

AASHTO GUIDE SPECIFICATIONS THERMAL EFFECTS IN CONCRETE BRIDGE SUPERSTRUCTURES

1989



Abridged Version of NCHRP Report 276
Thermal Effects in Concrete Bridge Superstructures

Published by the

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PREFACE

This document contains design guidelines for thermal effects in highway concrete bridge superstructures, and is an abridged version of "National Cooperative Highway Research Program Report 276, Thermal Effects in Concrete Bridge Superstructures." The NCHRP research project was initiated due to a few cases of distress in concrete bridges caused by thermal gradient stresses. It is noted in the report that foreign codes give much more significance to the effect of thermal gradient stresses than the AASHTO *Standard Specifications for Highway Bridges*, and a simplified method of analogy is recommended in Appendix A. The report, in Chapter Six, recognizes that the effect of temperature differentials in bridge superstructures have not been clearly established. The stresses that would be theoretically developed in a bridge by observed temperature gradients are inconsistent with observed performance of the bridges in many cases. This is the primary reason why a guide specification is recommended rather than a modification of the AASHTO design specifications. Field measurements of differential temperatures and thermal stresses through the sections of prestressed concrete box girder bridges clearly indicate significant differences that should be recognized and addressed by the designer of such structures.

Appendix A, B, C, and Chapter Three of NCHRP Report 276 were reformatted with minor changes to form the recommended "AASHTO Guide Specifications, Thermal Effects in Concrete Bridge Superstructures." This document is recommended for use to the bridge design community by the AASHTO Subcommittee on Bridges and Structures for this purpose. Copies of NCHRP Report 276, "Thermal Effects in Concrete Bridge Superstructures" should be obtained from Transportation Research Board, National Research Council, Washington, D.C. A table of contents from NCHRP Report 276 is included in this report.



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DESIGN GUIDELINES FOR THERMAL EFFECTS IN CONCRETE BRIDGE SUPERSTRUCTURES

1. PURPOSE OF THE GUIDELINES

These design guidelines include provisions for considering the effects of temperature on reinforced and prestressed concrete bridge superstructures. Temperature effects result from time-dependent fluctuations in the effective bridge temperature or from temperature differentials within the bridge superstructure. All concrete bridges should be designed for temperature effects resulting from time-dependent fluctuations in the effective bridge temperature. For serviceability considerations, prestressed concrete bridges should also be designed for the effects of temperature differentials within the bridge superstructure.

2. EFFECTIVE BRIDGE TEMPERATURES

All concrete bridges shall be designed to accommodate the stresses and movements resulting from a fluctuation in the effective bridge temperature. The values for the anticipated minimum and maximum effective bridge temperatures are dependent on the type of construction and on the minimum and maximum normal air temperatures at the bridge site. The minimum effective bridge temperature shall be obtained from Table 1, while the maximum effective bridge temperature shall be obtained from Table 2. Although this guide is only

Table 1 Correlation between normal daily minimum temperature and minimum effective bridge temperature.

Normal Daily Minimum Temperature °F	Minimum Effective Bridge Temperature Type of Superstructure		
	Concrete °F	Composite °F	Steel Only °F
-30	-3	-12	-43
-25	0	-9	-36
-20	3	-7	-30
-15	5	-4	-24
-10	8	-1	-17
-5	11	2	-10
0	13	4	-5
5	16	9	0
10	19	14	5
15	22	17	11
20	25	22	16
25	29	26	22
30	32	31	27
35	35	36	33
40	38	40	38

Table 2 Correlation between normal daily maximum temperature and maximum effective bridge temperature.

Normal Daily Maximum Temperature °F	Maximum Effective Bridge Temperature Type of Superstructure		
	Concrete °F	Composite °F	Steel Only °F
55	66	70	91
60	69	74	94
65	73	79	97
70	77	83	101
75	80	88	104
80	84	93	107
85	88	96	110
90	92	99	112
95	95	102	115
100	98	104	116
105	101	105	118
110	105	107	120

applicable to concrete bridges, results for effective bridge temperatures in composite and steel structures will be included. Unless more precise local meteorological data are available, the minimum normal air temperature shall be obtained from the map of isotherms included in Figure 1, and the maximum normal air temperature shall be obtained from the map of isotherms included in Figure 2.

3. DIFFERENTIAL TEMPERATURES

Provisions shall be made for stresses and movements resulting from differential temperatures within prestressed concrete superstructures. Both longitudinal and transverse stresses and movements resulting from the positive and negative vertical temperature gradients, described below, shall be considered for service stability crack control.

3.1 Positive Temperature Gradients

Vertical temperature differentials within concrete superstructures that result from the solar heating of the deck surface shall be assumed to vary at different depths of concrete, as shown in Figure 3. This gradient is only applicable to superstructures with a depth greater than 2 ft. Actual temperatures shall be assumed to vary in accordance with the values specified in Table 3 for the various solar radiation zones and thicknesses of black top surfacing on the bridge deck.

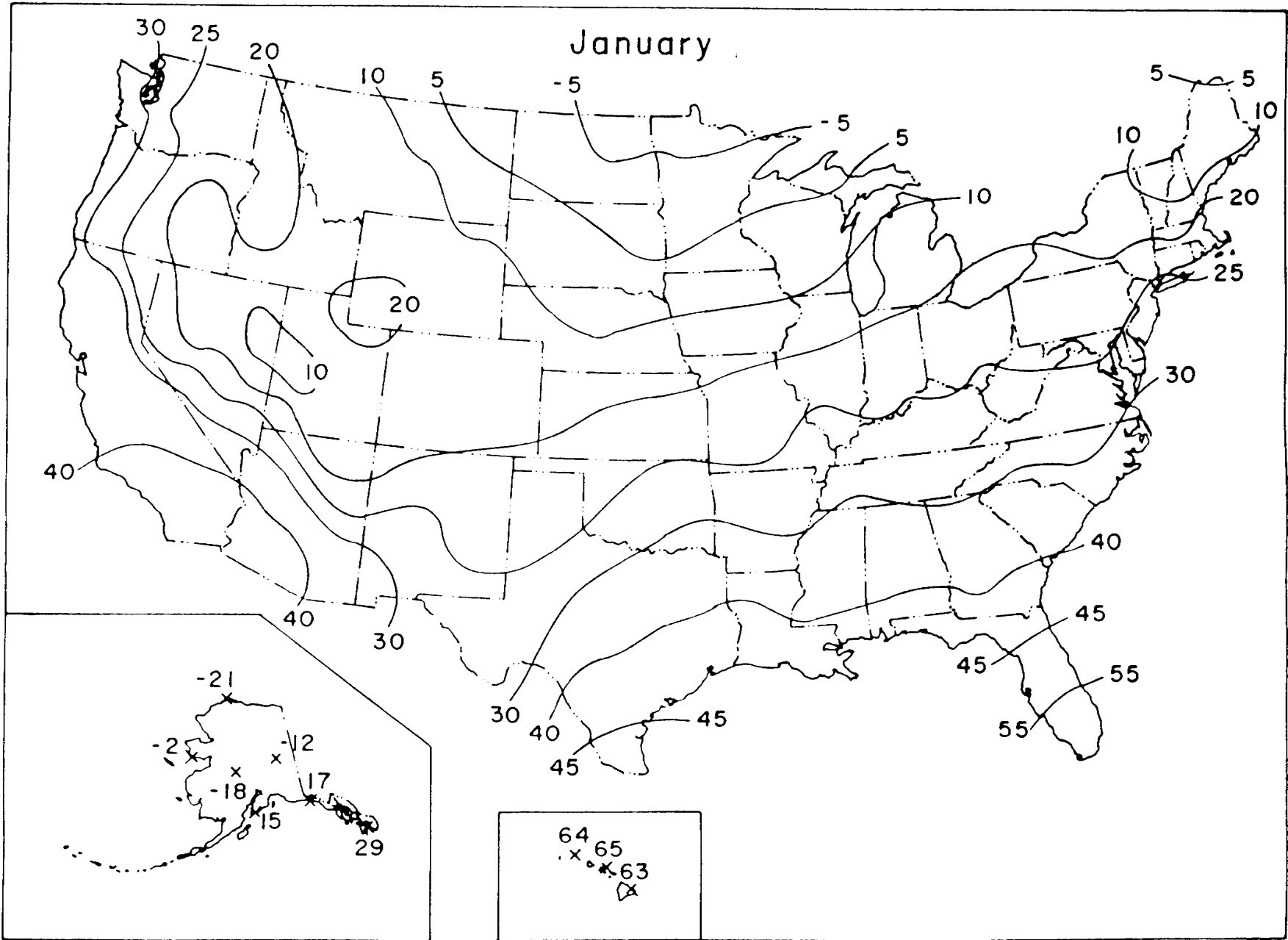


Figure 1. Normal daily minimum temperature (°F) for January.

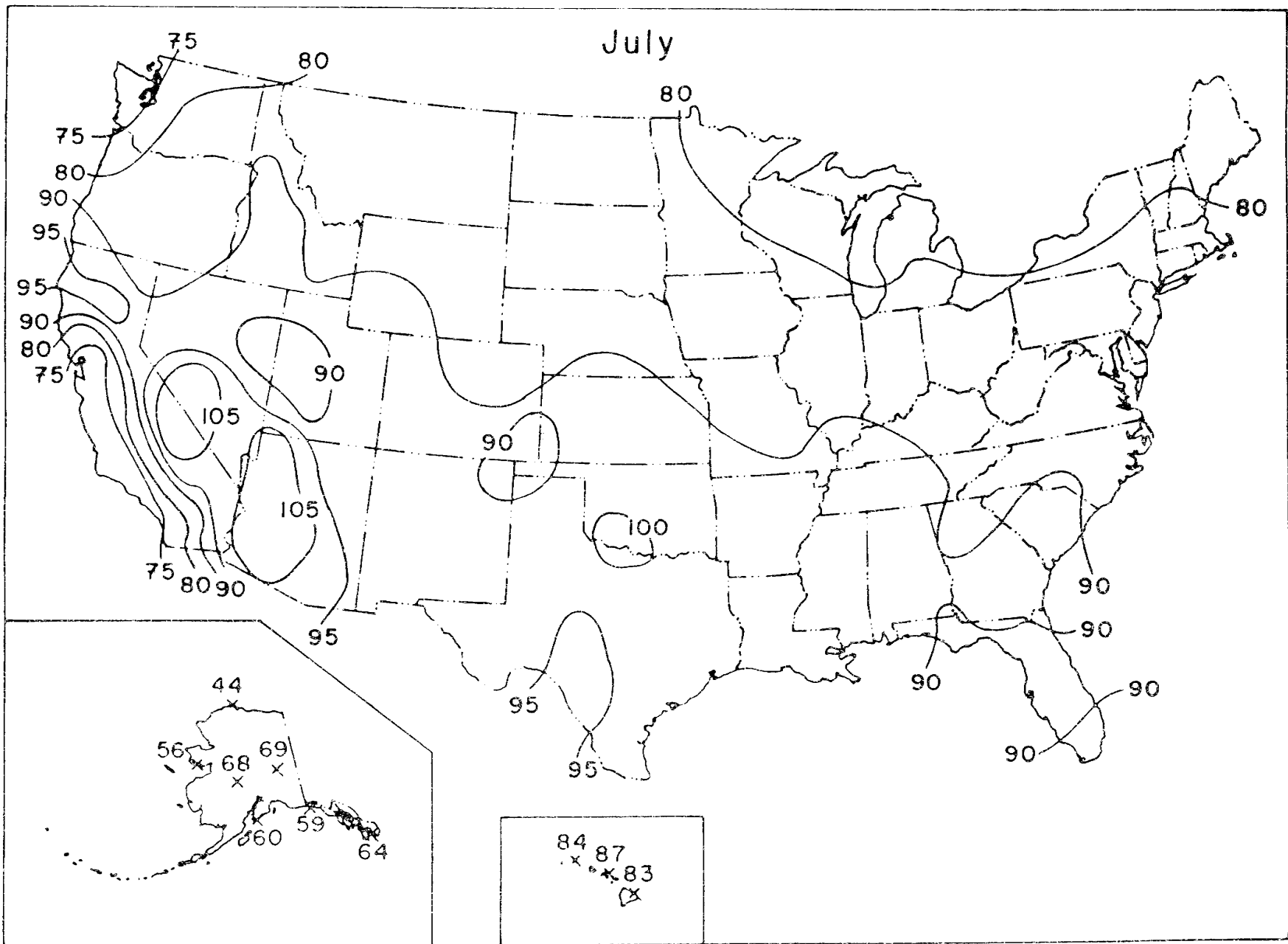
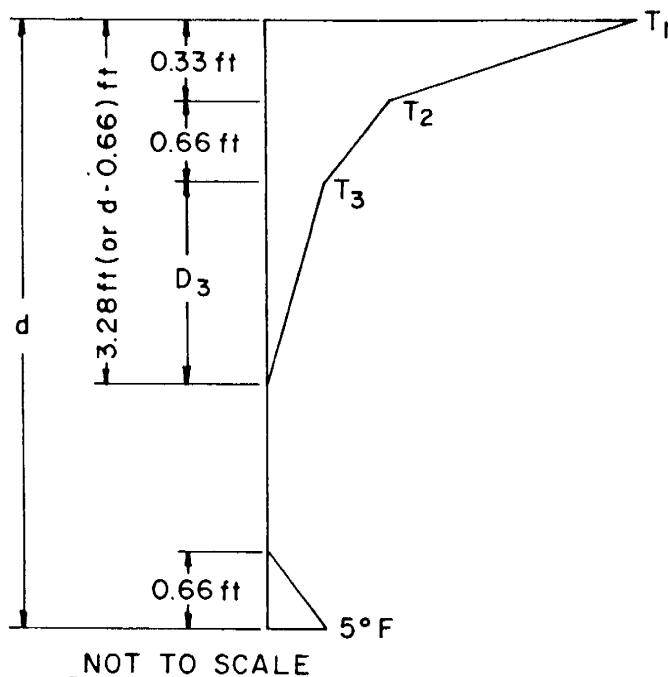


Figure 2. Normal daily maximum temperature (°F) for July.



(Note: For Superstructure depths greater than 2 feet)

Figure 3. Positive vertical temperature gradient within superstructure concrete.

Table 3 Temperature differentials within a concrete superstructure for a positive temperature gradient (see Fig. 4 for zone map).

Plain Concrete Surface			
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)
1	54	14	5
2	46	12	4
3	41	11	4
4	38	9	3

2 in. Blacktop			
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)
1	43	14	4
2	36	12	4
3	33	11	3
4	29	9	2

4 in. Blacktop			
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)
1	31	9	3
2	25	10	3
3	23	11	2
4	22	11	2

When determining the temperature variations within box girder bridges the values T₂ and T₃ shall be increased by 5°F. Maximum solar radiation zones are shown in Figure 4.

3.2 Negative Temperature Gradients

Temperature differentials within concrete superstructures that result from a rapid cooling of exposed concrete surfaces shall be assumed to vary at different depths, as shown in Figure 5. This gradient is only applicable to superstructures with a depth greater than 2 ft. Temperatures shall be assumed to vary with the maximum solar radiation zone and the thickness of black top surfacing on the bridge deck, as specified in Table 4.

4. COEFFICIENT OF THERMAL EXPANSION

The coefficient of thermal expansion used to determine temperature effects shall be based on the type of aggregate to be used, as specified in Table 5.

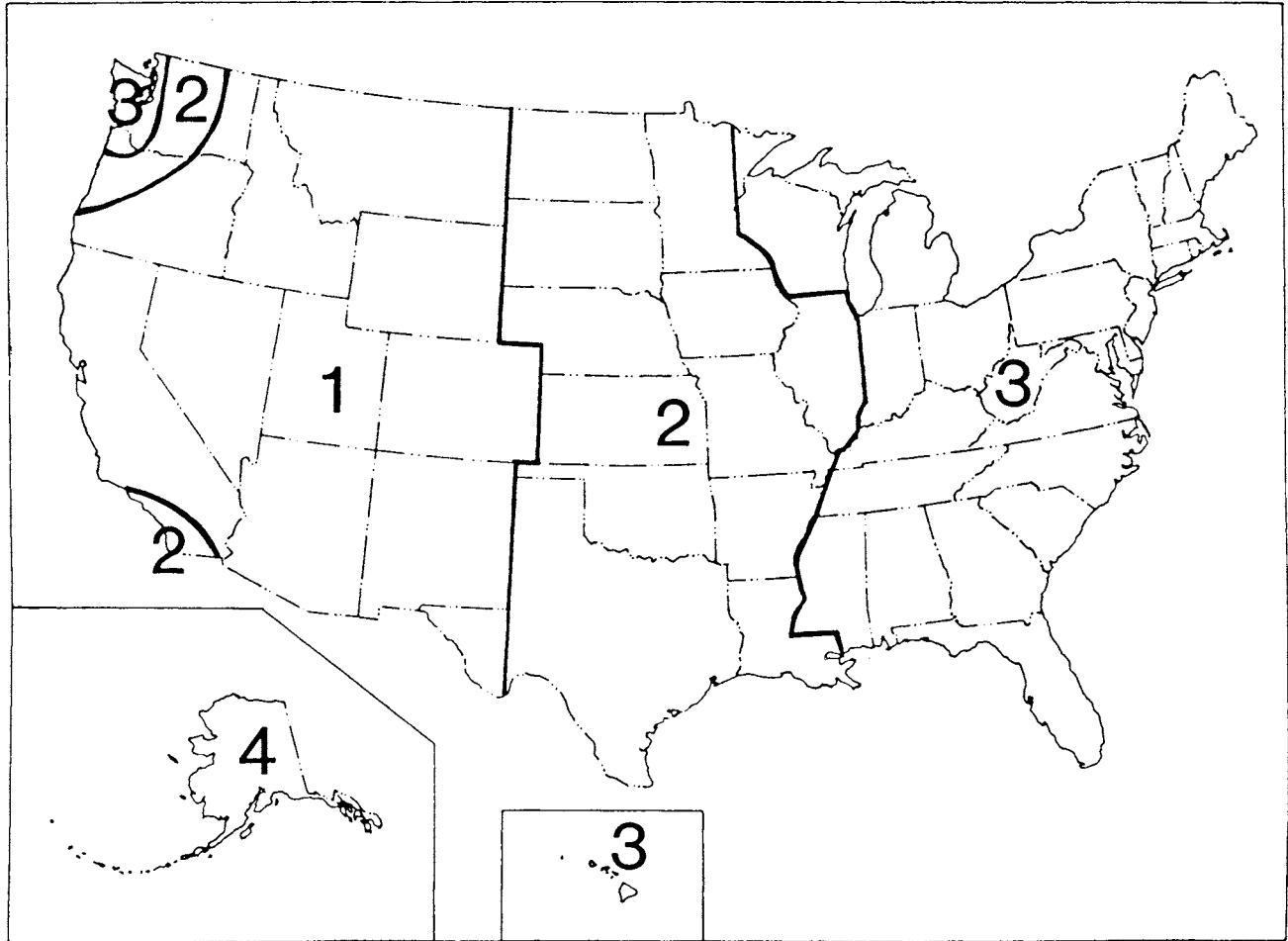
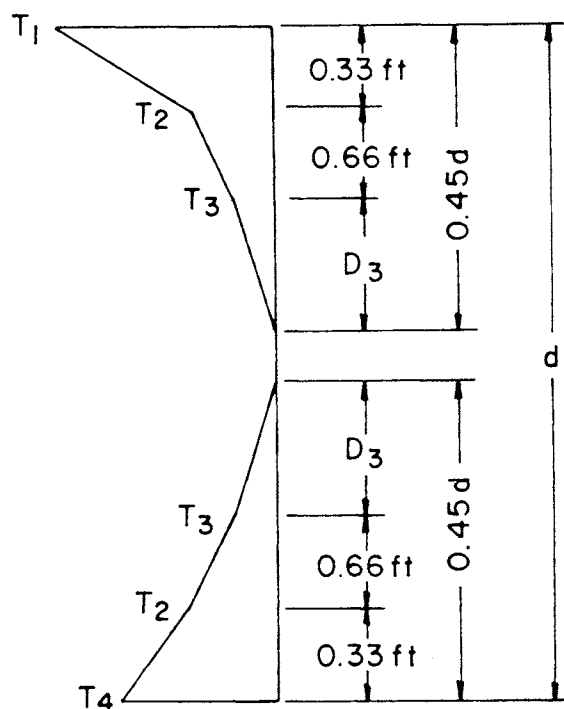


Figure 4. Maximum solar radiation zones for the United States.



NOT TO SCALE

(Note: For Superstructure depths greater than 2 feet)

Figure 5. Negative temperature gradient within superstructure concrete.

Table 4 Temperature differentials within a concrete superstructure for a negative temperature gradient (see Fig. A-4 for zone map).

Plain Concrete Surface				
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)	T ₄ (°F)
1	27	7	2	14
2	23	6	2	10
3	21	6	2	8
4	19	5	2	6

2 in. Blacktop				
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)	T ₄ (°F)
1	22	7	2	15
2	18	6	2	11
3	17	6	2	10
4	15	5	1	8

4 in. Blacktop				
Zone	T ₁ (°F)	T ₂ (°F)	T ₃ (°F)	T ₄ (°F)
1	16	5	1	12
2	13	5	1	9
3	12	6	1	8
4	11	6	1	8

Table 5 Coefficient of thermal expansion based on aggregate type (thermal coefficient of concrete based on fine and coarse aggregates).

AGGREGATE TYPE	THERMAL COEFFICIENT OF CONCRETE* (0.000001 per °F)
Quartzite	7.1
Quartz	6.4
Sandstone	6.5
Gravel	6.9
Granite	5.3
Dolerite	5.3
Basalt	5.0
Marble	2.4-4.1
Limestone	4.0

* Based on fine and coarse aggregates

5. ANALYSIS PROCEDURES

An analysis of temperature effects shall be performed to determine the stresses and movements expected to result from temperature-induced strains within specified elements of the bridge superstructure. The effects of structure continuity shall be included when analyzing both the effects of fluctuations in the effective bridge temperature and the effects of temperature differentials in the superstructure.

COMMENTARY ON DESIGN GUIDELINES FOR THERMAL EFFECTS IN CONCRETE BRIDGE SUPERSTRUCTURES

C1. APPLICABILITY OF THE GUIDELINES

All bridges are subjected to stresses and/or movements resulting from temperature variation. Although time-dependent variations in the effective bridge temperature have caused problems in both reinforced and prestressed concrete bridges, detrimental effects caused by temperature differentials within the superstructure have occurred, thus far, only in prestressed bridges.

Except in extreme cases, concrete bridges will not suffer a sudden loss of strength as a result of temperature changes. The primary detrimental effect from temperature variation is the formation of unacceptable cracks in the concrete that reduce the serviceability of the bridge. Strength loss may eventually result if these cracks contribute to accelerated deterioration. Safety could be affected if the deterioration were to escape detection, as might be the case if prestress strands concealed from inspection were to corrode. Because the total elimination of cracks in concrete bridges is not possible, these guidelines are designed to limit temperature-induced cracking to acceptable levels.

Although these guidelines do not specifically address false-work loads and temperature differentials resulting from the heat of hydration in thick members, they will be useful in determining those effects. Heat of hydration cooling can be an important cause of cracking, such as in the case of curing and/or cooling of the top deck slab which is cast on top of the previously constructed bottom slab and/or stems which provide restraint against movement.

C2. EFFECTIVE BRIDGE TEMPERATURES

Fluctuations in effective bridge temperatures result in expansion and contraction of the superstructure. These movements, in turn, induce stresses in supporting elements such as columns or piers, and result in horizontal movement of the expansion joints. The magnitude of these stresses and movements on a given bridge depends on the range of temperature variation and the temperature of the bridge at the time of construction. These guidelines establish the criteria for determining the minimum and maximum bridge temperatures that can reasonably be expected. For bridge designers to determine the amount of expansion and contraction that can be expected to occur on a given bridge to be

built in a given location, they will need to assume an effective temperature at the time of construction.

C2.1 Bridge Temperature Response

Emerson established a method for estimating minimum and maximum effective bridge temperatures based on the geographical distribution of minimum and maximum shade temperatures throughout the United Kingdom (19). The procedures established by Emerson were subsequently incorporated into British Standard BS 5400. Because the range of minimum and maximum temperatures for the United States is larger than that reported for the United Kingdom, it was necessary to extrapolate some of the curves relating effective bridge temperatures to minimum and maximum shade temperatures. Minimum temperatures for the United States range from -30°F to 40°F , as compared to a minimum temperature range of -11°F (-24°C) to 23°F (-5°C) for the United Kingdom. The extrapolated portions of the minimum temperature range presented by Emerson are shown in Figure C-1. Maximum temperatures for the United States range from approximately 55°F to 110°F , as compared to a maximum temperature range of 75°F (24°C) to 100°F (38°C) for the United Kingdom. The extrapolated portions of the maximum temperature range are also shown in Figure C-1. The values given in Tables C-1 and C-2 are based on these curves. Note that adjustments in the effective bridge temperature are not required for bridge surfacing.

C2.2 Minimum and Maximum Air Temperatures

The isotherms used for the minimum and maximum air temperature are taken from charts published in the "Climatic Atlas of the United States" (98). The minimum air temperatures were obtained from the normal daily minimum temperatures for the month of January, while the maximum air temperatures were obtained from the normal daily maximum temperatures for the month of July. These isotherms are based on average daily records for the 30-year period from 1931 through 1960. Although data are available that list the extreme daily minimum and maximum temperatures in the United States for a given period of time, there is no readily available published information that lists the duration in days that these extreme temperatures have

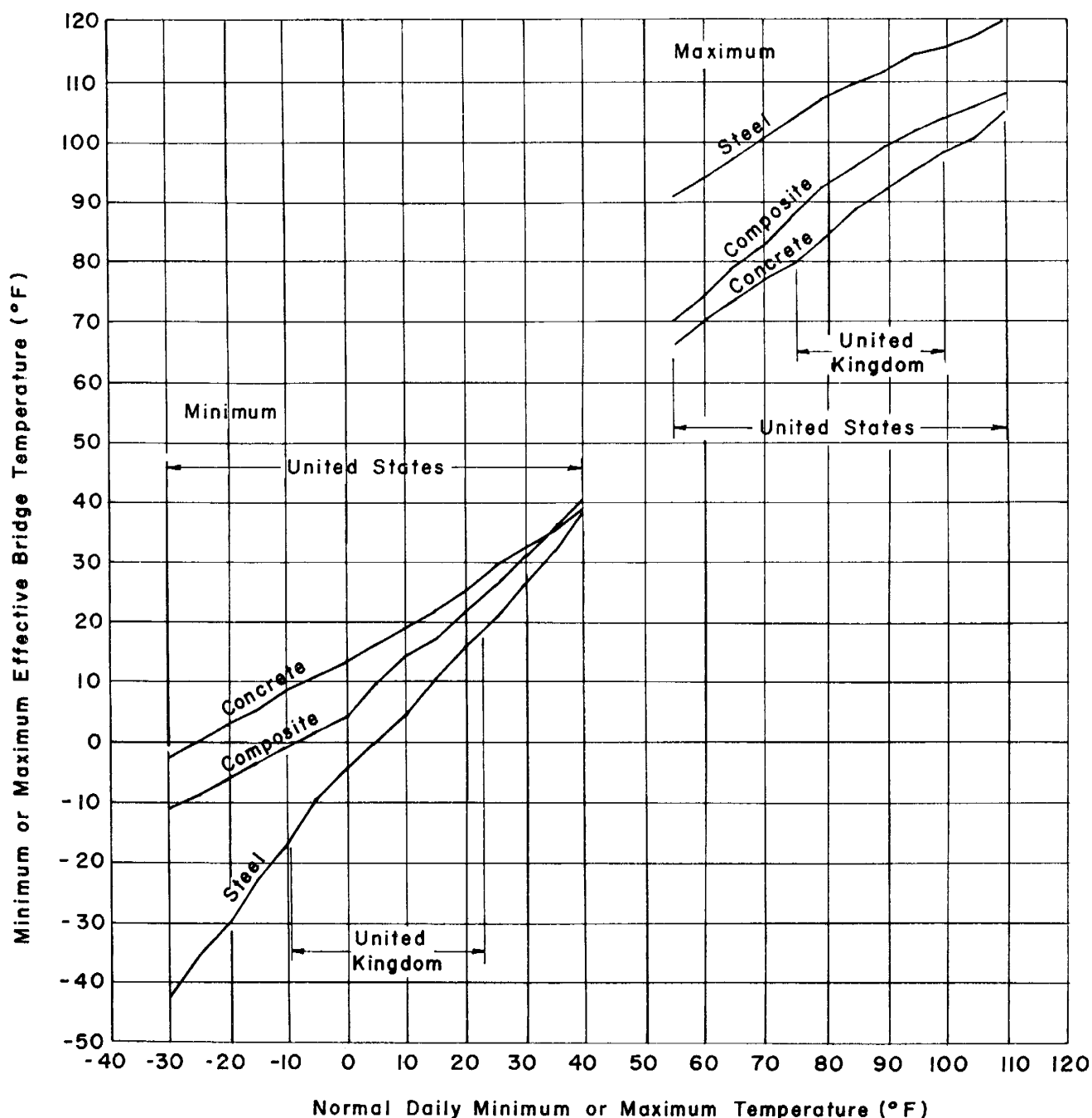


Figure C-1. Correlation between minimum or maximum temperature and minimum or maximum effective bridge temperature.

occurred. Since bridges require 2 to 3 days to respond to a given minimum or maximum temperature, additional data on the actual duration are required. In the "Climatography of the United States No. 84," minimum and maximum extremes for each day are averaged for the years 1941 through 1970 (101). Maximum extreme temperatures occurring at 20 randomly selected stations were compared with the isotherms for the normal daily maximums and found to agree within 6°F.

Minimum extreme temperatures were also compared with the isotherms for the normal daily minimums and found to agree within 6°F. Initially, it was thought that the extremes on a day-to-day basis (averaged over the 30-year period from 1941 through 1970) would be substantially different from those obtained from the isotherms. On the basis of this comparison, it may be concluded that the isotherms selected will yield fairly accurate approximations of the minimum and maxi-

Table C-1 Correlation between normal daily minimum temperature and minimum effective bridge temperature.

Normal Daily Minimum Temperature °F	Minimum Effective Bridge Temperature Type of Superstructure		
	Concrete °F	Composite °F	Steel Only °F
-30	-3	-12	-43
-25	0	-9	-36
-20	3	-7	-30
-15	5	-4	-24
-10	8	-1	-17
-5	11	2	-10
0	13	4	-5
5	16	9	0
10	19	14	5
15	22	17	11
20	25	22	16
25	29	26	22
30	32	31	27
35	35	36	33
40	38	40	38

imum extremes for the United States. Local meteorological data may be more applicable in mountainous areas, coastal areas, urban areas, and sheltered, low-lying areas where frost pockets may develop. It is recommended that local meteorological data rather than isotherms be used for unusually large or complex bridges located in regions where extreme temperature conditions are known to occur.

C3. DIFFERENTIAL TEMPERATURES

Variations in temperature at different depths of the superstructure caused by solar radiation effects may result in significant temperature-induced fiber stresses. These stresses are induced in two ways. The first way occurs when bending moments are generated in continuous spans as a result of the differences between the deformations in the top and bottom fibers. These deformations will cause a deflection in the superstructure; stresses result when this deflection is restrained by structure continuity. The second way in which stresses are induced is when nonlinear temperature variations through the depths of the section cause initially plane sections of the superstructure to become distorted. Because shallow superstructures have not been adversely affected in the past by temperature differentials, design thermal gradients were developed for superstructures with depths greater than 2 ft.

Most typical structures have not experienced difficulties because of temperature differentials. Recently, however, concrete bridge designs have become more sophisticated. As a result, span lengths have increased and designers have kept superstructure weights at a minimum. This has resulted in a reduction of reserve

Table C-2 Correlation between normal daily maximum temperature and maximum effective bridge temperature.

Normal Daily Maximum Temperature °F	Maximum Effective Bridge Temperature Type of Superstructure		
	Concrete °F	Composite °F	Steel Only °F
55	66	70	91
60	69	74	94
65	73	79	97
70	77	83	101
75	80	88	104
80	84	93	107
85	88	96	110
90	92	99	112
95	95	102	115
100	98	104	116
105	101	105	118
110	105	107	120

strength for temperature-induced stresses, a reduction which has caused unacceptable cracking in some bridge superstructures. Much of this unacceptable cracking could have been avoided had the designer accurately considered the effects of differential temperatures.

Bridges can be protected from excessive temperature-induced stresses in several ways. One method is to resist the tensile force produced by the tensile stresses by providing a sufficient quantity of mild reinforcement in the zone of tension. Stresses in reinforcement should be limited to $0.6 f_y$ for crack control. Extra prestressing steel may also be used. However, it is recommended that the designer not rely on the tensile strength of concrete.

C3.1 Positive Temperature Gradients

Positive temperature gradients occur when solar radiation, large diurnal temperature variations, and/or low wind speed conditions produce a higher temperature in the bridge deck. Each of these individual weather conditions varies throughout the United States, and they can combine to produce extreme positive temperature distributions in concrete bridge superstructures in some locations. Experimental data from 26 SOLMET stations in the United States were used to compute the maximum temperature differences of a 2-m (6.56-ft) deep concrete bridge structure (73). In order to obtain solar radiation zones in the United States these temperature differences were superimposed on solar radiation contours for the month of July (99). The maximum solar radiation zones for an unsurfaced deck, a 50-mm (2-in.) blacktop deck, and a 100-mm (4-in.) blacktop deck are shown in Figures C-2, C-3, and C-4, respectively. The United States has been divided into four climatic zones (see Fig. C-5), each reflecting the maximum expected positive temperature



AVERAGE DAILY GLOBAL SOLAR RADIATION
ON A HORIZONTAL SURFACE (MJ/m^2)

July

COMPUTED MAXIMUM TEMPERATURE
DIFFERENCE ($^{\circ}\text{C}$)

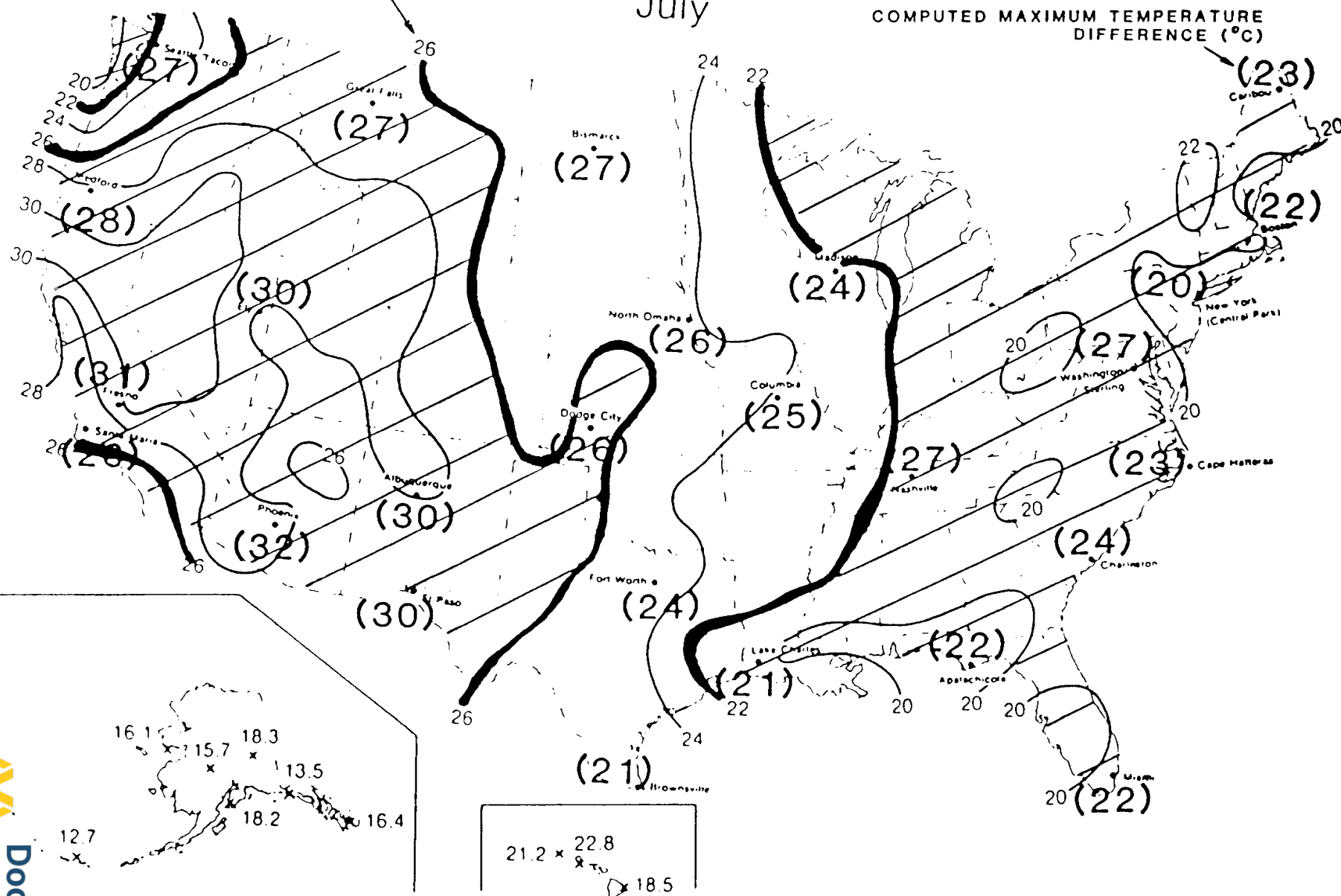


Figure C-2. Maximum solar radiation zone for a 2-m (6.56-ft) deep bridge structure (unsurfaced).