREEK BRIDGE
BOTTOM STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1981)



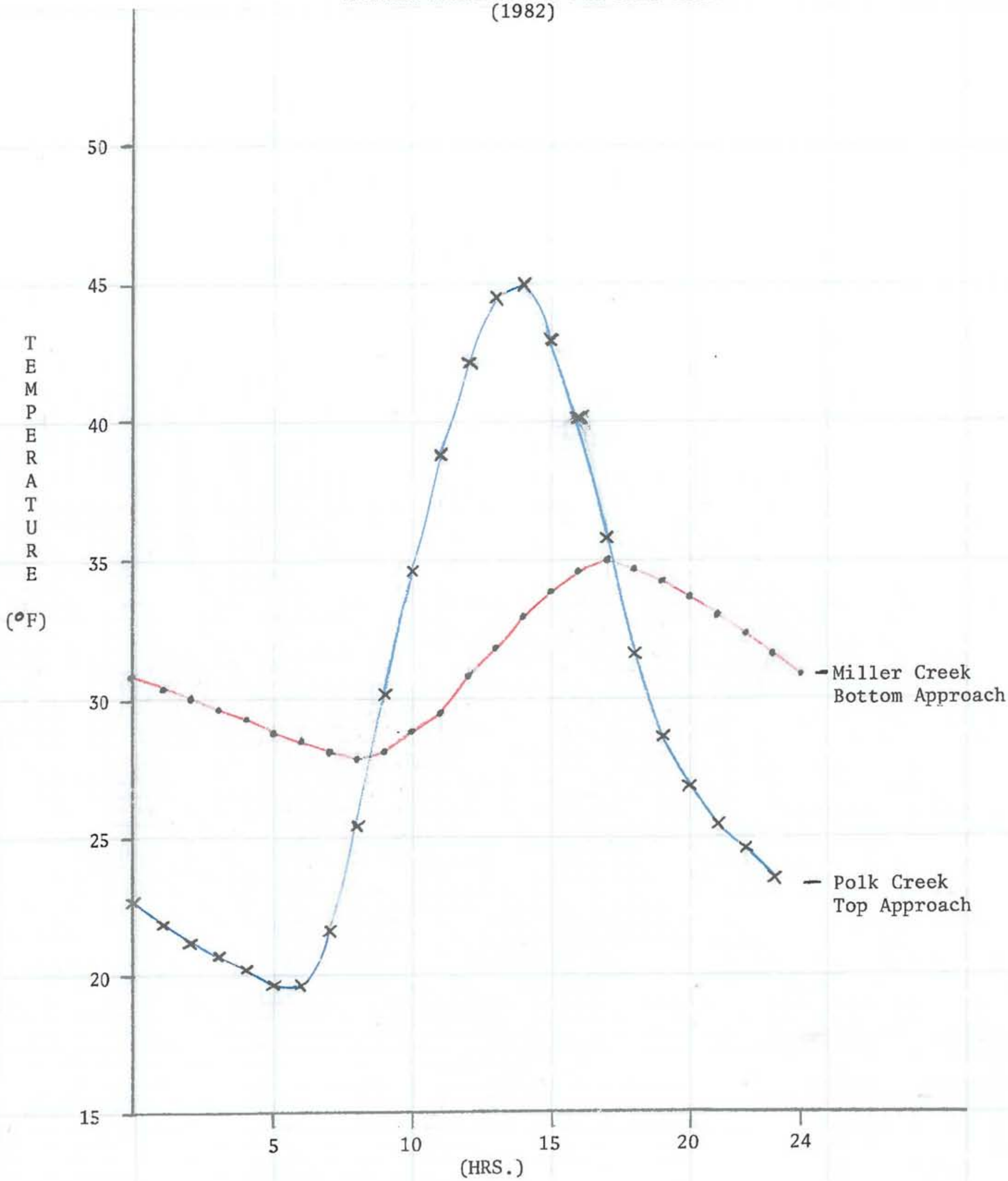
MILLER CREEK BRIDGE
BOTTOM STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1982)



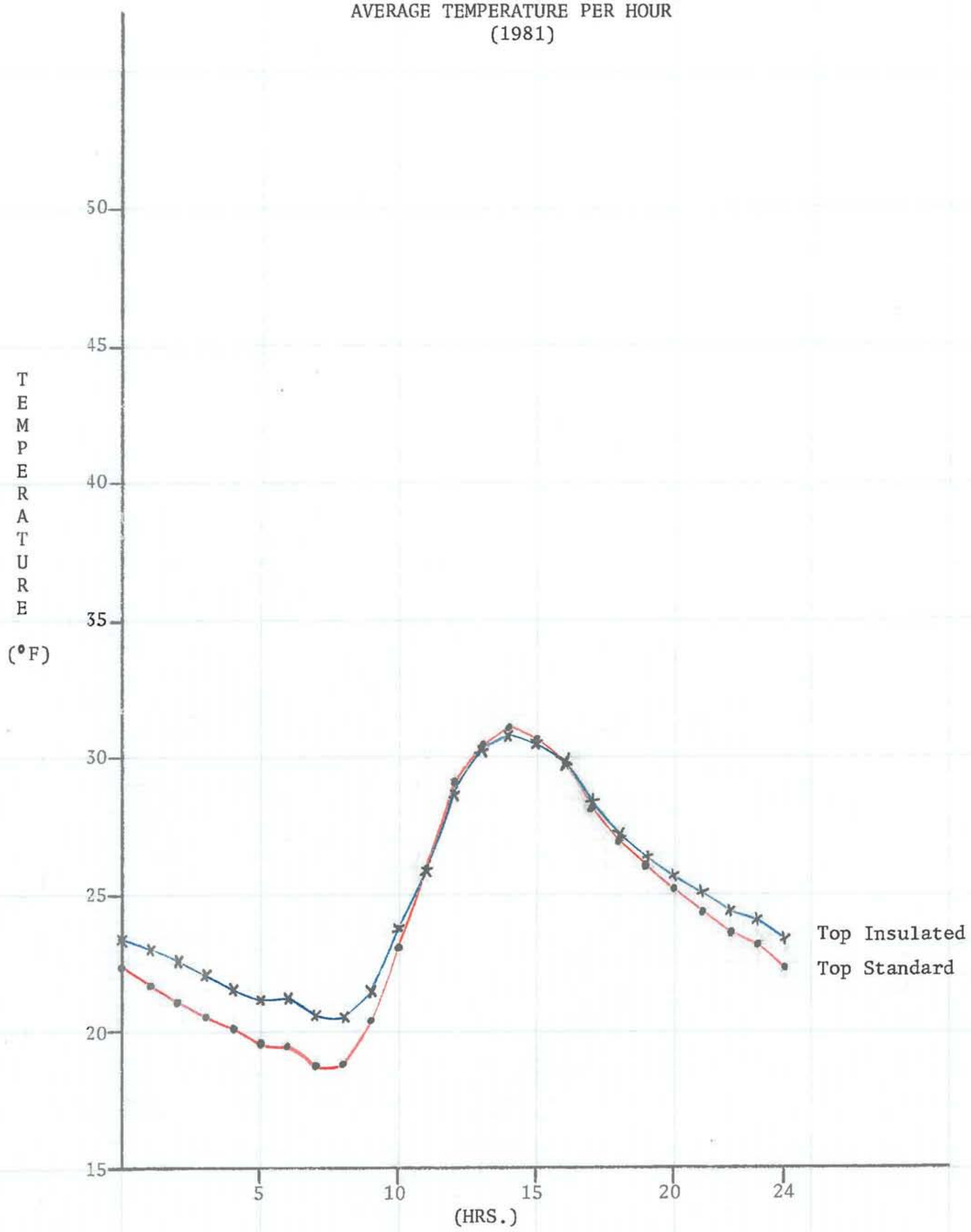
TOP APPROACH POLK CREEK AND
BOTTOM APPROACH MILLER CREEK
AVERAGE TEMPERATURE FOR EACH HOUR
(1981)



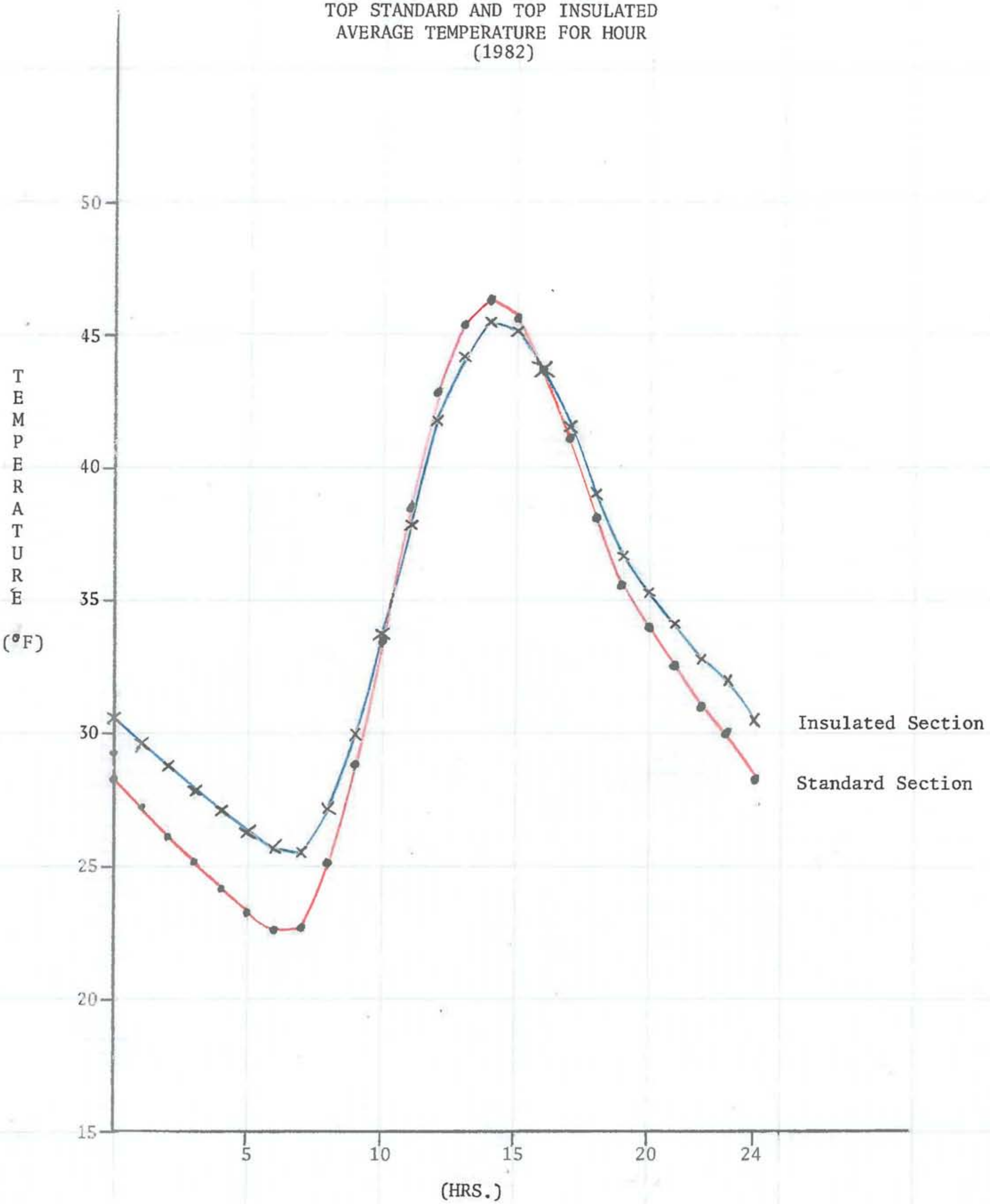
TOP APPROACH POLK CREEK AND
BOTTOM APPROACH MILLER CREEK
AVERAGE TEMPERATURE FOR EACH HOUR
(1982)



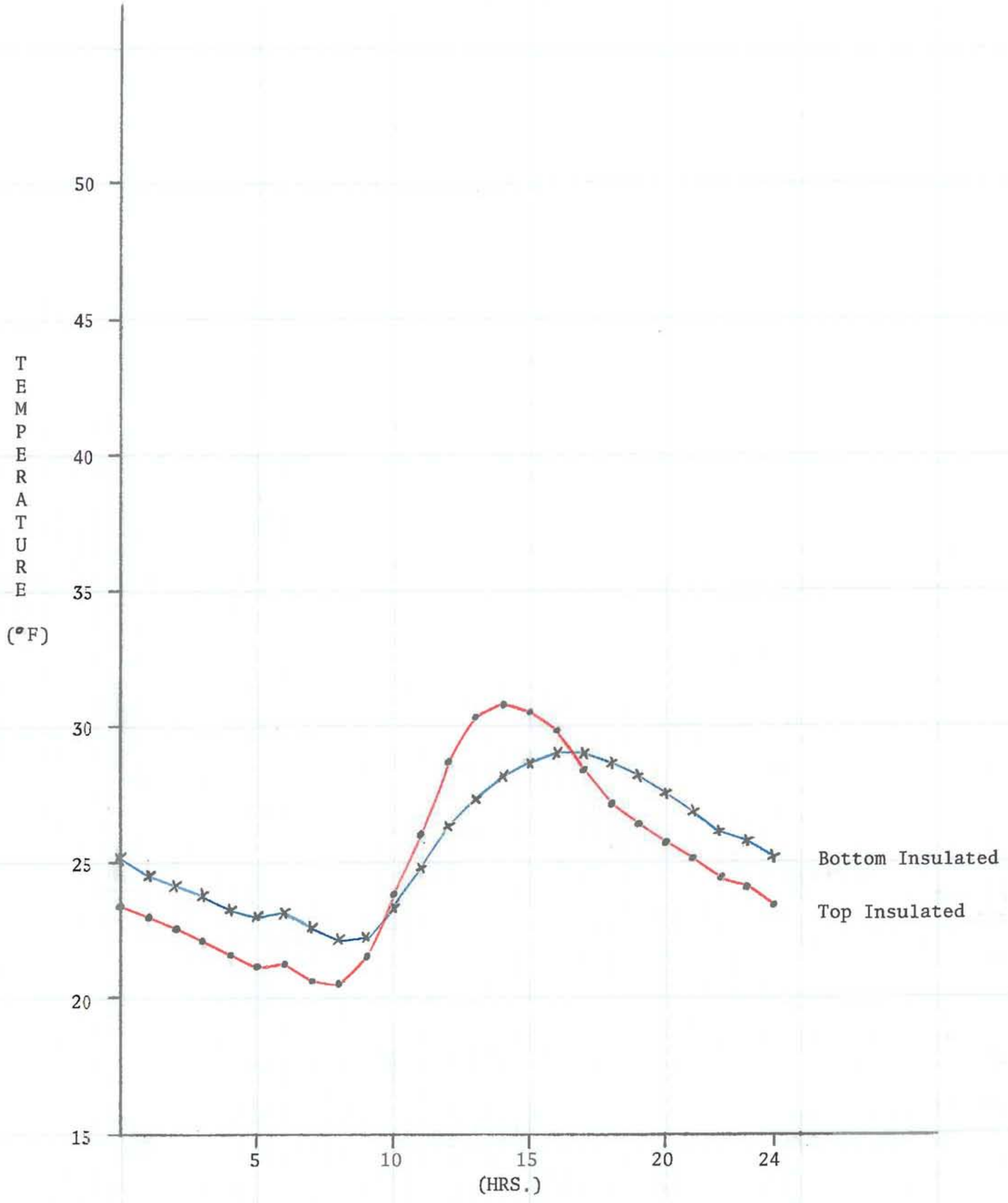
DOWD JUNCTION BRIDGE
TOP STANDARD AND TOP INSULATED
AVERAGE TEMPERATURE PER HOUR
(1981)



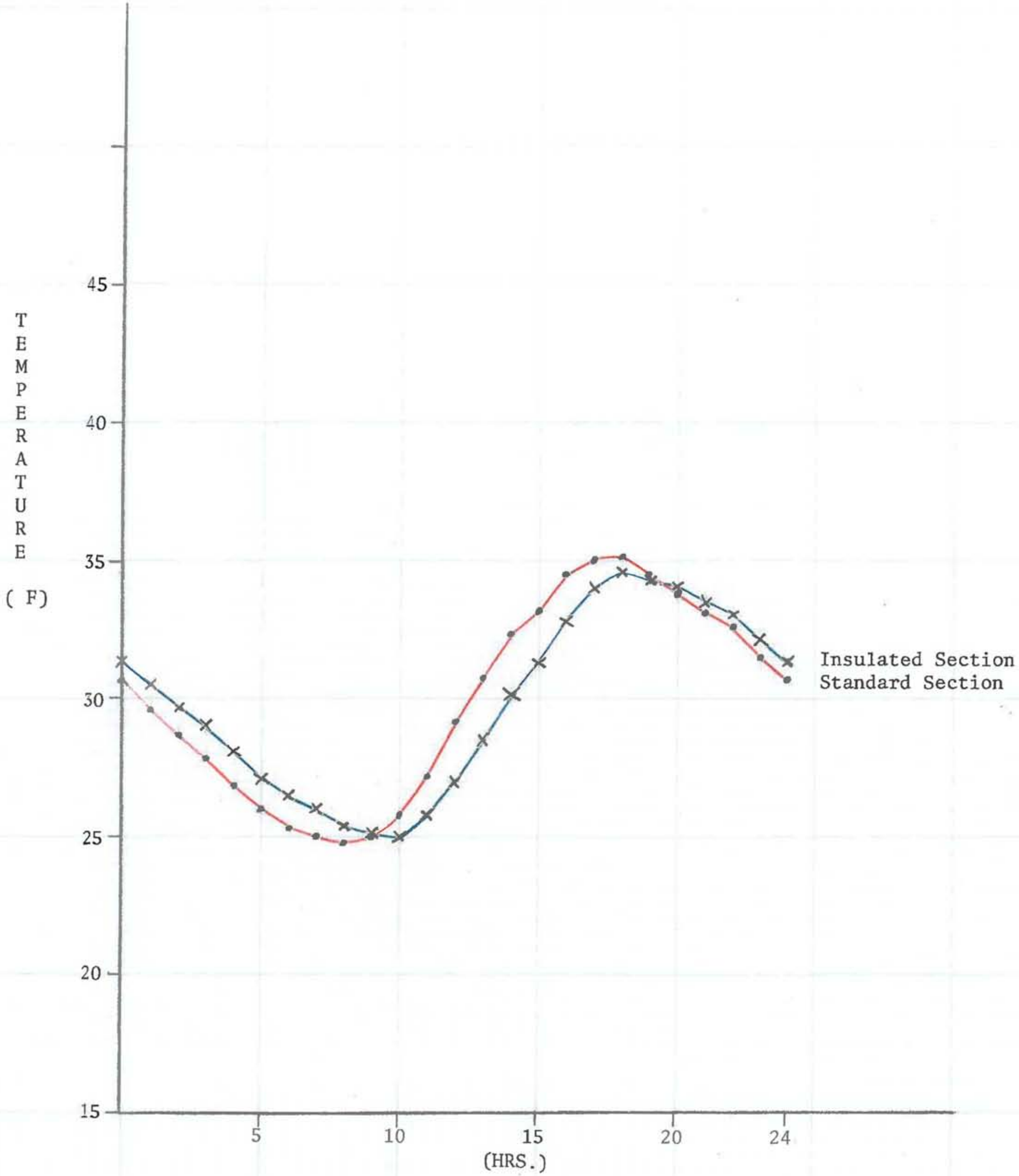
DOWD JUNCTION BRIDGE
TOP STANDARD AND TOP INSULATED
AVERAGE TEMPERATURE FOR HOUR
(1982)



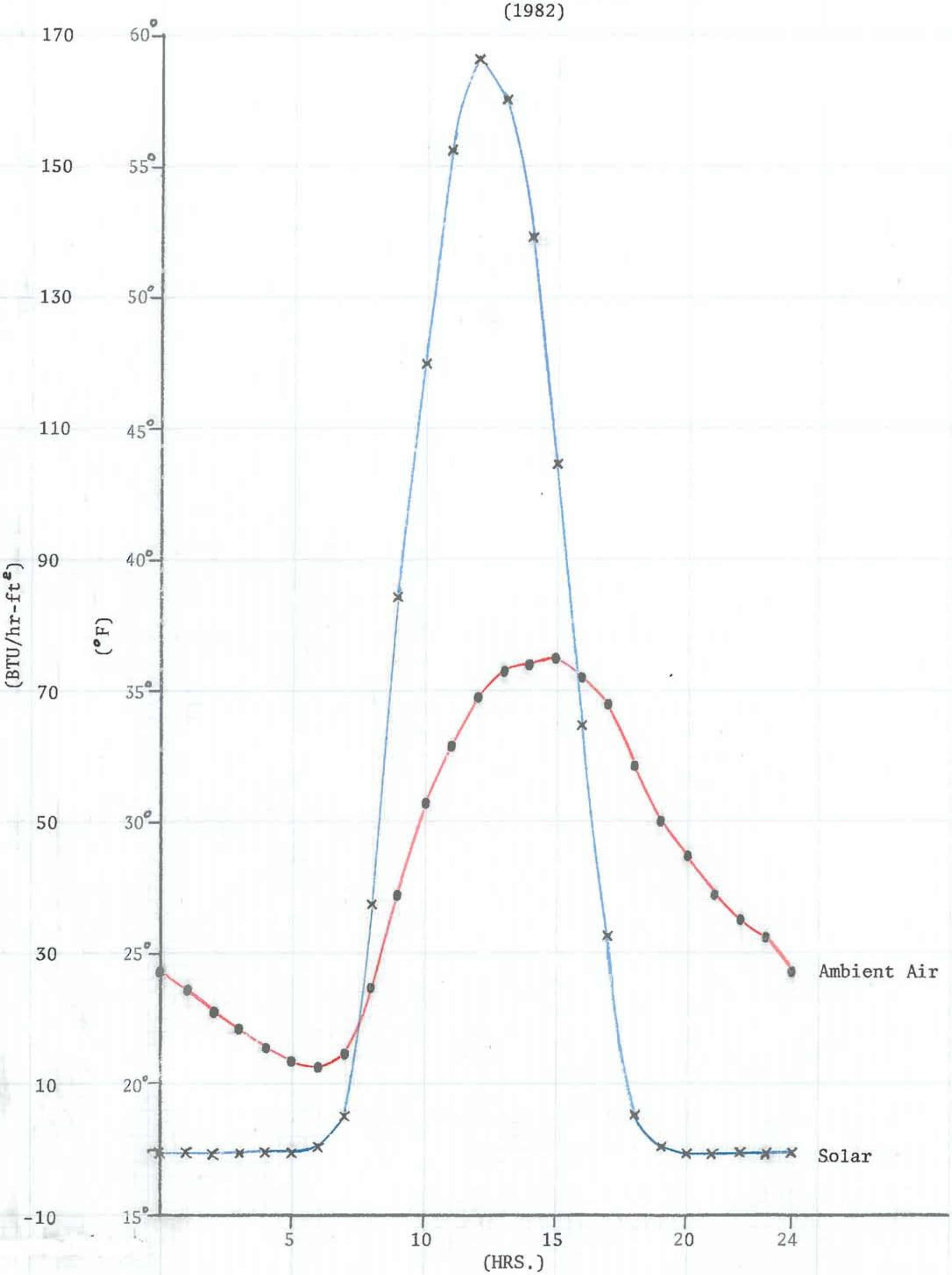
DOWD JUNCTION BRIDGE
TOP INSULATED AND BOTTOM INSULATED
AVERAGE TEMPERATURE PER HOUR
(1981)



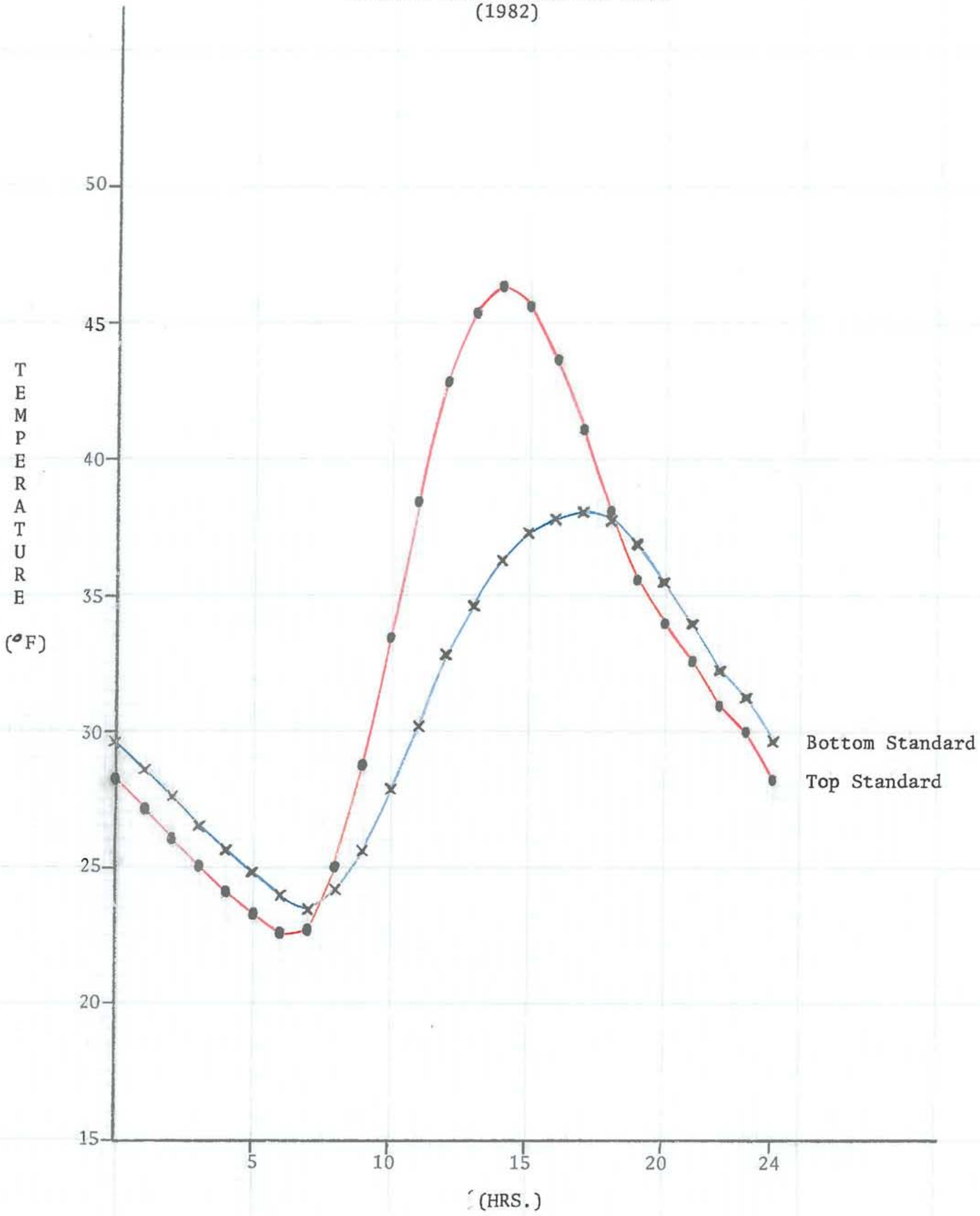
POLK CREEK BRIDGE
BOTTOM STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1982)



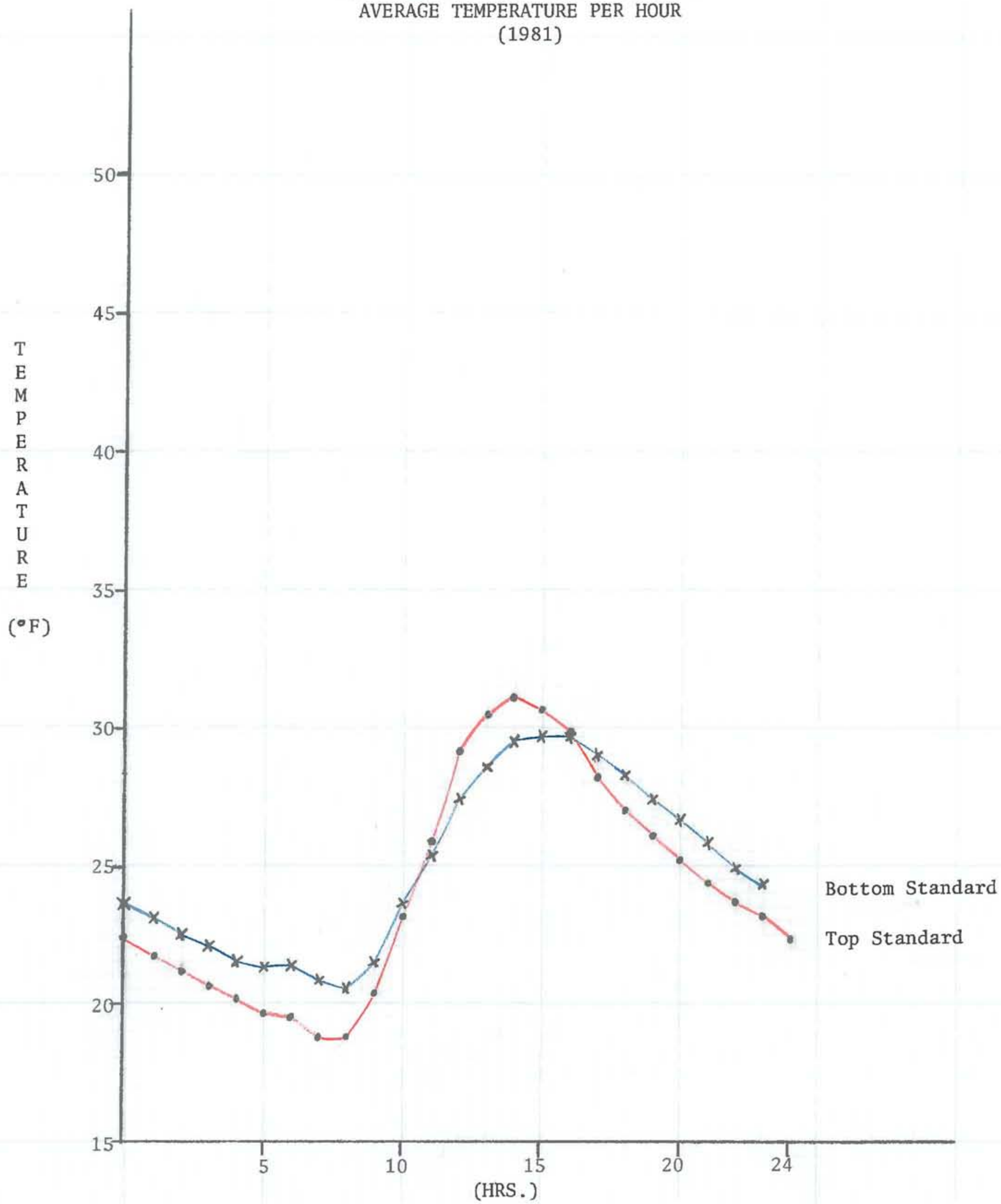
DOWD JUNCTION BRIDGE
SOLAR AND AMBIENT AIR VS. TIME
(1982)



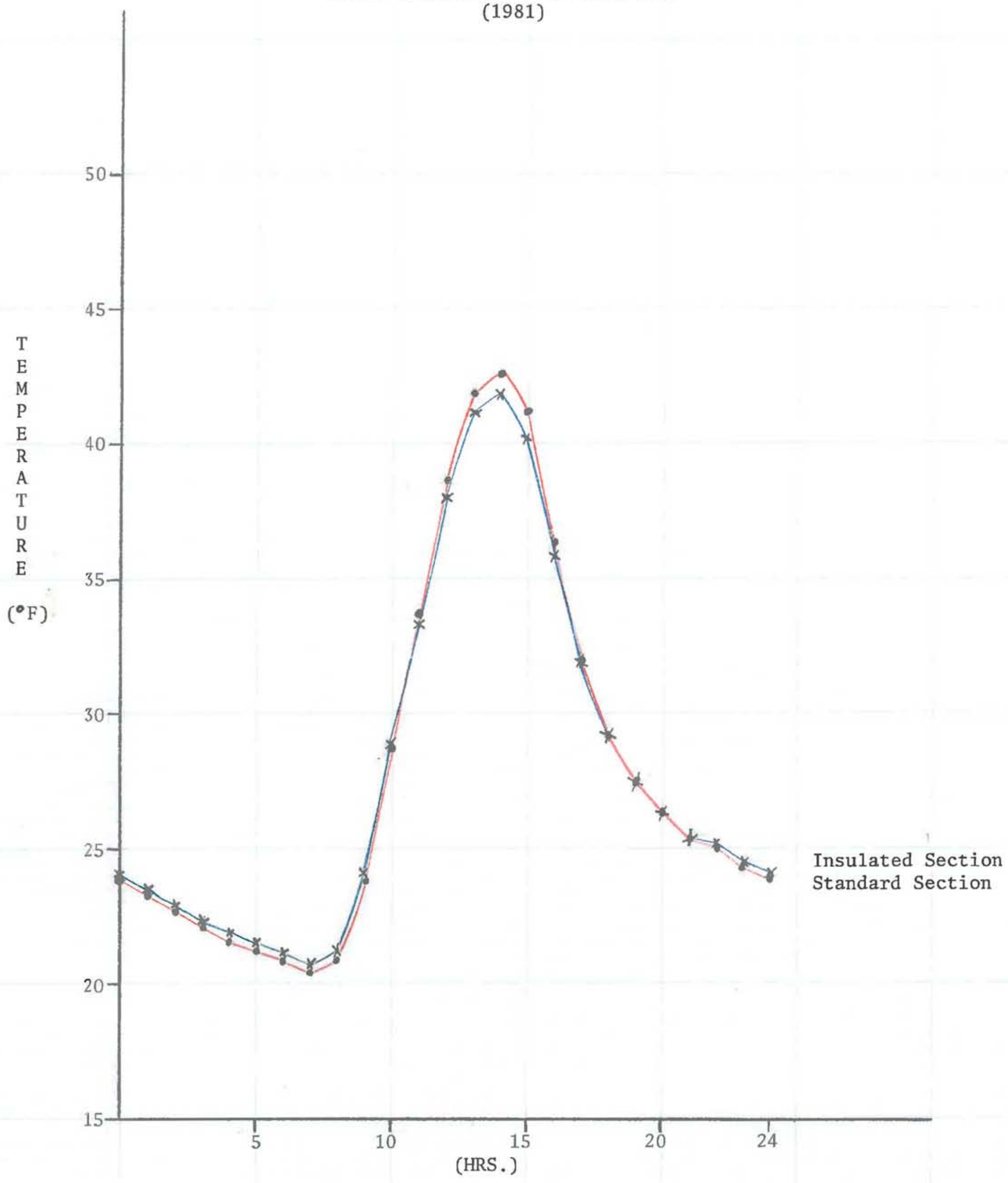
DOWD JUNCTION BRIDGE
TOP STANDARD AND BOTTOM STANDARD
AVERAGE TEMPERATURE FOR HOUR
(1982)



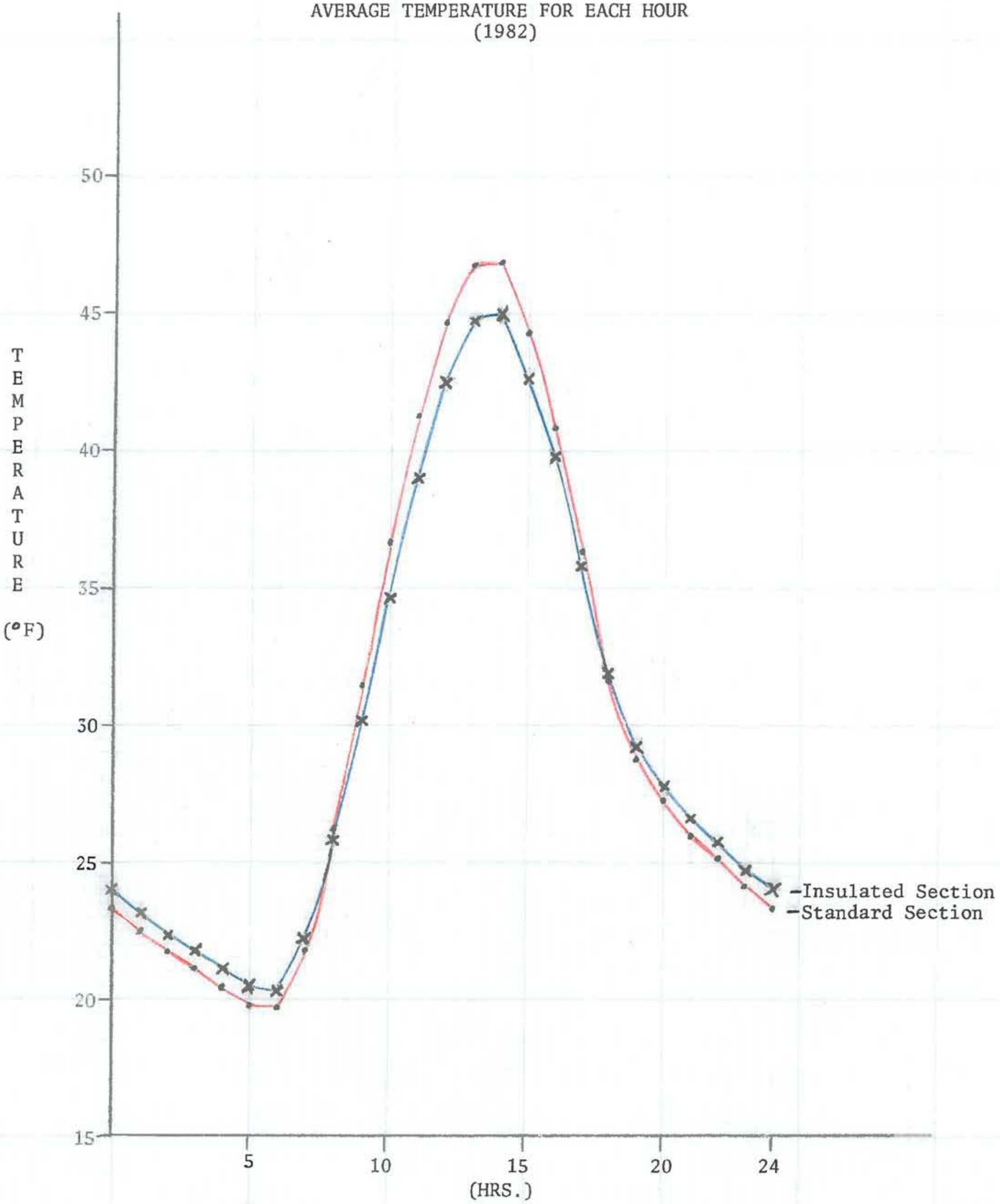
DOWD JUNCTION BRIDGE
TOP STANDARD AND BOTTOM STANDARD
AVERAGE TEMPERATURE PER HOUR
(1981)



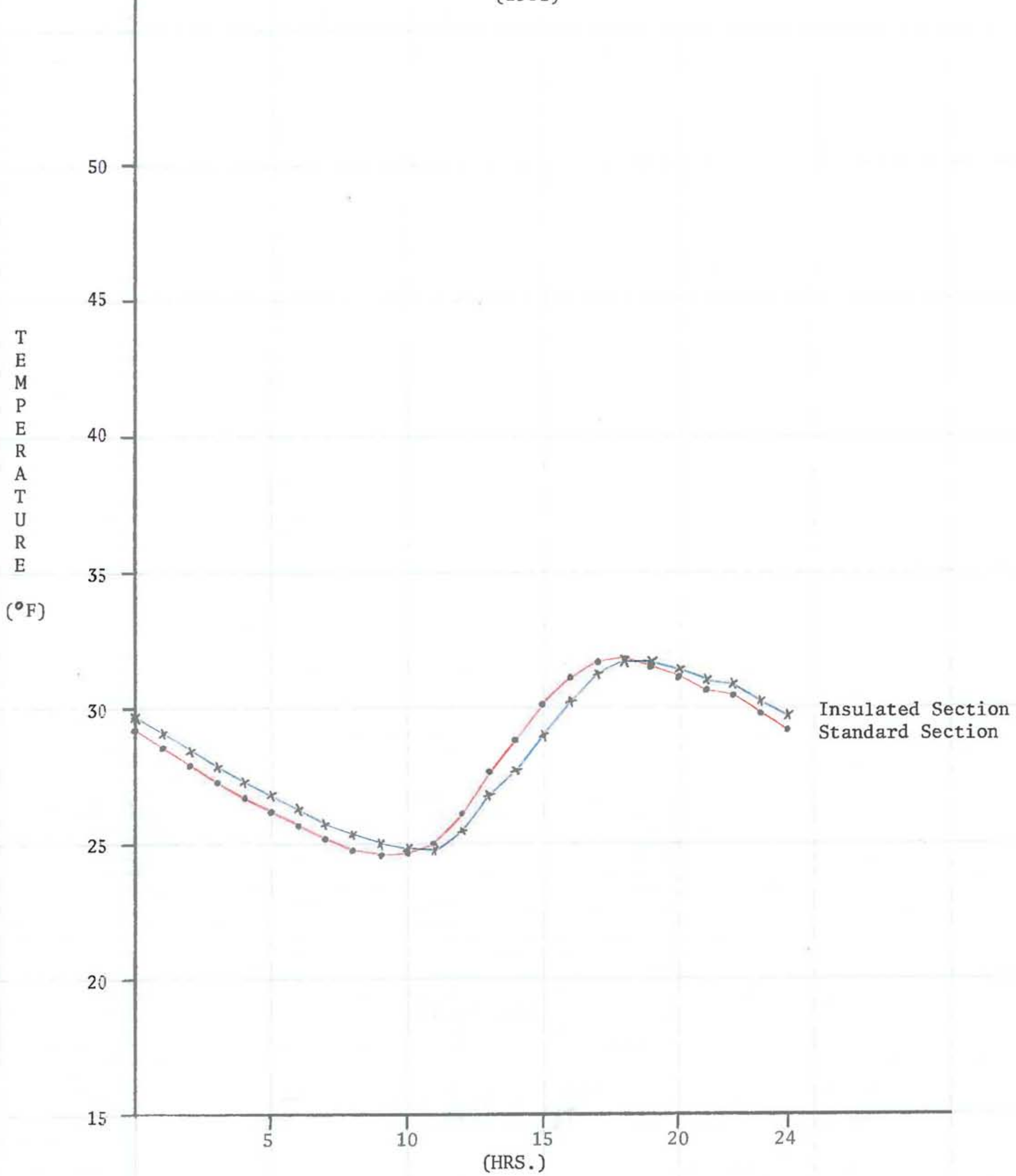
POLK CREEK BRIDGE
TOP STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1981)



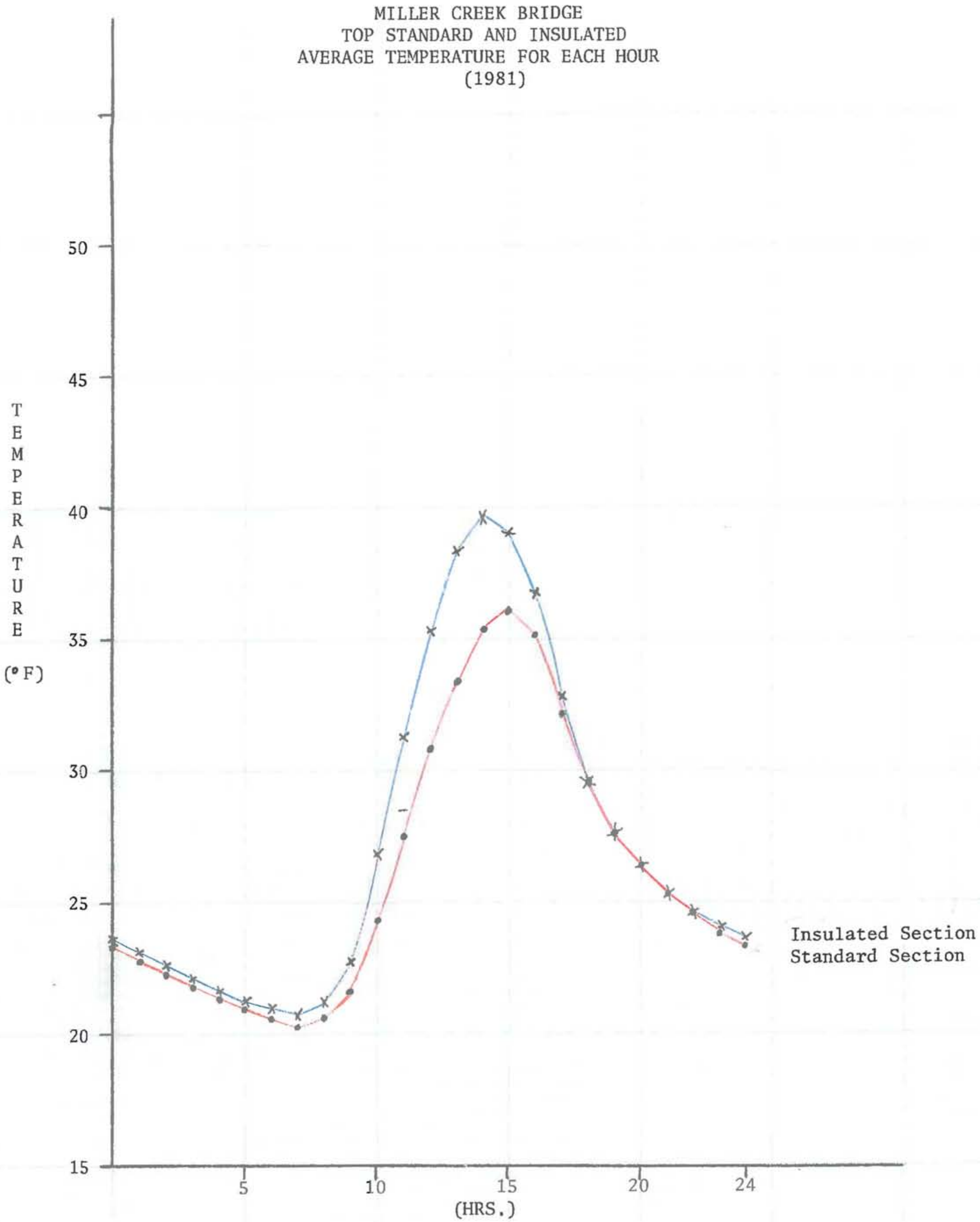
POLK CREEK BRIDGE
TOP STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1982)



POLK CREEK BRIDGE
BOTTOM STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1981)



-3° on Top
standard section



MILLER CREEK BRIDGE
TOP STANDARD AND INSULATED
AVERAGE TEMPERATURE FOR EACH HOUR
(1981)

DOWD JUNCTION BRIDGE
TOP STANDARD AND TOP APPROACH
AVERAGE TEMPERATURE PER HOUR
(1981)