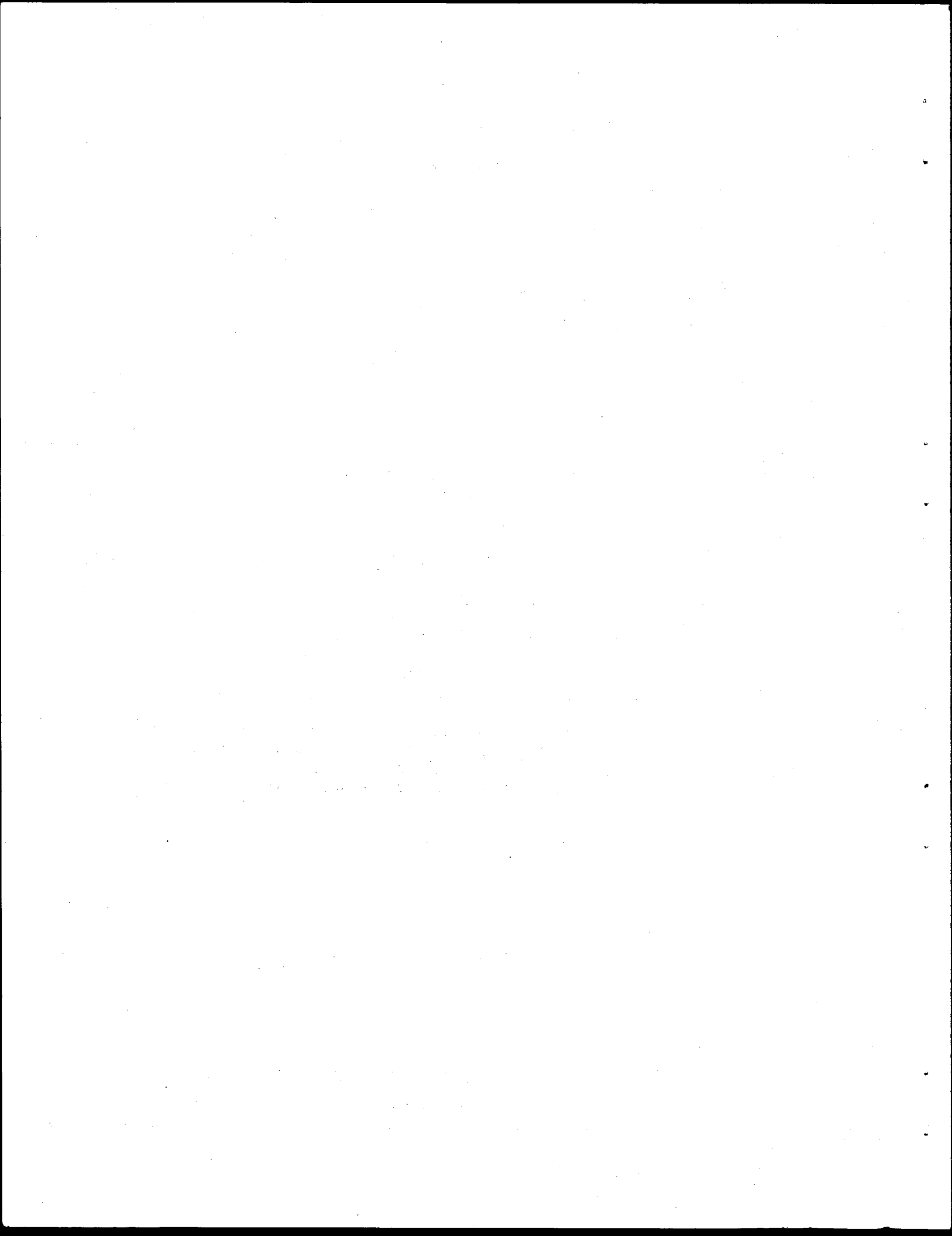


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ENVIRONMENTAL FACTORS RELEVANT TO PAVEMENT CRACKING IN WEST TEXAS

by

Samuel H. Carpenter
Robert L. Lytton
Jon A. Epps

Research Report Number 18-1

Environmental Deterioration of Pavement
Research Project 2-8-73-18

conducted for

The Texas Highway Department

in cooperation with the
U.S. Department of Transportation
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by the

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Texas Transportation Institute
Texas A&M University
College Station, Texas

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The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This report describes the environmental influences in the west Texas area which are important in studying non-load associated pavement cracking. Included herein are results of various other studies and their relationship to the west Texas area. The majority of data presented was obtained from U.S. Weather Bureau Publications except where noted. This is one of a series of reports emanating from the project entitled "Environmental Deterioration of Pavement." The project, sponsored by the Texas Highway Department in cooperation with the Federal Highway Administration, is a comprehensive program to verify environmental cracking mechanisms and recommend maintenance and construction measures to alleviate the problem.

LIST OF REPORTS

Report No. 18-1, "Environmental Factors Relevant to Pavement Cracking In west Texas," by Samuel H. Carpenter, Robert L. Lytton and Jon A. Epps, describes the environment existing in west Texas and relates it to other studies to determine its severity.

ABSTRACT

Environmental variables important in pavement cracking studies are catalogued for west Texas. This portion of the state is shown to receive the most severe environmental changes. Results from other studies, mainly in Canada, are interpreted in terms of the information gathered for west Texas. These data indicate that pavement deterioration in west Texas is more likely the result of thermal fatigue than low temperature cracking. Environmental influence in the base and subgrade which has not been properly considered previously is discussed.

Moisture redistribution is related to the Thornthwaite Moisture Index. This index predicts moisture-suction levels in the subgrade which may dry out the base course causing shrinkage cracking. A regression analysis verified the applicability of these indices to west Texas.

Key Words. Low-temperature cracking, thermal-fatigue cracking, shrinkage cracking, weather, suction, Thornthwaite moisture index.

SUMMARY

Environmental data important in pavement cracking are catalogued for west Texas. These data will provide a common base for computer studies of the cracking problem. The data collected delineate areas of study important to the west Texas area not considered in other studies.

IMPLEMENTATION STATEMENT

Numerous computer codes have been developed to predict cracking during the life of a pavement. The data presented herein will provide a common base for input into these codes for study of the west Texas area. The data point out the inadequacies of previous studies when they have been applied to the west Texas area and they show the more influential mechanisms acting in west Texas. This information will aid design engineers as well as field engineers in considering all possible causes of pavement deterioration.

INTRODUCTION

Although highway engineers have been concerned about pavement distress not associated with traffic loads for several decades, only recently has the extent and importance of this distress been recognized. A recent symposium (25) has indicated that several mechanisms not associated with traffic loads can be responsible for pavement cracking. These mechanisms, as shown in Table 1, include reflection cracking, thermal cracking, selective absorption of asphalt by porous aggregates, and moisture changes. These mechanisms are not well understood and are not adequately considered in pavement design methods, nor are provisions made for them in construction methods and material specifications. To date, the bulk of published literature has been concerned mainly with establishing a procedure to predict observed field behavior. The mechanisms, when considered, have been considered independently of one another. The mechanisms listed are coupled, however, and must be studied together.

Thermal cracking, which produces transverse cracks has been extensively studied for the asphaltic concrete. Rates of temperature drop, minimum temperature, and asphalt properties enter into the calculations of when the induced stresses will exceed the tensile strength of the mix. It is not as apparent, but just as true, that the base course and even the subgrade will undergo contraction upon freezing. This will produce the same general type of transverse cracking when these cracks reflect through the asphaltic concrete.

Table 1. - Pavement Cracking Mechanisms

Surface	Asphalt concrete Surface treatment	<ol style="list-style-type: none"> 1. Reflection cracking from base, subbase or subgrade 2. Thermal cracking - temperature change 3. Absorption of asphalt by aggregate (volcanic, limestone, sandstone) (could be selective absorption) 4. Loss of volatiles in bituminous materials 5. Loss of moisture - drying shrinkage
Base	Untreated Cement Treated Lime Treated Asphalt Treated	<ol style="list-style-type: none"> 1. Reflection cracking from subbase and subgrade 2. Thermal cracking - primarily stabilized materials 3. Absorption of asphalt by aggregate 4. Loss of moisture- primarily cement and lime stabilized
Subbase	Untreated Lime or Cement Treated	<ol style="list-style-type: none"> 1. Reflection cracking from subgrade 2. Thermal cracking 3. Loss of moisture - primarily stabilized materials
Subgrade		<ol style="list-style-type: none"> 1. Shrinkage 2. Swell 3. Consolidation or compaction 4. Thermal cracking
		<p><u>Examples of Coupled Effects</u></p> <ol style="list-style-type: none"> 1. Hardening of asphalt 2. Wheel load

Moisture differentials between the base course and subgrade will also produce transverse cracking. A base course, which is usually compacted at or wet of optimum moisture content, over a naturally dry subgrade will build in a differential which will dry out the base course from below causing transverse shrinkage cracks. These cracks may then reflect up through the asphaltic concrete.

The ability of the asphaltic concrete to resist cracking is affected by the resiliency of the material. This resiliency can be related to the volatiles in the asphalt. The amount of volatiles in the mix at any time varies, and may be seriously affected by the aggregate used in the mix. The aggregates that will selectively absorb the lighter asphalts will be more porous and perhaps more subject to degradation. Loss of the volatiles will harden the asphalt, making it more susceptible to cracking.

The constant repetition of temperature cycles also serves to weaken the load carrying ability of the pavement system both in the asphalt cement mix and the base course material. This thermal fatigue of the pavement system can be more damaging than the one-time fracture caused by a temperature drop.

An understanding of these mechanisms is necessary to design economical remedial maintenance programs and to alter future designs, construction methods, and material specifications to reduce or eliminate this type of pavement distress. To understand the mechanisms of pavement cracking, it is necessary to understand the major variables which initiate and propagate the cracks. In the mechanisms mentioned here, it is evident that environmental effects have a major influence on the behavior of pavements.

Environmental effects have long been recognized as being influential in the construction and performance of pavements. Over fifty years ago Eno (11) made the statement that "any definite information, easily available to the

engineer and contractor, about any climatic factor enables them to more surely build good roads." This statement has become more important today as pavement performance becomes more critical. Extensive studies have catalogued environmental data over the United States (5, 11, 14). Other studies have been conducted over very small areas when precise environmental fluctuations must be known (9, 18). Both types of studies are important to the process of designing pavements. A study of the literature shows a significant amount of weather data has already been tabulated. Even with these data available, there remains a difficulty in predicting the extremes of the weather variables at a given location since the data may vary a large amount over a very small area (11).

The data presented in this report show the severity of the environment in west Texas. In all instances, the western portion of the state has the most severe weather conditions for pavement cracking. The initial use of the data presented will be in providing climatic input data for a recently developed computer code which attempts to predict the amount of transverse pavement cracking assuming that thermal cracking of the asphalt surface layer is the only mechanism involved (28). These data should provide a consistent base from which to make comparisons of the thermal transverse cracking problem in various areas of west Texas (6). The climatic data will also allow soil moisture suction values in pavement subgrades to be predicted. Information in this report will be to provide reference climatic data for pavement designers in the future.

The area of Texas which is plagued by extensive transverse cracking is the western portion of the state. This section consists of four major geographical regions which are:

1. High Plains
2. Low Rolling Plains
3. Trans-Pecos
4. Edwards Plateau

These regions are shown in Figure 1. To provide an adequate coverage of the area in question a total of twenty-two weather stations were chosen to represent the area. These stations are shown in Figure 2. These stations provide substantial data which allow comparisons between stations and data quantities to be predicted between stations.

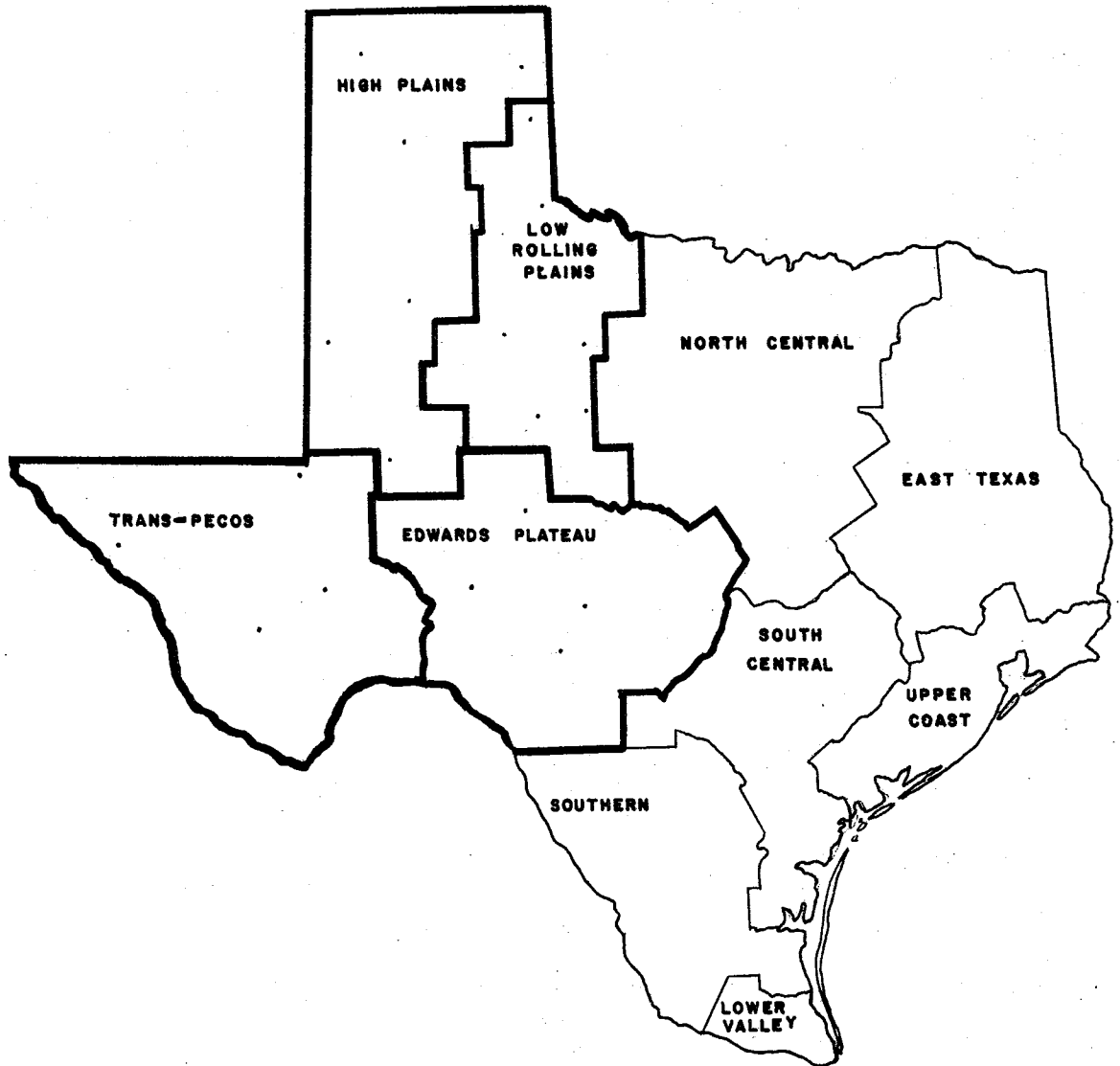


FIG. I.- GEOGRAPHICAL REGIONS OF TEXAS.

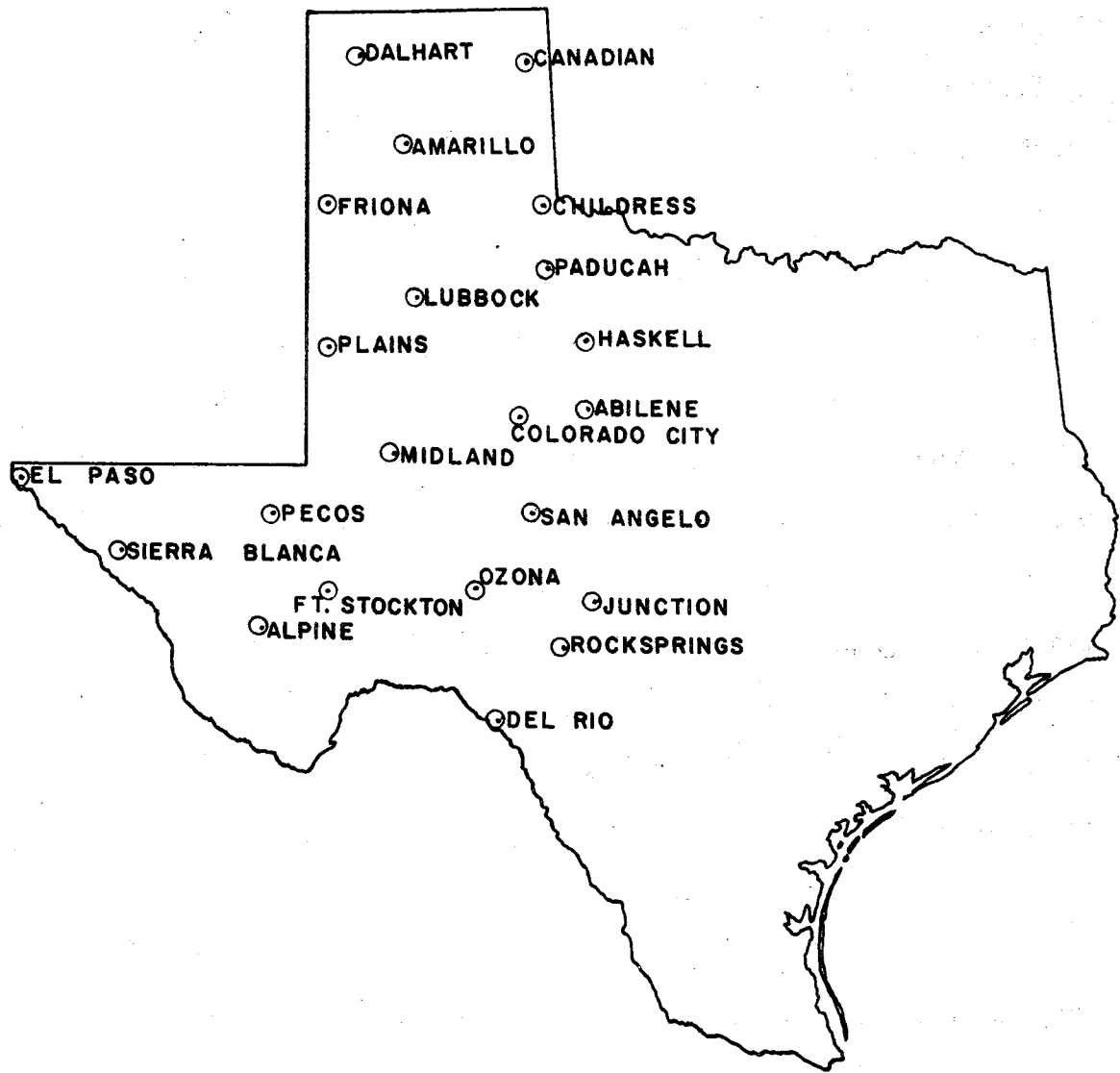


FIG 2. -WEATHER STATIONS USED TO
COMPILE DATA.

ENVIRONMENTAL INDICATORS AND THEIR RELATIONSHIP TO ENGINEERING PROBLEMS

An environmental indicator is a relative value, formed by a combination of weather variables which describes the climate prevalent in a region. The indicators are formed by determining a relationship between a measured physical occurrence and the weather variables which cause it. A general indicator is one that is usually based on precipitation and evaporation, as these quantities are easily obtainable and have a major influence on the engineering behavior of most structures.

Transeau (34) developed a Precipitation-Effectiveness index which attempted to use the amount of rain and evaporation. Russell (27) developed a ratio of precipitation to evaporation. Ångström developed a humidity coefficient which is directly proportional to the amount of precipitation and inversely proportional to an exponential function of temperature. These indicators are based on measured rainfall and evaporation, which are very highly related to each other. As such, a correlation between one of these environmental indicators and some engineering phenomena will not be truly meaningful as there can be no true independent variable.

Thornthwaite (33) introduced the concept of potential evapo-transpiration. This quantity is defined as the amount of water which would be returned to the atmosphere by evaporation from the ground surface and transpiration by plants if there was an unlimited supply of water to the plants and ground. A map of this quantity as it is distributed across Texas is shown in Figure 3. Using this potential evapo-transpiration measure as a basis, a rational classification of the climate is possible since this variable is independent of

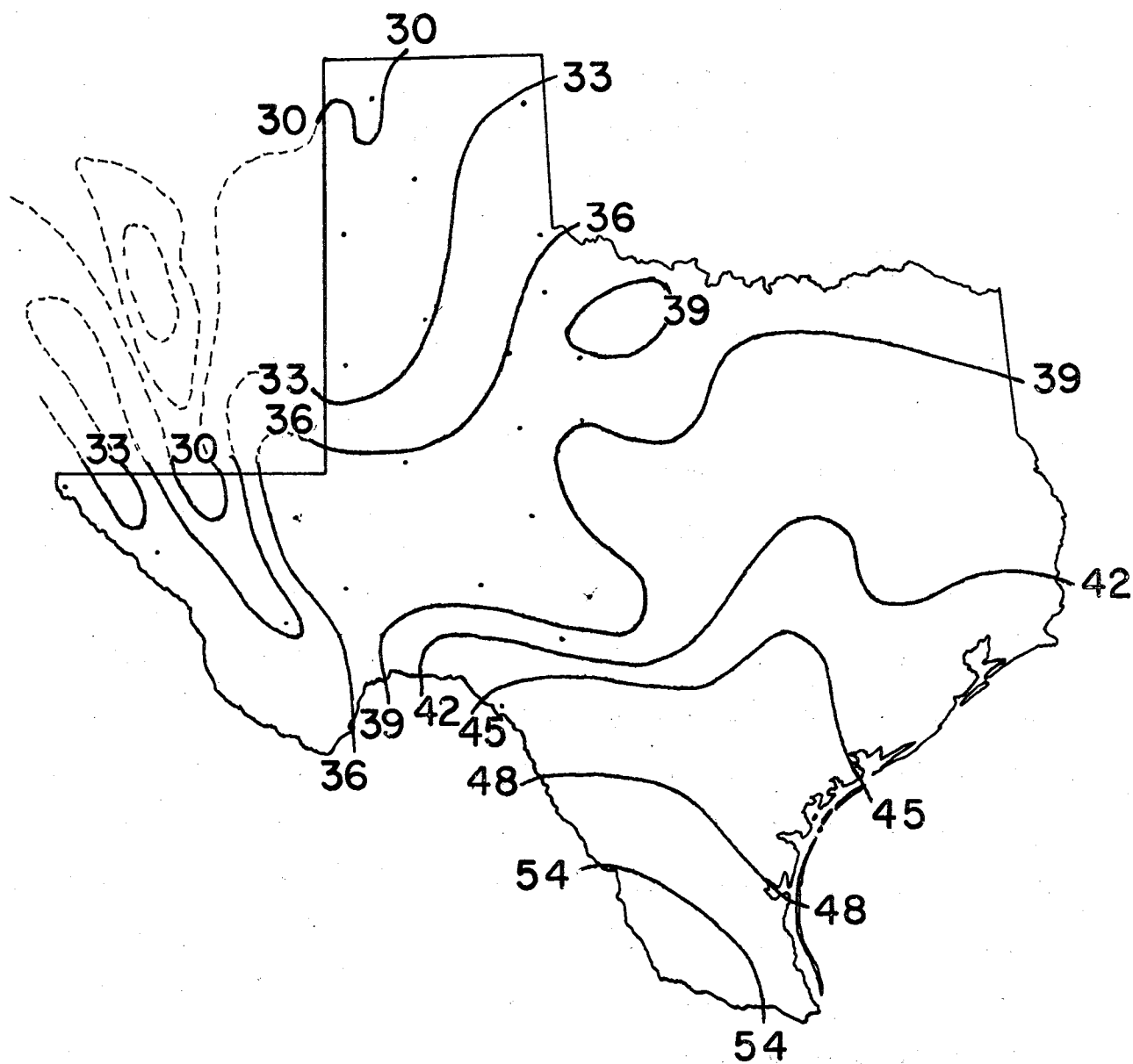


FIG. 3.— AVERAGE ANNUAL POTENTIAL
 EVAPOTRANSPIRATION , COMPUTED
 BY THORNTHWAITE. (33)

local soil and vegetation conditions. Though transpiration may not be an active mechanism in a pavement structure (4), it must be considered in order to define the environment which will influence the performance of the pavement.

The investigators above were attempting to determine the conditions of humidity i.e., a moisture surplus or deficit, in the soil (2). Using the concept of Potential Evapo-Transpiration, Thornthwaite proposed his moisture index.

$$I_m = \frac{100S - 60d}{E_p} \quad (1)$$

where

I_m = moisture index,

S = surplus of water in inches,

d = deficit of water in inches, and

E_p = Potential Evapo-Transpiration in inches.

The surplus and deficit of moisture must be considered separately as they occur in different seasons of the year for most places. A moisture surplus will store water in the subsoil water region, thus making more water available to deep rooted plants, lessening the effect of a drought. In this manner a surplus of six inches in one season will counteract ten inches deficiency in another season. The soil may store only a finite value of rainfall, usually 4-6 inches, before the remainder will runoff and be unavailable for the next seasonal moisture deficiency. This relationship is shown in Figure 4 for Dalhart, Texas. By a simple bookkeeping procedure, these data may be converted to surplus and deficit moisture; and then into the moisture index. Thornthwaite's moisture index for Texas is shown in Figure 5. The calculations, assumptions, and validation for use in the West Texas area are given in Appendix I.

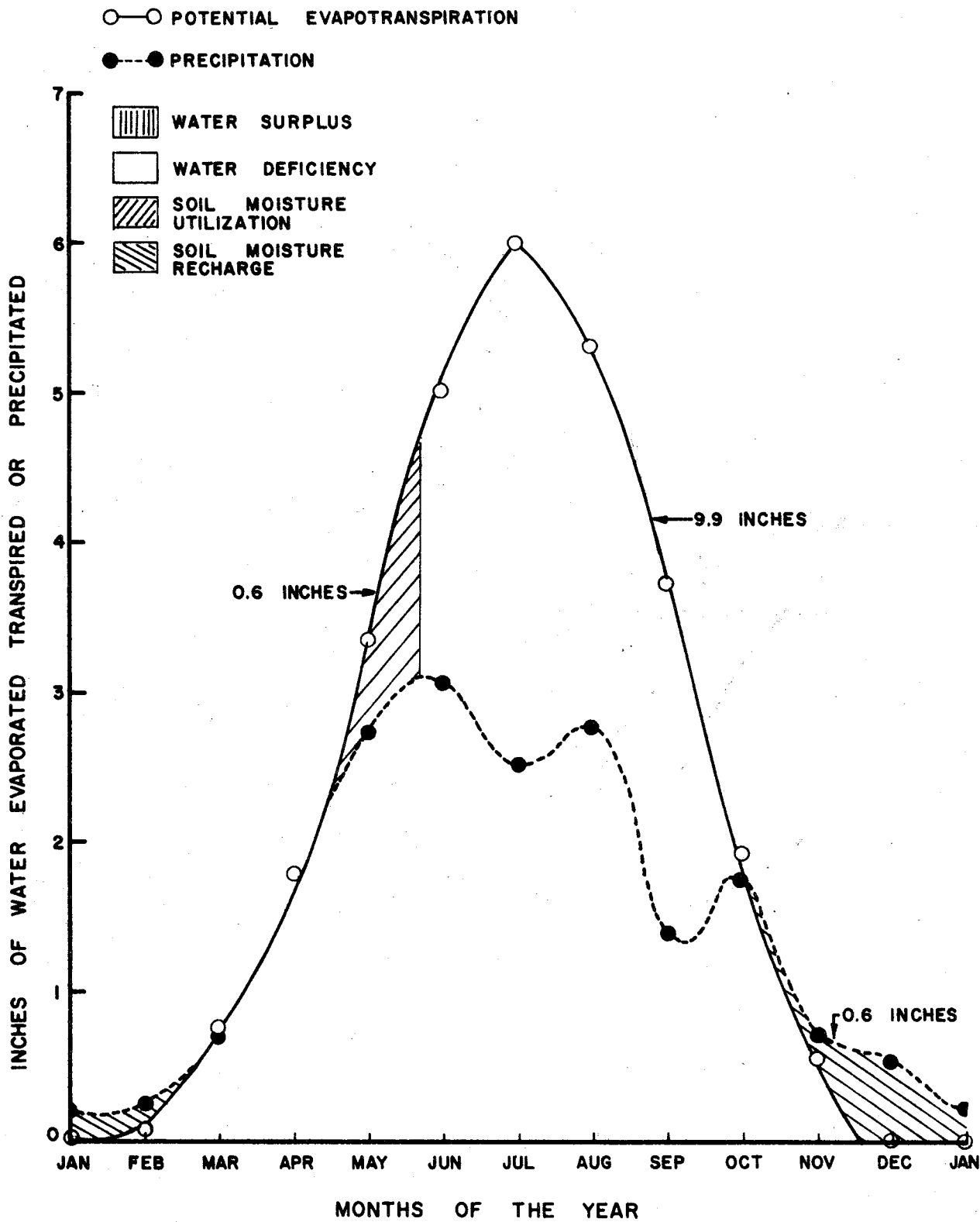


FIG. 4.—MARCH OF PRECIPITATION AND POTENTIAL EVAPOTRANSPIRATION THROUGH THE YEAR FOR DALHART, TEXAS.(33)

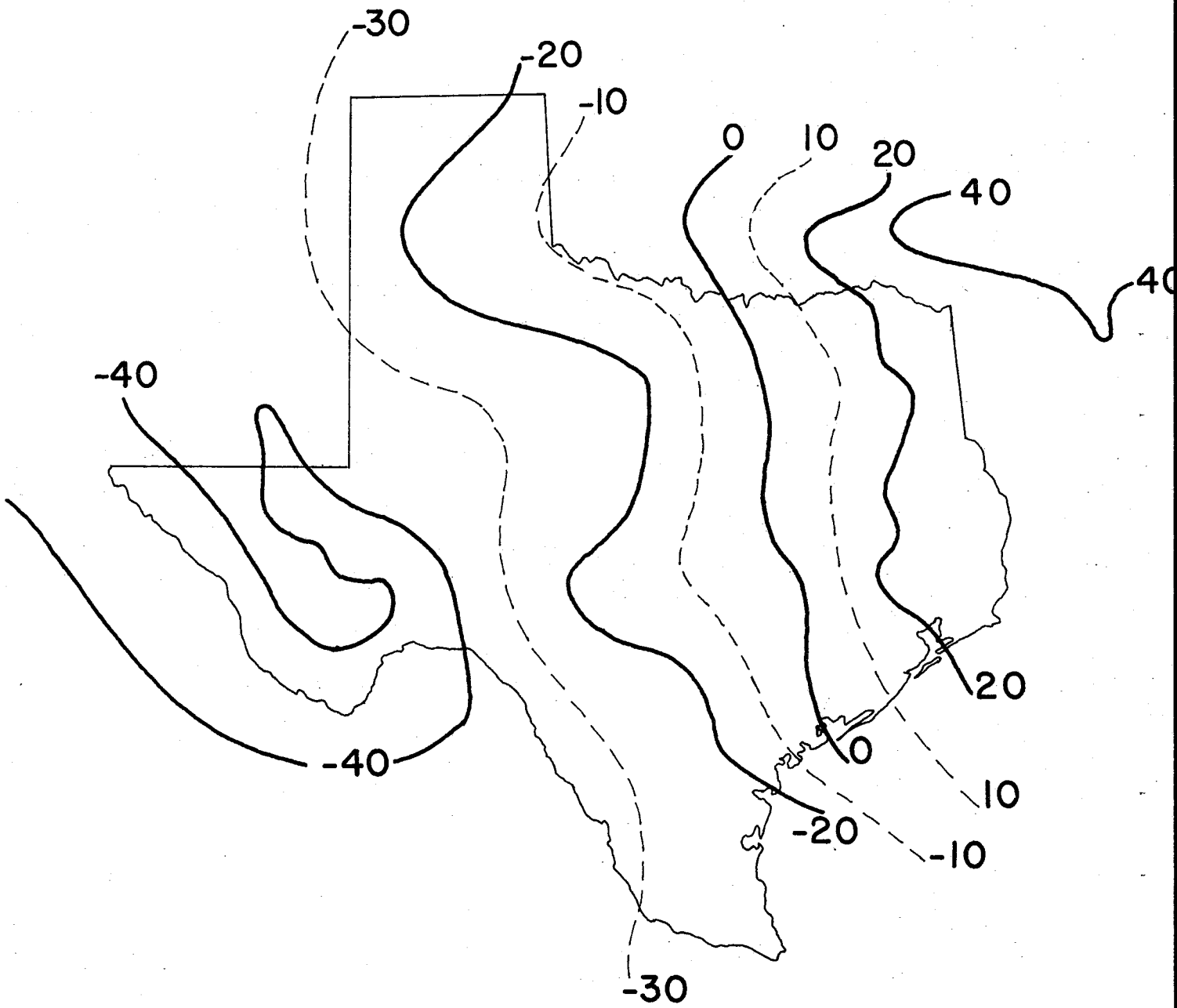


FIG. 5.- THORNTHWAITE MOISTURE INDEX. (33)

The Thornthwaite moisture index has shown promise in relating climate to engineering performance. As applied to pavements, there is a useful relationship. The moisture index has been related to the equilibrium suction level which develops in the subgrade along the centerline of a pavement (26). This relationship, as developed by Russam and Coleman, is shown in Figure 6. This relationship has been verified for several climatic regions (1). Using this relationship and the moisture index previously shown, a map of the expected suction levels in the subgrades may be constructed. Figure 7 shows predicted equilibrium suction levels for a clay subgrade. The actual value of suction will vary with the existing type of subgrade soil. Suction measurements in the Bryan - College Station area beneath pavements with clay subgrades have verified the relationship with the moisture index for that area. This area lies along the zero moisture index line as shown in Figure 7. The high suction values predicted for west Texas show that dry subgrades have the potential for drawing a lot of moisture out of overlying base course layers, thus causing shrinkage cracking.

Along with the moisture in the soil, the effect of temperature on the pavement must be considered. For most types of pavement distress the cold weather will be the most influential. Three controlling variables for frost action have been outlined by Sourwine (30) to be:

1. The intensity of the cold (average minimum temperature).
2. The duration of the cold period.
3. The frequency of a cold period of a given intensity.

Most researchers have attempted to predict the depth of freezing in terms of the surrounding air temperature. This relationship is highly influenced by the type of surface and the type and amount of radiation (12), and the amount of wind (36).

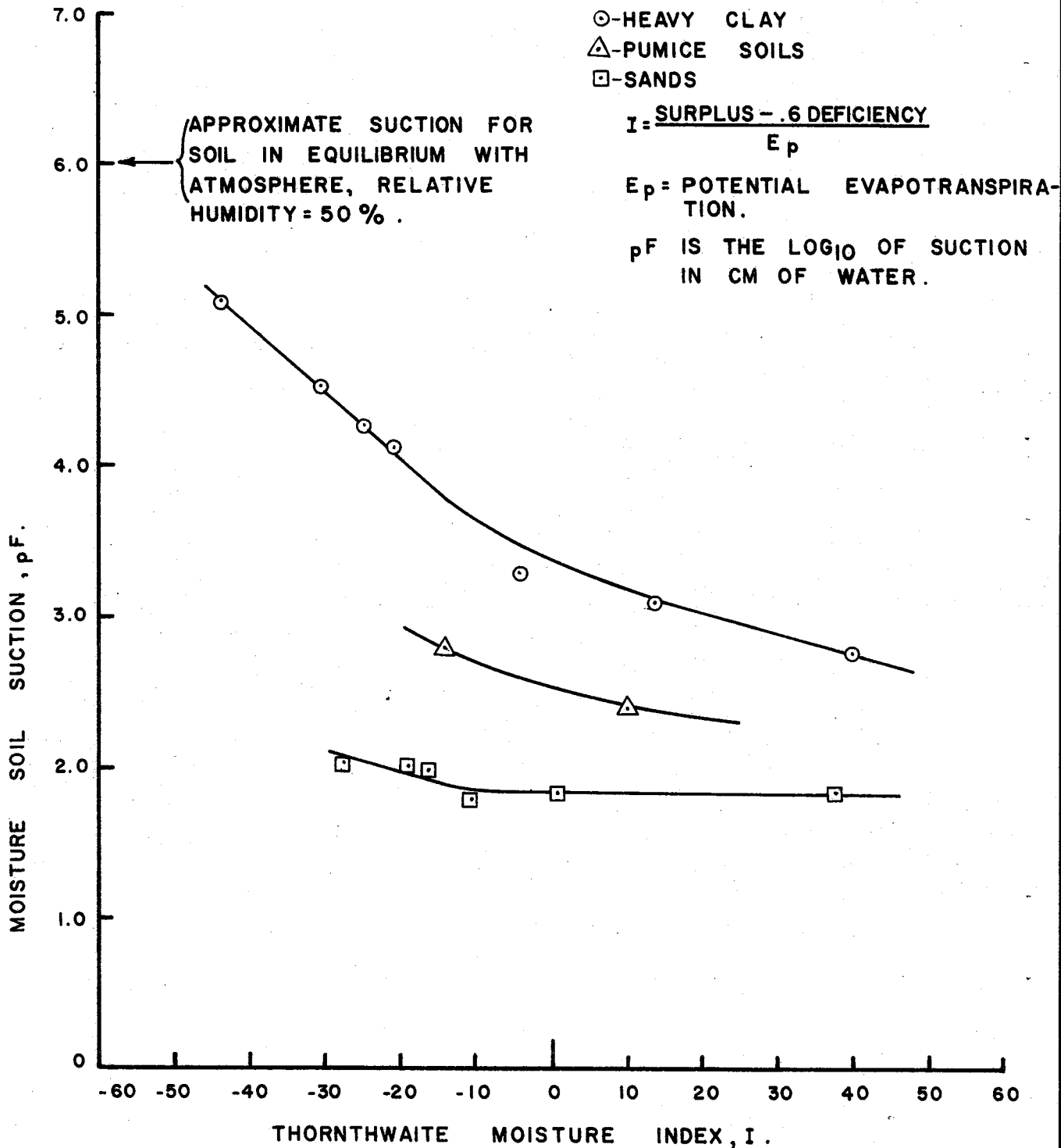


FIG. 6.- SUBGRADE SUCTION AS A FUNCTION OF THE MOISTURE INDEX. (26)

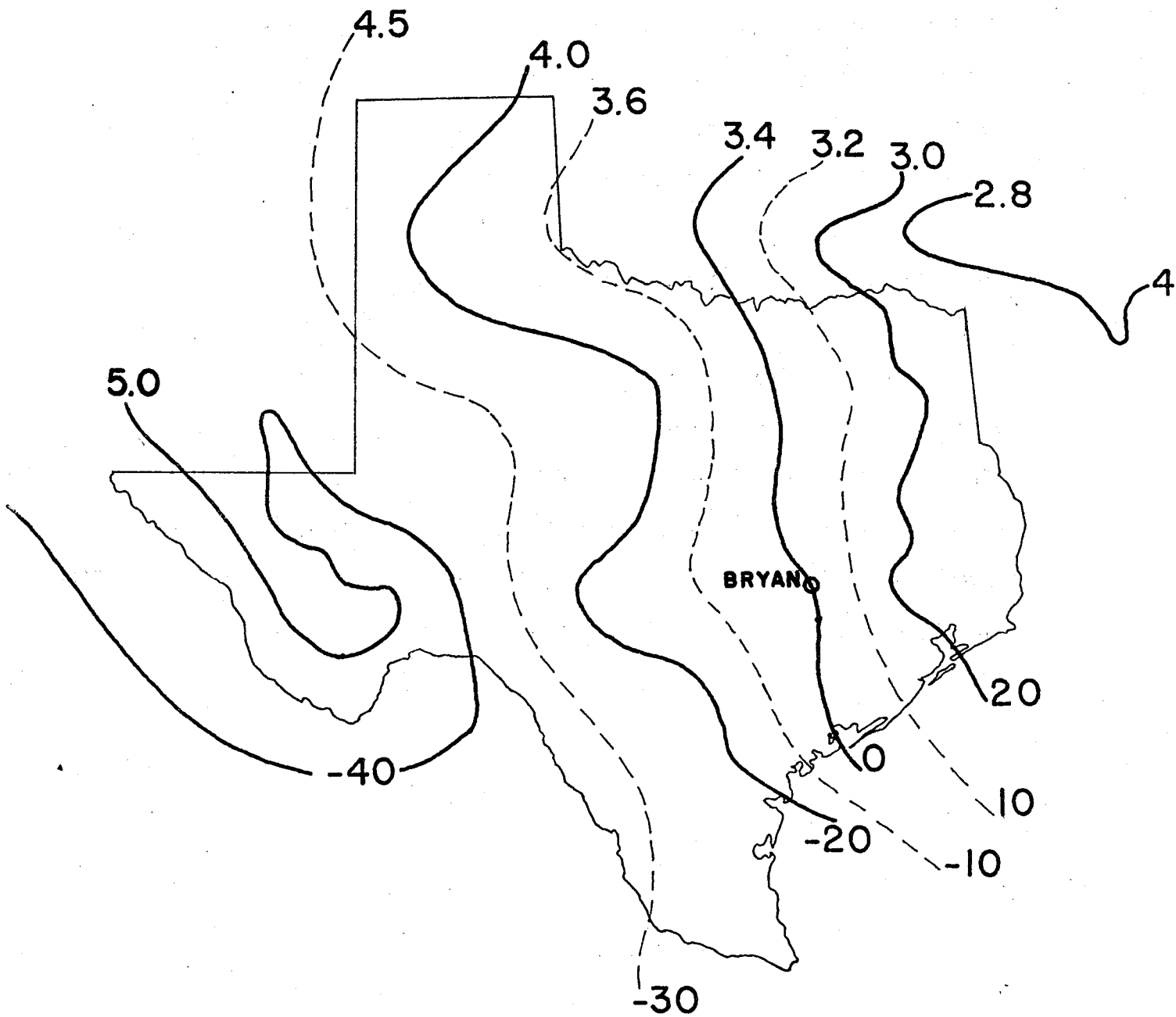


FIG. 7.- PREDICTED SUCTION IN SUBGRADE BELOW A PAVEMENT (UPPER VALUE, $pF = \log(\text{cm. of H}_2\text{O})$ BASED ON THORNTHWAITE MOISTURE INDEX (LOWER VALUE) FOR A CLAY SUBGRADE.

Sourwine conducted extensive studies into frost occurrence and its influence on highway design. He first suggested the "degree-hour index" (31) which was defined as the total number of hours the air temperature stayed below a critical value which would initiate freezing at the surface. He assumed a critical value of 23°F. This freezing index concept has evolved to its present day form which uses the degree-day rather than the degree-hour (12). A degree-day is defined as the algebraic difference between the mean daily air temperature and 32°F multiplied by the duration of the temperature in terms of days. The freezing index is the difference between the maximum and minimum points on a cumulative plot of degree-days. Reasonably good results have been obtained for correlations between the degree-day freezing index and the depth of frost penetration (21, 29, 8, 10, 19). Figure 8 shows the design freezing index for Texas (20). The contours of average annual frost penetration shown in Figure 9 (17) are similar to those in Figure 8 and show the kind of correlation that can be obtained.

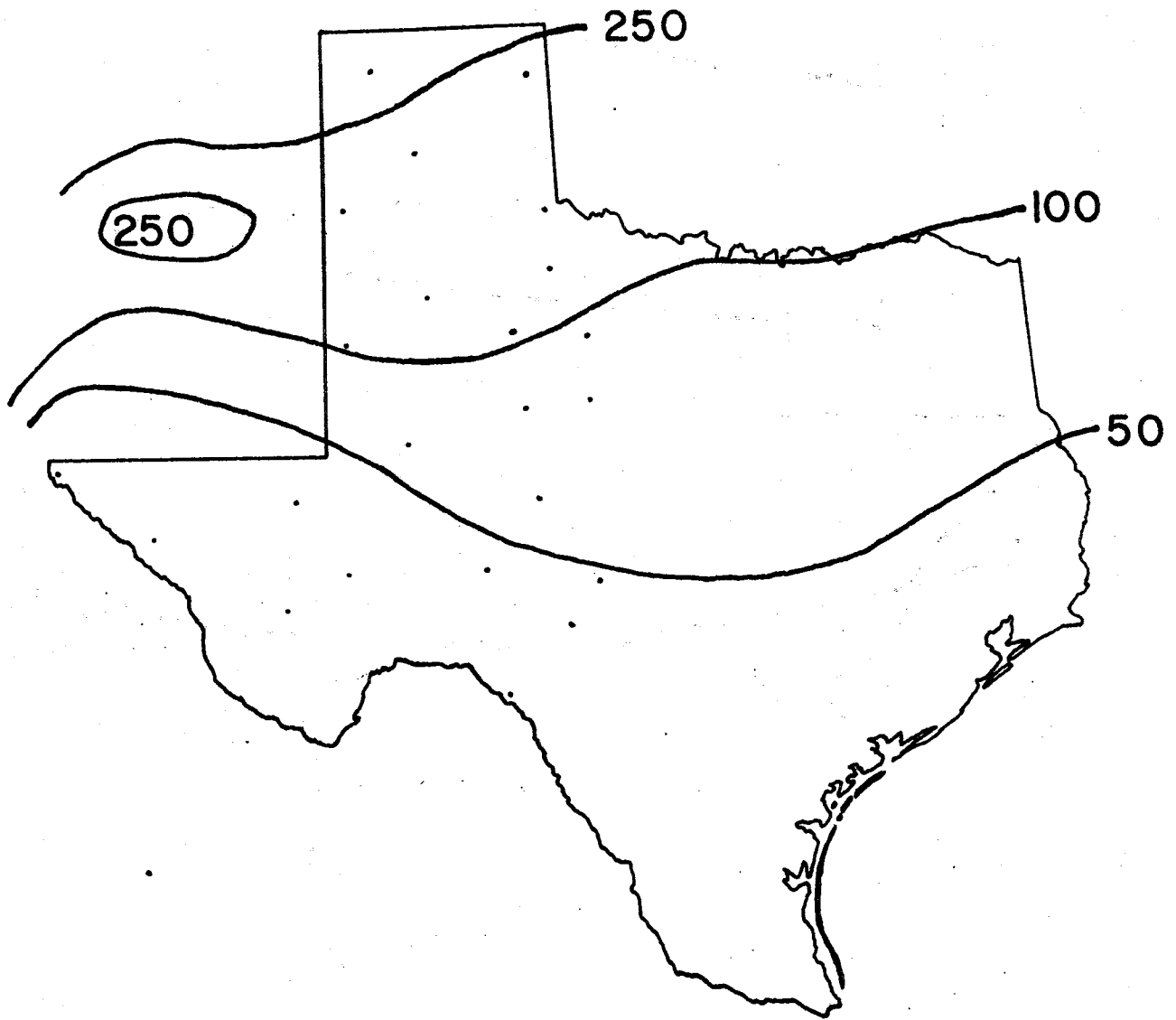


FIG.8.-DISTRIBUTION OF DESIGN FREEZING INDEX. (20)

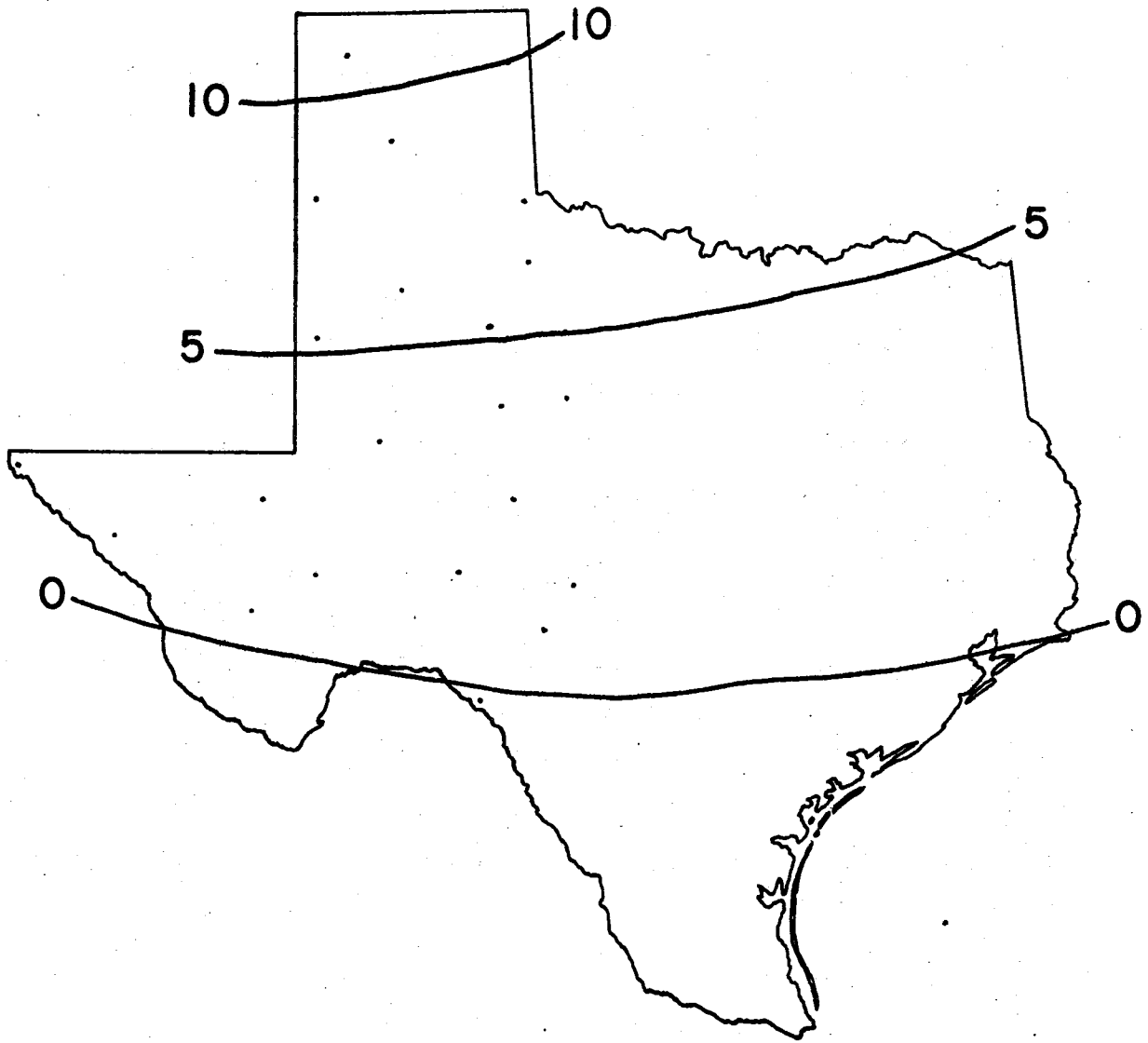


FIG.9.-AVERAGE ANNUAL FROST
PENETRATION IN INCHES.(17)

RESULTS OF PREVIOUS STUDIES APPLIED TO THE PAVEMENT CRACKING PROBLEM IN WEST TEXAS

The transverse cracking phenomenon is a complex portion of the overall flexible pavement cracking problem. At present, there are several thousands of miles of primary highways in Texas with this type of distress and many more thousands of miles throughout the United States and Canada. Previous studies have concentrated on the asphaltic concrete as the source of cracking and attributed the transverse cracking to extreme low temperature (thermal cooling) or thermal fatigue (temperature cycling).

Low temperature cracking studies in Canada have indicated that the main problem is low temperature induced cracking (31, 28). In this mechanism, a low temperature, coupled with the rate at which the low temperature is reached, induces tensile stresses which exceed the tensile strength of the asphaltic concrete mix. This produces transverse cracks at regularly spaced intervals. This concept cannot explain the problem in west Texas since, as McLeod (22) states, "As low temperature transverse pavement cracking appears to be a problem in any region with a freezing index above about 250, approximately the Northern third of the United States is affected." Recalling the freeze index shown in Figure 8, Texas should not have extensive low temperature cracking. The mean annual minimum temperature expected to occur during the year is shown in Figure 10.

Rate of Temperature Drop

The rate of drop in temperature is also important in low temperature thermal cracking (22). This quantity is very difficult to predict accurately

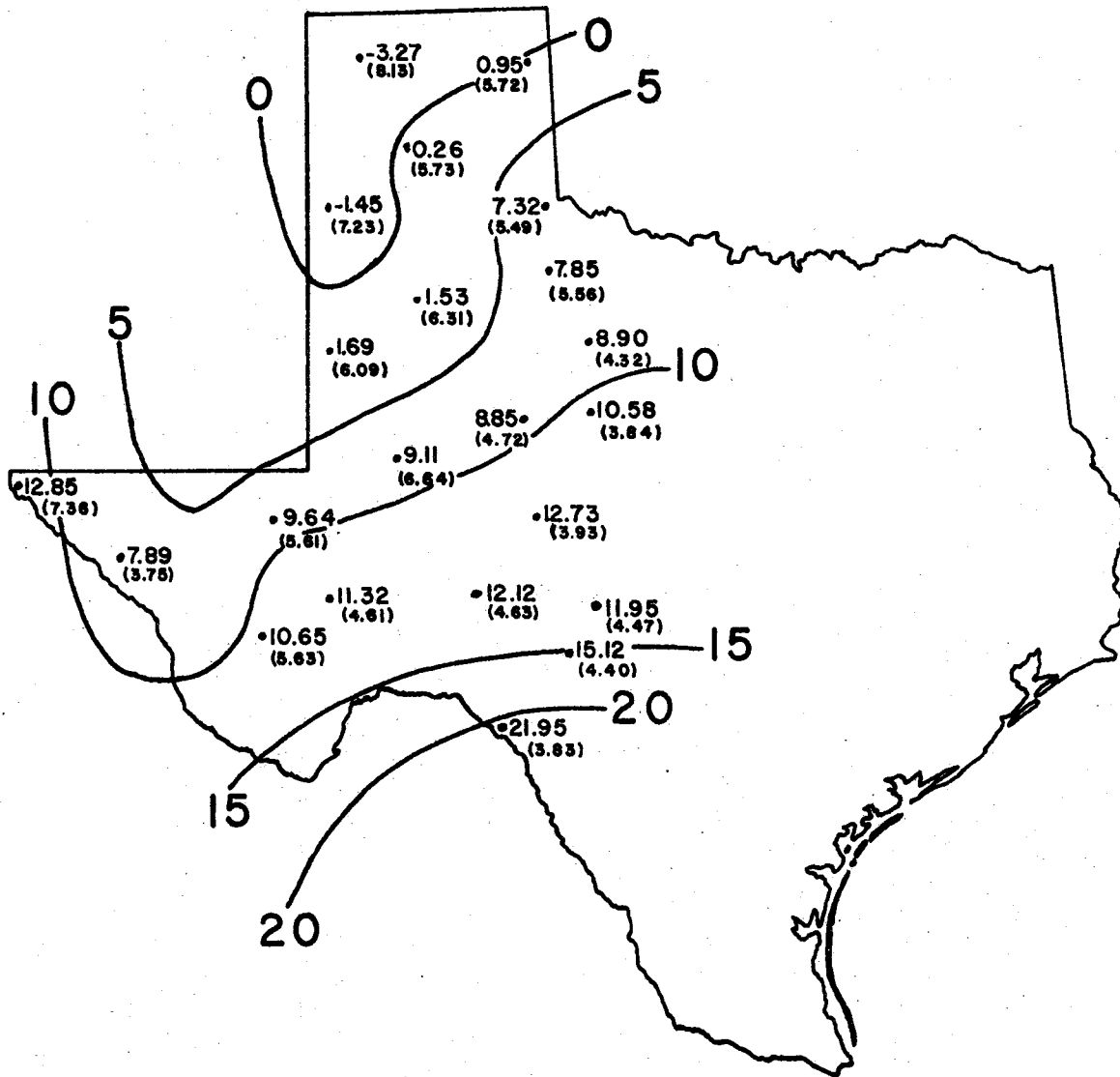


FIG.10.— MEAN ANNUAL MINIMUM TEMPERATURE, 1953 TO 1971.

from reported data. Averaged values mask the importance of the rate which would accompany a severe cold front. The values shown in Table II show the largest recorded drop during the year for different locations in Texas. This illustrates the extreme variability of the quantity. In Figure 11, the three highest monthly values have been averaged. Figure 11 demonstrates the fact that the western portion of the state will be subjected to a larger rate of temperature drop than the remainder of the state.

Data on the rate of temperature drop for each city could be put in a form similar to that shown in Figure 12 for a western Canadian road site near Manitoba (7). Using the data given in Table II, it is evident that the west Texas area may be expected to experience temperature drops which will produce rates greater than those commonly found in Canada. This indicates a more severe condition of induced tensile stresses in west Texas. The distribution in Figure 12 is typical of a number of sites in the referenced study, and could be expected to closely parallel any data for Texas, thus intermediate values could be selected.

Temperature Cycling (Thermal Fatigue)

Thermal fatigue or temperature cycling is much more prevalent in the west Texas area than other areas of the state. This is shown in Figure 13 which shows the annual average number of freeze-thaw cycles based on air temperature. Like the value of air temperature used in obtaining the freeze-index, the value will be indicative of the level of thermal-fatigue the pavement will undergo; while not actually being measured pavement temperatures. There is a definite trend showing the western portion of the State experiencing the greater number of cycles. Tuckett and Littlefield (35)

TABLE II. HIGHEST RATE OF TEMPERATURE DROP
BELOW 45° FARENHEIT PER HOUR.

City/Year	1966	1967	1968	1969	1970	Maximum Difference
Amarillo	7	6	5	5.3	6	2
Abilene	6	6.7	7.3	10.3	10	4.3
El Paso	6.7	6.3	5.7	6	5.7	1.0
Lubbock	7.7	6.7	5.7	12	8	6.3
Midland	7	6	6	9	7.3	3
San Angelo	8	7.3	5.3	5.3	6.3	2.7

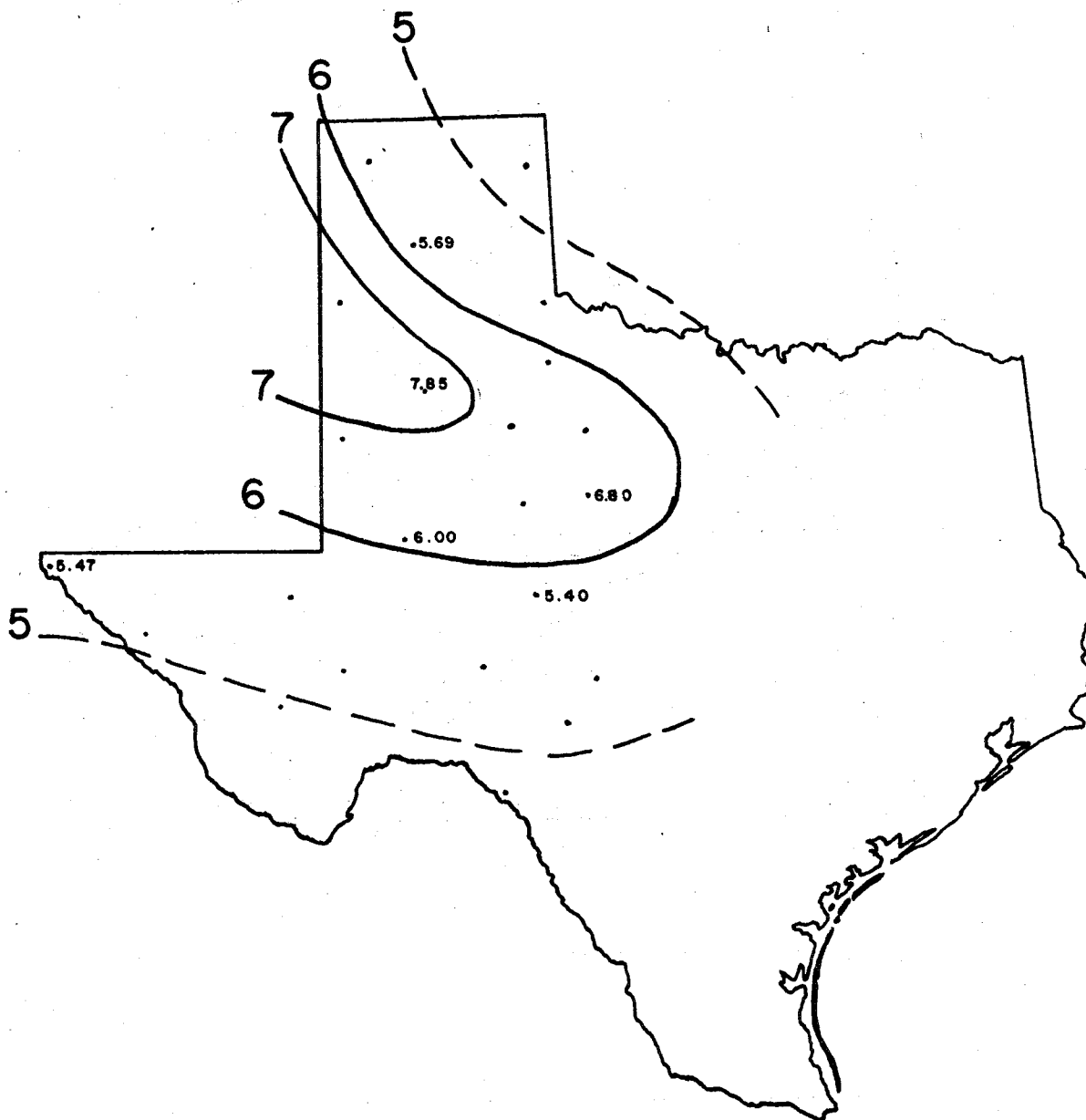


FIG.II.—RATE OF TEMPERATURE DROP BELOW
 45° F. TAKEN FROM HIGHEST MONTHLY
 VALUE. (°F/HOUR)

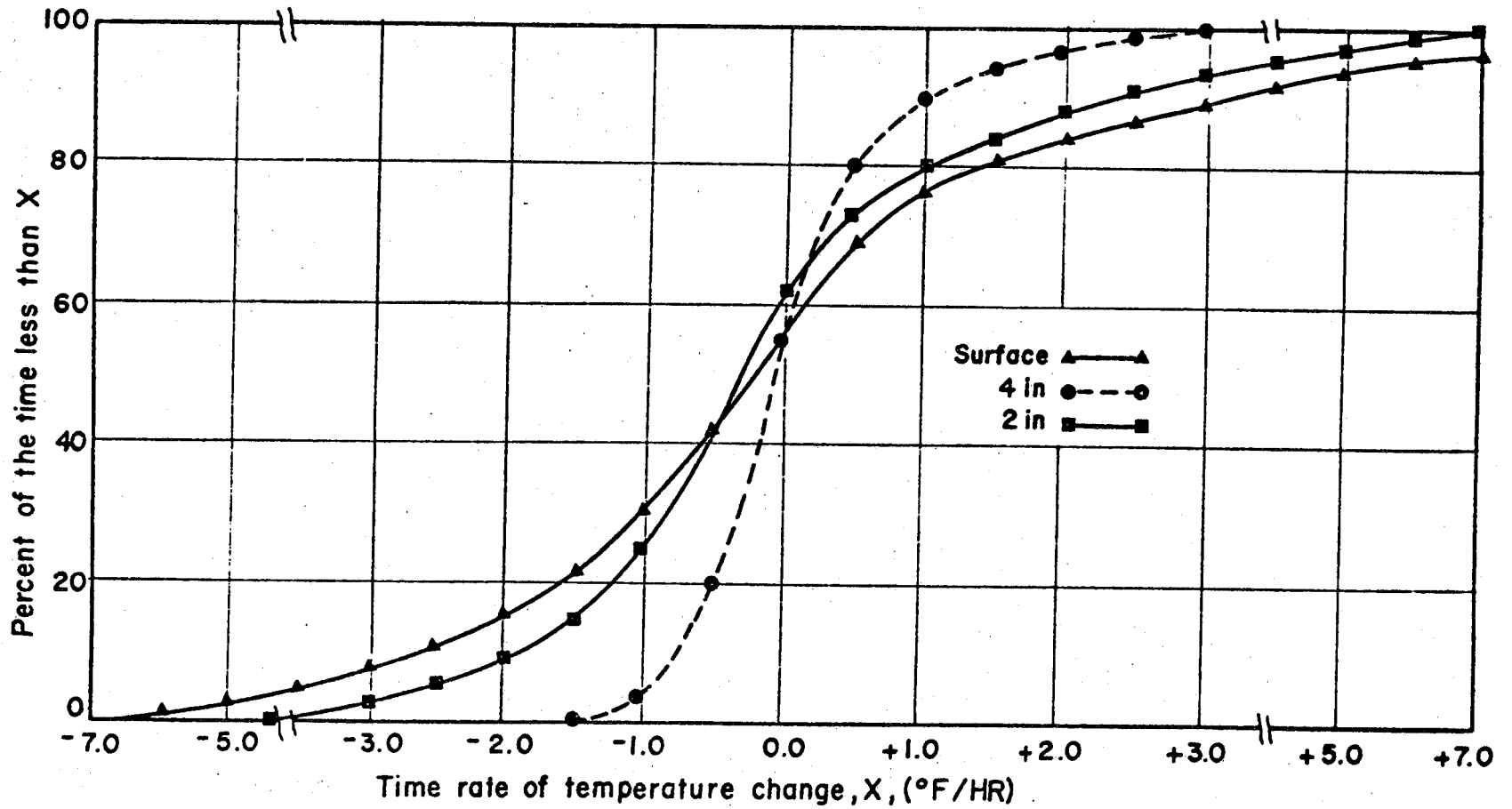


FIG.12.— TIME RATE OF TEMPERATURE CHANGE DISTRIBUTIONS OF THE ASPHALTIC CONCRETE (7)

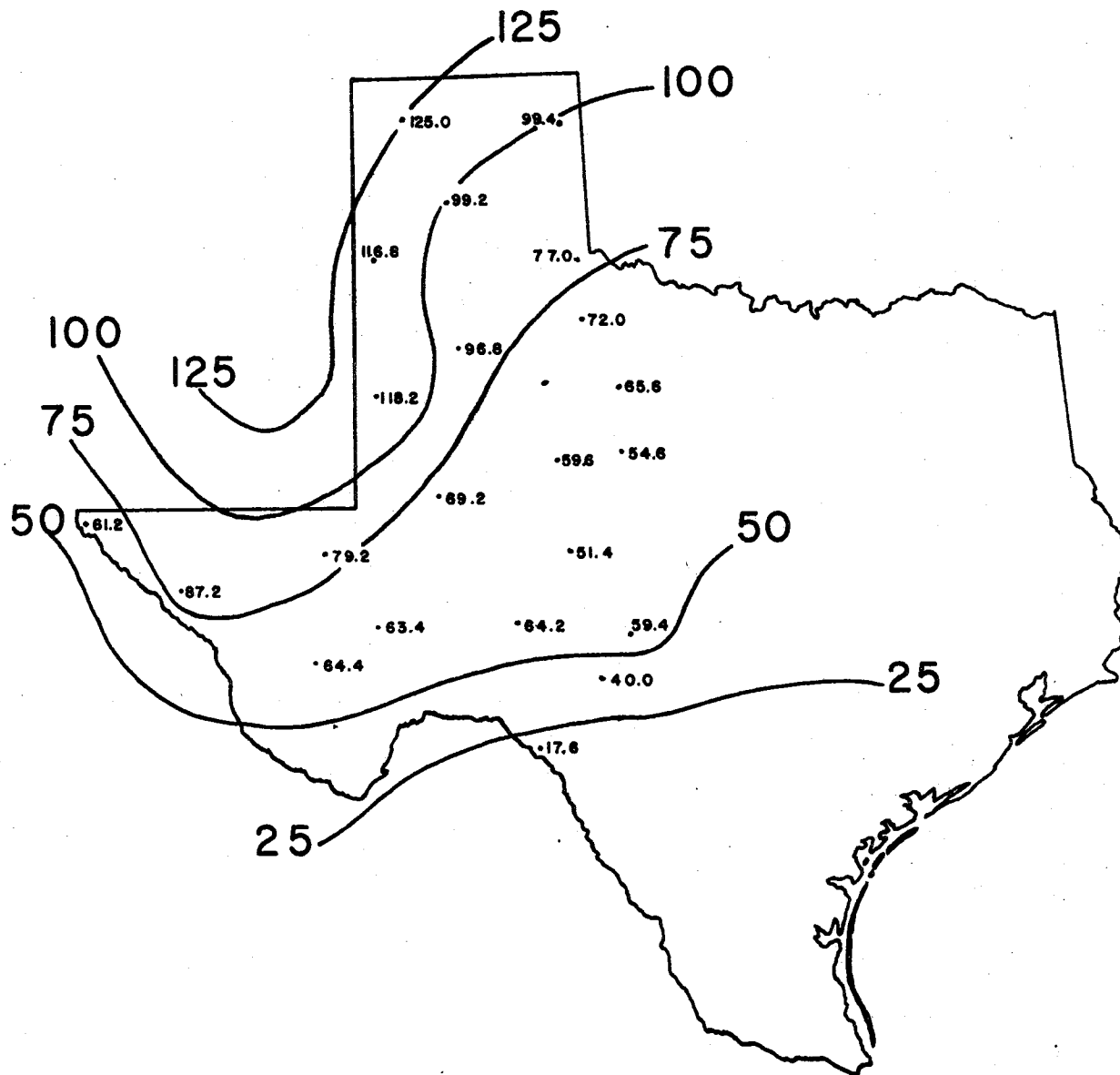


FIG.13. - ANNUAL AVERAGE NUMBER OF FREEZE THAW CYCLES, AIR TEMPERATURE.

have shown the effects of loadings due to temperature cycling. While directing themselves mainly to the question of mix variables, the effects of temperature cycling are clearly shown. An increased number of cycles increases the stress built up by any one temperature cycle. Although the cycles themselves may not produce failure, they serve to stiffen the asphaltic concrete. Consequently, a severe cold spell, while of short duration and possibly not reflected in the long term averages, will produce sufficient internal stresses to initiate cracks which will then propagate under the normal weather conditions. In this manner, sudden massive pavement failures may occur nearly simultaneously over rather large areas.

Various schemes have been proposed to predict the amount of cracking at any time in a pavement's life. These have been mainly regression analyses which determined a relative influence of each variable considered on the total amount of cracking. Shahin and McCullough (28) used data collected mainly in Canada; and through regression analysis constructed a computer code to predict the amount of cracking at any time in the life of a pavement. This model dealt almost entirely with the asphalt portion of the pavement structure. Although this mathematical model must still be verified and perhaps revised, the overall importance of climatic variables should remain the same. The relative influence of each variable is shown in Figure 14. It should be noted that the more important variables are the environmental factors.

Hajek and Haas (15) evaluated more than twenty variables in their analyses. They utilized only five variables in their final equation. The variables are:

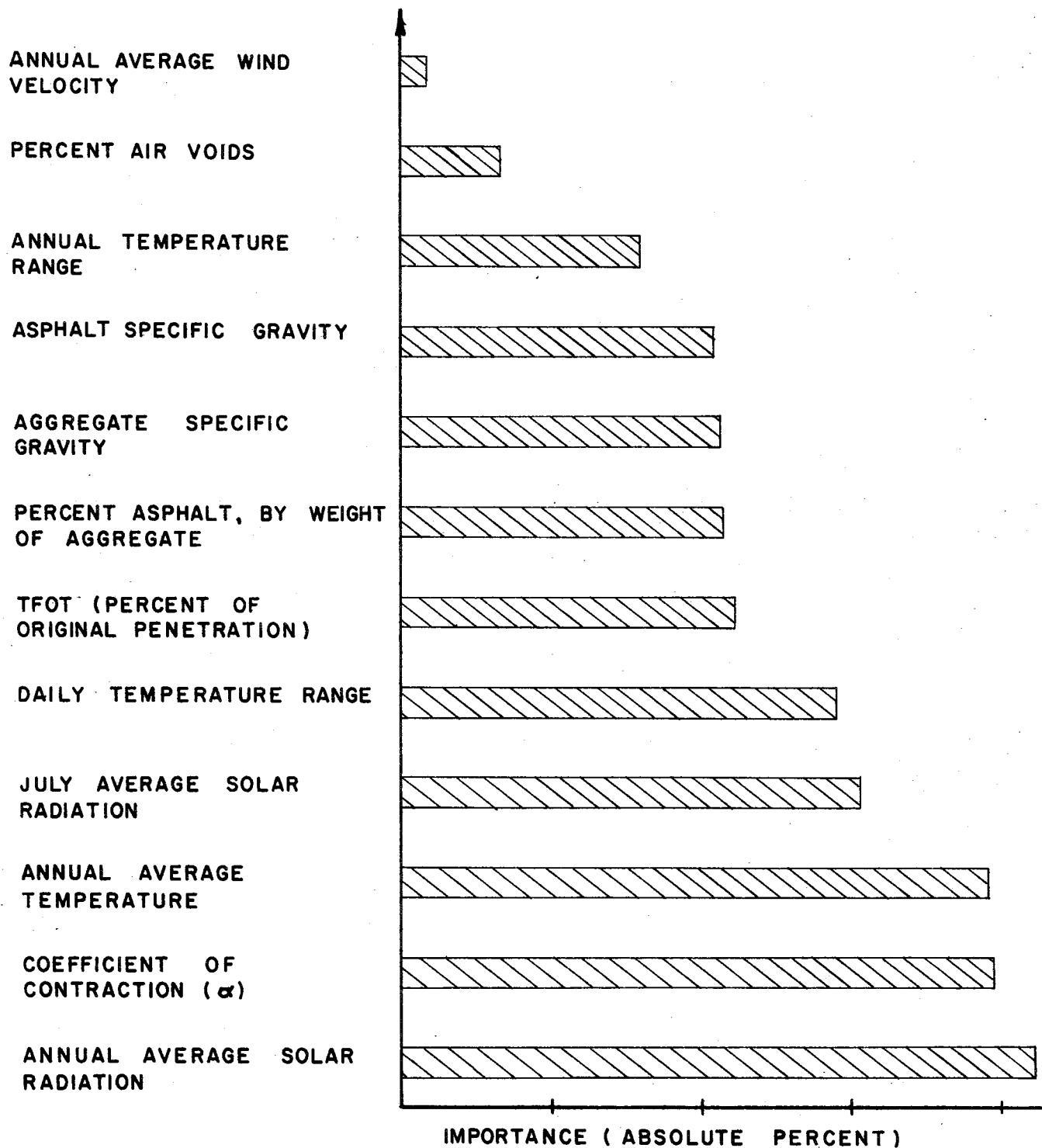


FIG.14.—IMPORTANCE OF INDIVIDUAL VARIABLES REGARDING THEIR EFFECT ON THERMAL-FATIGUE CRACKING (28)

1. Stiffness of original asphalt cement,
2. Thickness of all asphalt concrete layers,
3. Age of asphalt concrete layers,
4. Winter design temperature, and
5. Subgrade type.

The winter design temperature is defined as the lowest temperature at or below which only one percent of the hourly ambient air temperatures in January occur for the severest winter during a ten-year period. This has been related to the freezing index for Canada. This relationship is shown in Figure 15. This relationship would indicate a winter design temperature between 5 to 8 degrees Fahrenheit. This value would appear to be slightly low for the west Texas area. The interesting feature of this study is that the type of subgrade material, gravel, sand or clay, is recognized as being influential in the amount of cracking.

Other Important Climatic Variables

Solar Radiation

The fact that the climatic variables are of prime importance is a conclusion borne out in all studies. The annual average daily solar radiation (16) is shown in Figure 16. This value is extremely influential in changing pavement temperatures, heating the surrounding air, and causing changes in the asphalt. The west Texas area can clearly be seen to receive the larger amount of radiation in the State. Monthly values of mean daily solar radiation are compiled in Appendix II. To predict the seasonal variation of solar radiation, the values for June and July, which represent the maximum values which will occur during the year, must be known (28).

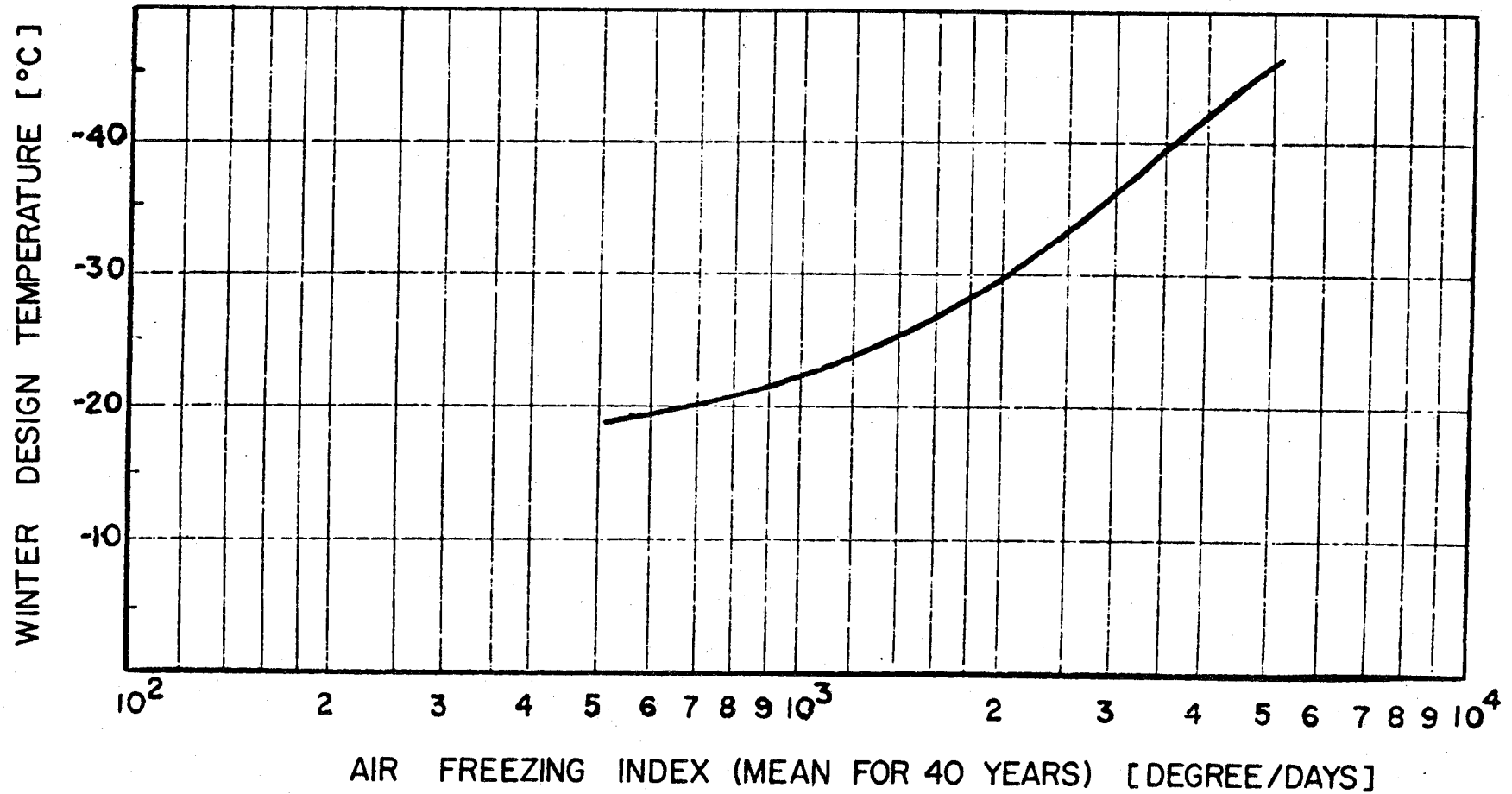


FIG.15.—RELATIONSHIP BETWEEN FREEZING INDEX AND WINTER DESIGN TEMPERATURE.(7)

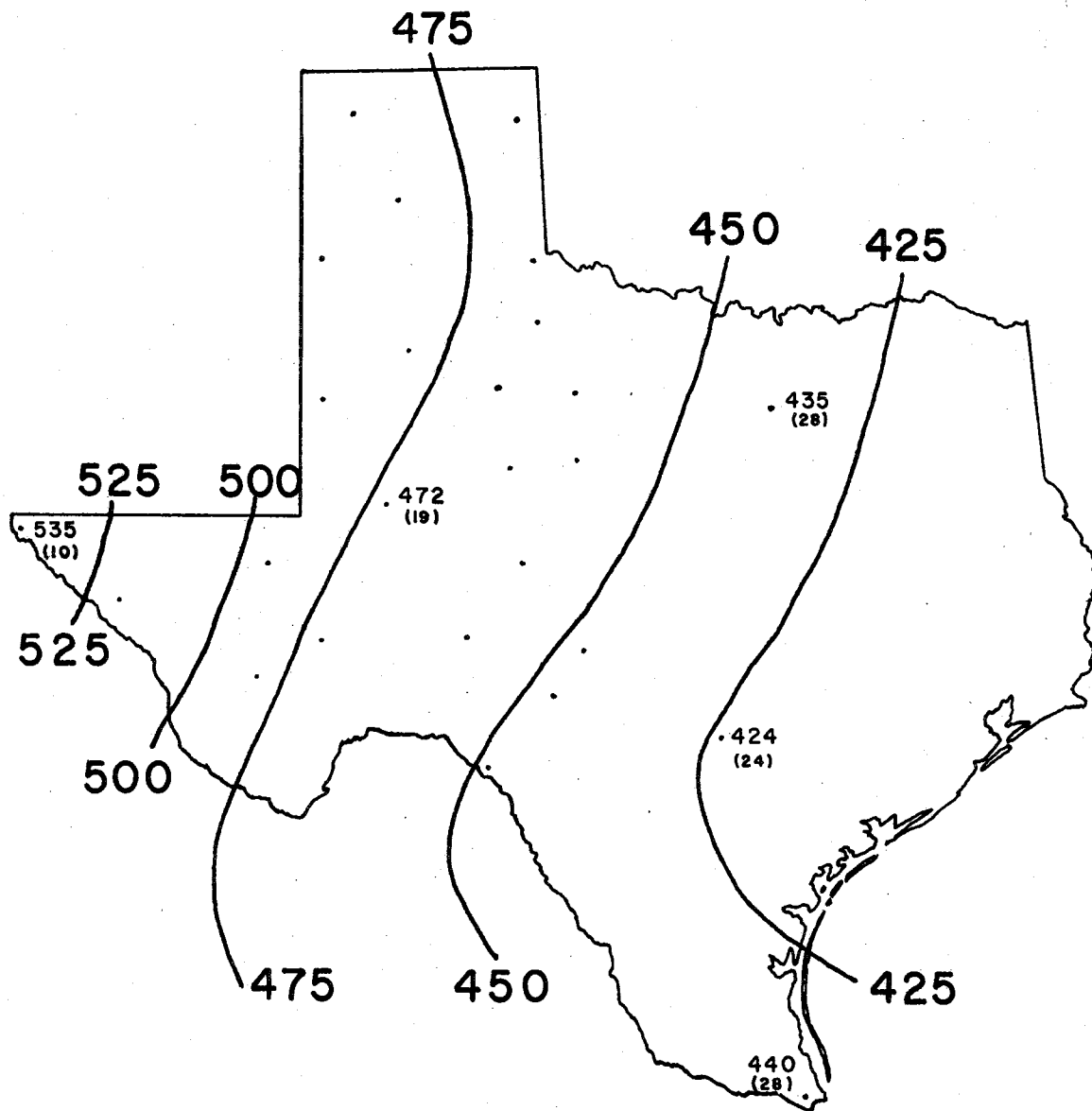


FIG. 16.- MEAN DAILY SOLAR RADIATION,
ANNUAL, (LANGLEYS/DAY).(16)

Temperature Averages and Ranges

The annual average temperature and the mean daily temperature range are integral parts of a relationship for predicting pavement temperatures (3). These weather bureau data are useable in predicting a worst minimum pavement temperature. Straub (32) stated "It should be noted that minimum temperatures of the surface seldom drop below the lowest air temperature, barring an unusually clear night producing a so-called radiation frost." The annual average temperature in Figure 17 and the daily temperature range in Figure 18 again demonstrate that the west Texas area has the more severe ranges of these variables. The annual average temperature is lower and the daily temperature range is larger than in any other part of the State. Yearly values of the mean daily temperature range are in Appendix III.

The annual temperature range, Figure 19 and the annual wind velocity, Figure 20, are the least important climatic variables shown in Figure 14. However, they do complete a picture of the total environment and do exert some influence on pavement behavior. They are included in at least two analysis schemes (28, 7) and are presented here for completeness.

Long-Term Moisture Balance

While not explicitly mentioned in the previous studies dealing with the prediction of transverse cracks, the moisture in the subgrade, base, and native material is extremely important. This was shown in the derivation of several environmental indicators earlier in this report. The mean annual precipitation is shown in Figure 21. As expected, it shows a smaller amount of rainfall in the west Texas area. In areas with such a small amount of total rainfall, it would appear that moisture damage would be the result of mistakes in the

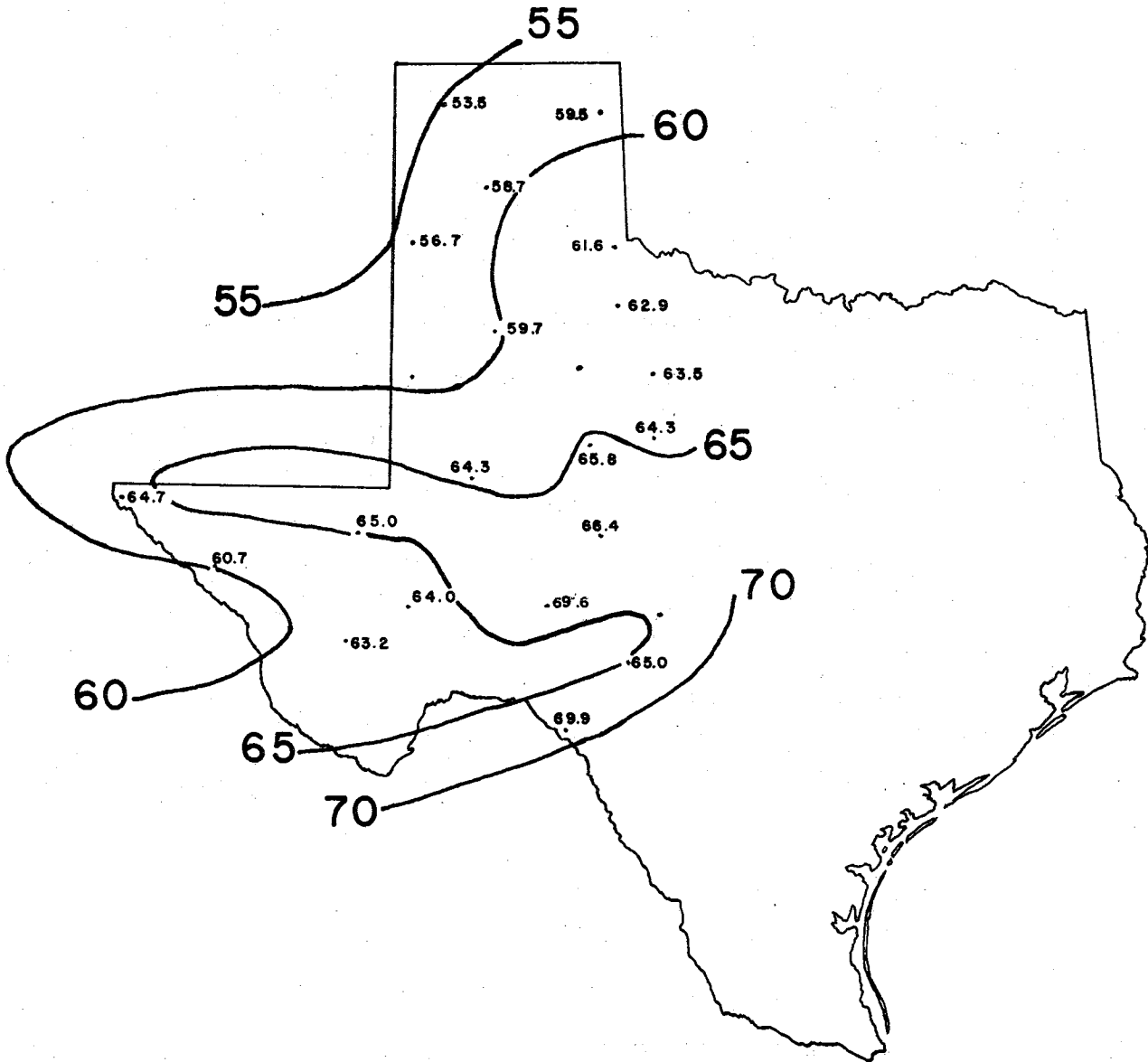


FIG.17. - MEAN ANNUAL AVERAGE TEMPERATURE.

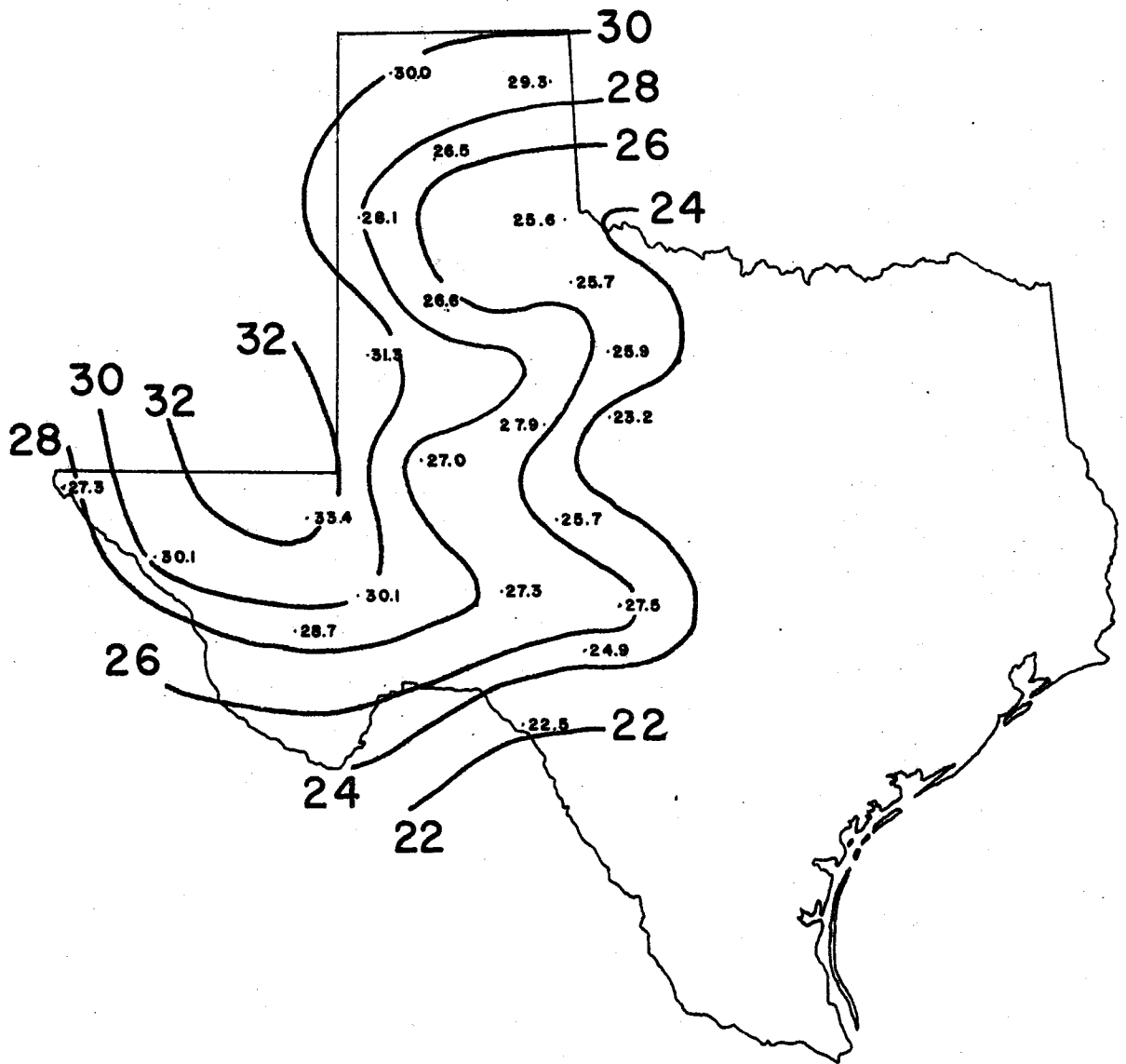


FIG.18.— MEAN DAILY TEMPERATURE RANGE.

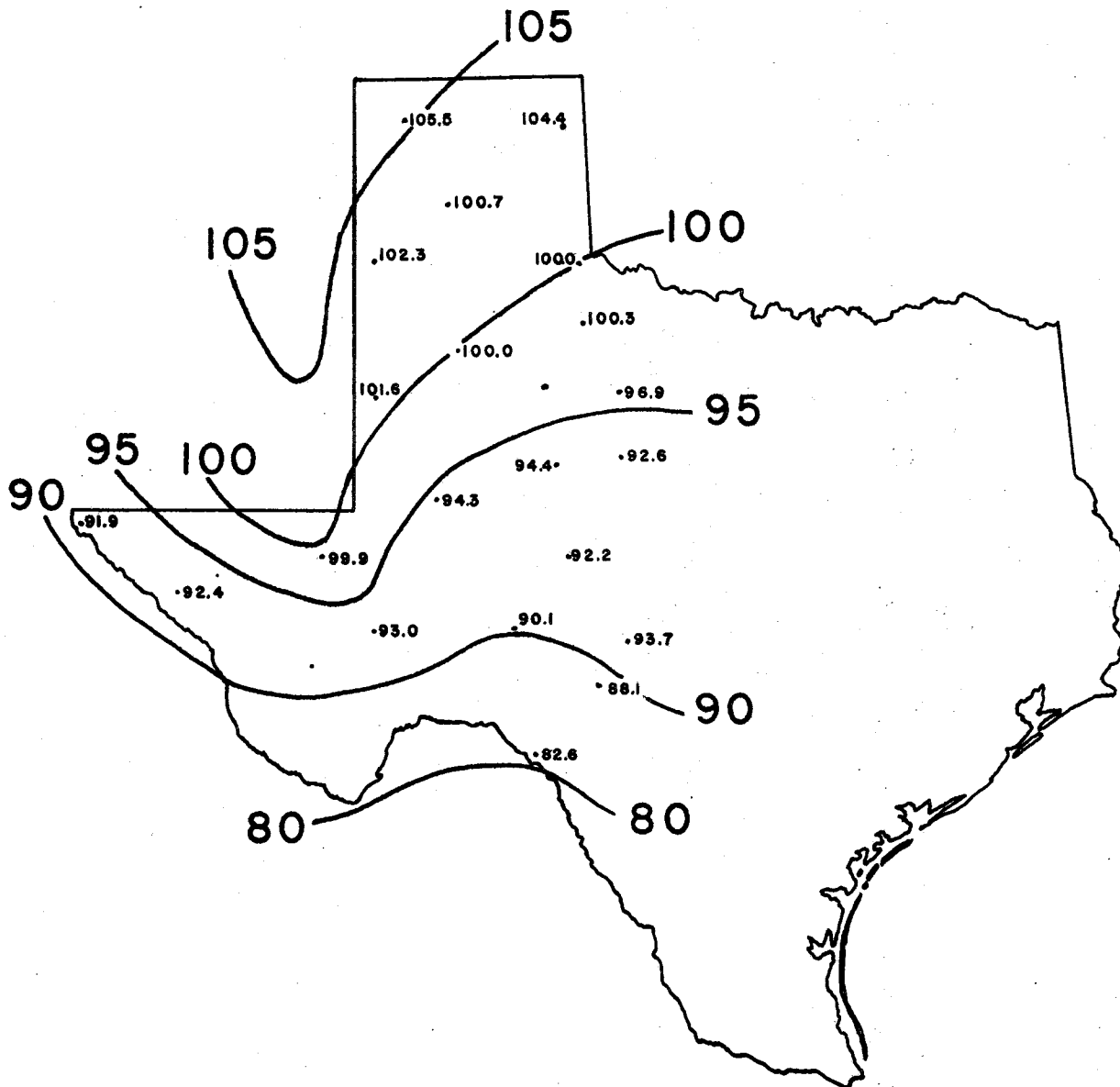


FIG.19-MEAN ANNUAL TEMPERATURE RANGE,
MAXIMUM TO MINIMUM.

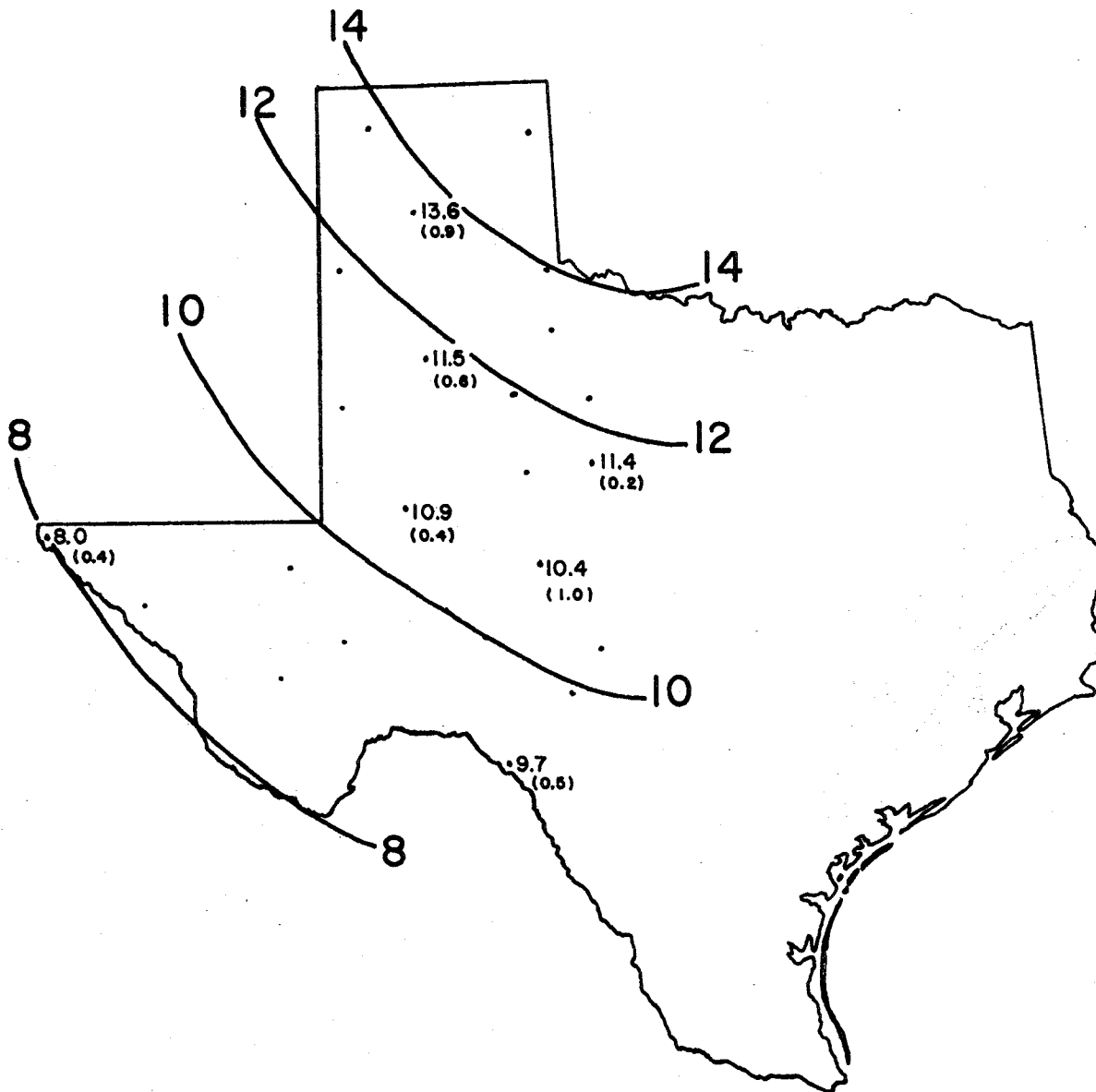


FIG.20-MEAN ANNUAL WIND VELOCITY
IN MILES PER HOUR.

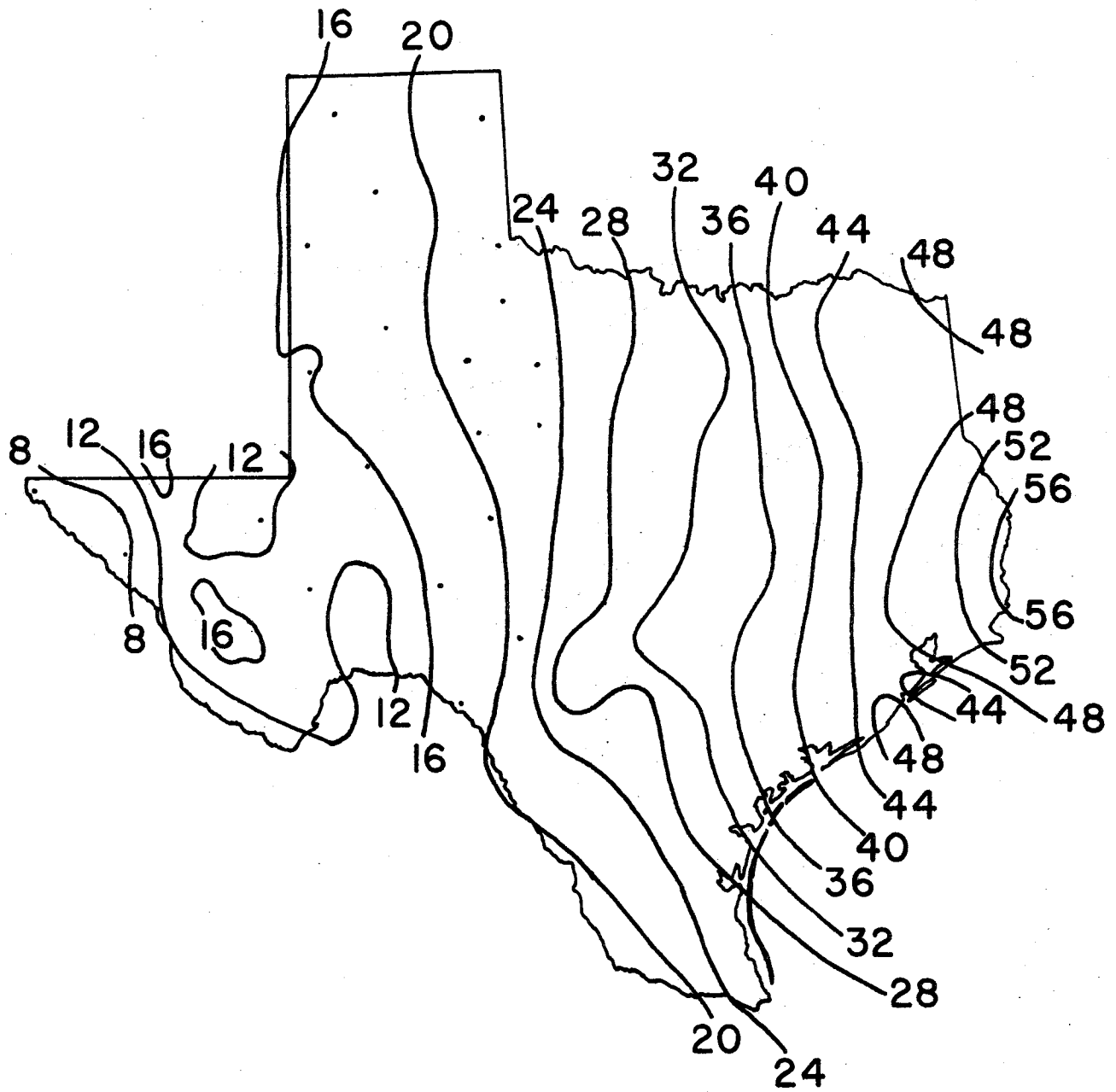


FIG. 21.—MEAN ANNUAL PRECIPITATION,
IN INCHES, 1930 TO 1961.

design or construction of the pavement cross section which results in inadequate drainage. This conclusion, in part, was borne out in a report by Frey (13) which suggests that moisture redistribution and excessive fines in the base, and structural inadequacies contributed to the formation of transverse cracks.

This study was conducted after extensive failure of pavements in west Texas occurred in 1958. An extended period of drought, 1947 to 1956, was broken in 1957 and followed by several years of larger than average rainfall. During the extended dry period extensive cracking of the natural soil would occur. The large influx of moisture in 1957 and 1958 would then have an open route into the lower soils and into the subgrade of the pavements. This action would account for widespread deterioration in a relatively short period. Thus, the moisture state of a pavement system when constructed in relation to the past moisture conditions may be a valuable indicator of potential pavement distress. This moisture condition may be discerned from a study of the departure of precipitation from the long term mean. These data are given in Appendix IV.

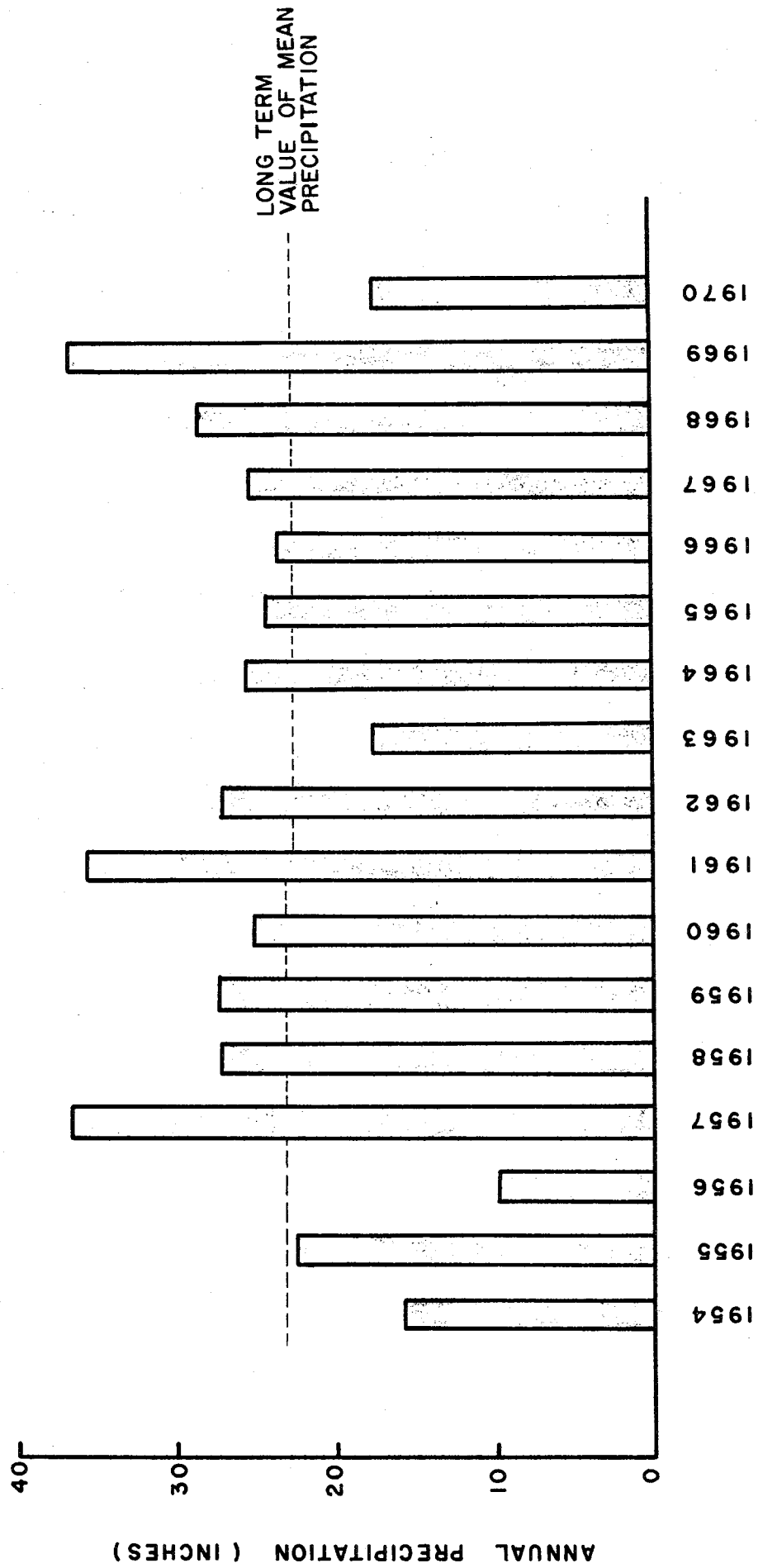


FIG. 22. - BARGRAPH OF TOTAL ANNUAL PRECIPITATION, ABILENE.

CONCLUSIONS AND RECOMMENDATIONS

From the data presented for the west Texas area and the conclusions of previous studies several conclusions may be drawn concerning the transverse cracking problem in west Texas.

1. Low temperature thermal cracking of pavements is less influential than in other parts of the United States and Canada.
2. Stresses induced by rate of temperature drop are likely to be higher in west Texas than in Canada (where the entirety of data has been collected to date) and probably in other portions of the United States.
3. Thermal fatigue would be more of a problem in west Texas and the United States than in Canada.
4. In all instances, the west Texas portion of the state appears to be subject to the more severe action of the climatic variables associated with low temperature, thermal fatigue and shrinkage cracking.
5. The importance of having accurate measurements of climatic variables is borne out in all studies.
6. The base course and subgrade have not been adequately researched, recorded, or considered in previous studies.
7. Moisture redistribution and state of moisture (suction) in the base and subgrade materials is extremely important in studying the behavior of the pavement. A reliable relationship between an environmental indicator and the equilibrium suction beneath a highway in the subgrade exists. This environmental indicator

(Thornthwaite moisture index) has been validated for the west Texas area by regression against similar known quantities derived specifically for the west Texas area.

8. The transverse cracking problem in west Texas is a much more complicated phenomenon than can be predicted by considering only the asphaltic concrete surface course. Much work remains to be done in relating the interactions of the various mechanisms.

The data presented in this report represents the initial step in establishing a basis for comparison between predictive methods. The data will prove useful to the engineer in considering the environmental influence on pavements being designed.

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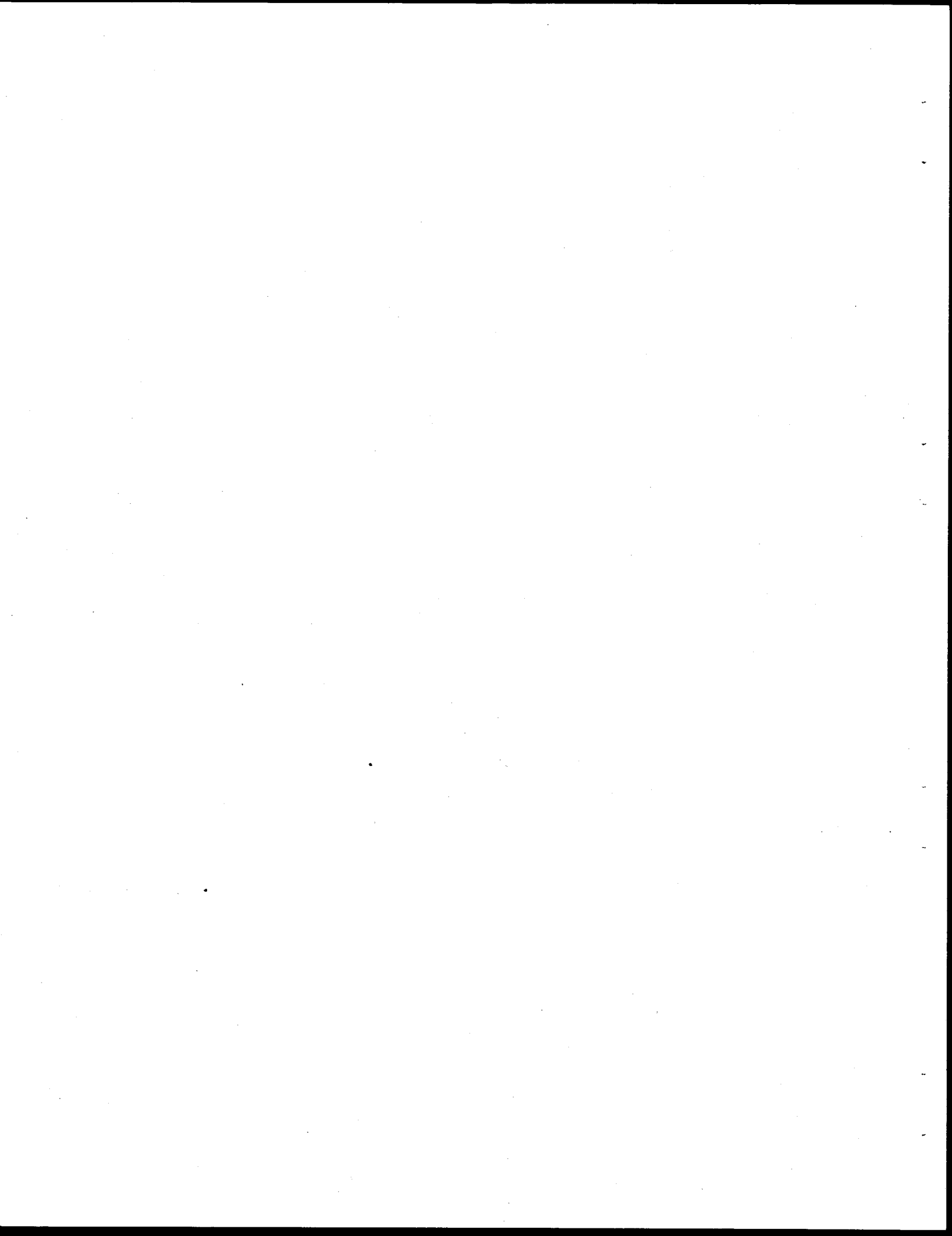
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APPENDIX I. - DETERMINING SUBGRADE MOISTURE WITH AN ENVIRONMENTAL INDICATOR

As stated previously, a relationship has been verified on various continents (Europe, Africa and Australia) between an environmental indicator (The Thornthwaite Moisture Index) and the equilibrium state of moisture suction in the subgrade beneath a pavement. The state of moisture beneath a pavement has been shown by many investigators to be very influential on the pavement behavior (1). If the environmental indicator can be validated with climatic variables from the west Texas area, a valid predictive tool will be available. The Thornthwaite indices were developed for the northeastern United States and expanded to the other portions of the U.S. As such, their use in connection with the west Texas area has been questioned.

The relationship for monthly potential evapotranspiration is expressed by an equation of the form:

$$e = Ct^a \quad (2)$$

where:

e is the potential evapotranspiration per month in cm.

t is the mean monthly temperature in °C.

C and a are coefficients which vary with location.

A special equation has been developed for coefficients c and a which allows them to vary from a low number in cold climates to a high number in hot climates. A monthly index is first obtained:

$$i = (t/5)^{1.514} \quad (3)$$

where

t = mean monthly temperature in °C

This index is summed over the year to get a heat index, I. This index varies inversely with coefficient C and will closely approximate coefficient a in a polynomial equation given as:

$$a = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (1.792 \times 10^{-2})I + 0.49239 \quad (4)$$

The general relationship given by equation (2) may be expressed as:

$$e = 1.6(10^t/I)^a \quad (5)$$

This gives unadjusted monthly values of potential evapotranspiration. They must be adjusted for the length and number of days. This correction factor is dependent on the latitude of the station where the temperatures were needed. The west Texas area lies in latitude 30°N to 35°N. Correction values for these latitudes are given in Table AI. By multiplying each monthly value of e by its appropriate correction factor and then summing, the yearly potential evapotranspiration is obtained.

The moisture index given in equation (1) may be calculated using the potential evapotranspiration and rainfall data for respective monthly values. The data may be tabulated for demonstration purposes as has been done in Table BI for the Dalhart Texas data shown in Figure 4. The calculations shown are based on an assumption that the soil may store no more than 6 inches of water at any one time. Thus, there could be no surplus in Table BI as the storage never approaches 6 inches. The deficit is 9.8 inches during the year. The potential evapotranspiration for the year is 28.7 inches which corresponds fairly well with the values given in Figure 3 for Dalhart. The moisture index is calculated to be 21 which is not drastically different from the long term values given in Figure 6.

TABLE A1. - MEAN POSSIBLE DURATION OF SUNLIGHT
IN TERMS OF 30 DAYS OF 12 HOURS EACH

No. Latitude	J	F	M	A	M	J	J	A	S	O	N	D
30	.90	.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	.98	.89	.88
31	.90	.87	1.03	1.08	1.18	1.18	1.20	1.14	1.03	.98	.89	.88
32	.89	.86	1.03	1.08	1.19	1.19	1.21	1.15	1.03	.98	.88	.87
33	.88	.86	1.03	1.09	1.19	1.20	1.22	1.15	1.03	.97	.88	.86
34	.88	.85	1.03	1.09	1.20	1.20	1.22	1.16	1.03	.97	.87	.86
35	.87	.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	.97	.86	.85

TABLE BI. COMPARATIVE MOISTURE DATA FOR DALHART TEXAS AFTER THORNTHWAITE

	J	F	M	A	M	J	J	A	S	O	N	D
Potential evapotrans	0	.1	.8	1.8	3.4	5.0	6.0	5.4	3.8	1.9	.6	0
Precipitation	0.2	.3	.8	1.8	2.7	3.1	2.5	2.8	1.4	1.8	.7	.5
Moisture Change	+0.2	+2	0	0	-.7	-.3	0	0	0	0	.1	.5
Storage	.8	1.0	1.0	1.0	.3	0	0	0	0	0	.1	.6
Actual evapotrans	0	.1	.8	1.8	3.4	3.4	2.5	2.8	1.4	1.8	.6	0
Water Deficit	0	0	0	0	+0	1.6	3.5	2.2	2.4	.1	0	0
Water Surplus	0	0	0	0	0	0	0	0	0	0	0	0

$$I_m = \frac{100(\text{Surplus}) - 60(\text{Deficit})}{E_p} = \frac{-60(9.8)}{28.7} = -20.5$$

The necessary data were assembled for the west Texas area and the potential evapotranspiration was calculated for five years for each city in the analysis. The average values are shown in Figure IA. The variation from the values given by Thornthwaite (33) and shown in Figure 3 is very small. Thus, accurate representations of these quantities may be obtained for Texas.

The question that arises is whether or not the values obtained are valid indicators of the engineering phenomena they are predicting for the west Texas area. If the potential evapotranspiration could be accurately and precisely correlated with a value derived solely for the west Texas area the relationship could then be validly utilized with a higher degree of confidence in predicting subgrade suction values.

Moe and Griffiths (23) have taken Texas Agricultural Experiment Station data on evaporation at selected Texas cities and performed a multiple regression analysis which establishes a relationship between evaporation and the mean monthly maximum temperature. This regression takes the form:

$$E = AT_m + B$$

where

E is the monthly evaporation in inches,

A is the slope of the regression line,

B is the intercept of the regression line, and

T_m is the mean monthly maximum temperature in °F.

It was found that the coefficients, A and B varied in an orderly manner across the state. As such, a simple means to determine evaporation was constructed. The A and B coefficients are plotted in Figure IB and Figure IC respectively. It becomes a simple matter to calculate the actual evaporation in inches for each month for any city if the mean monthly maximum temperature is known.

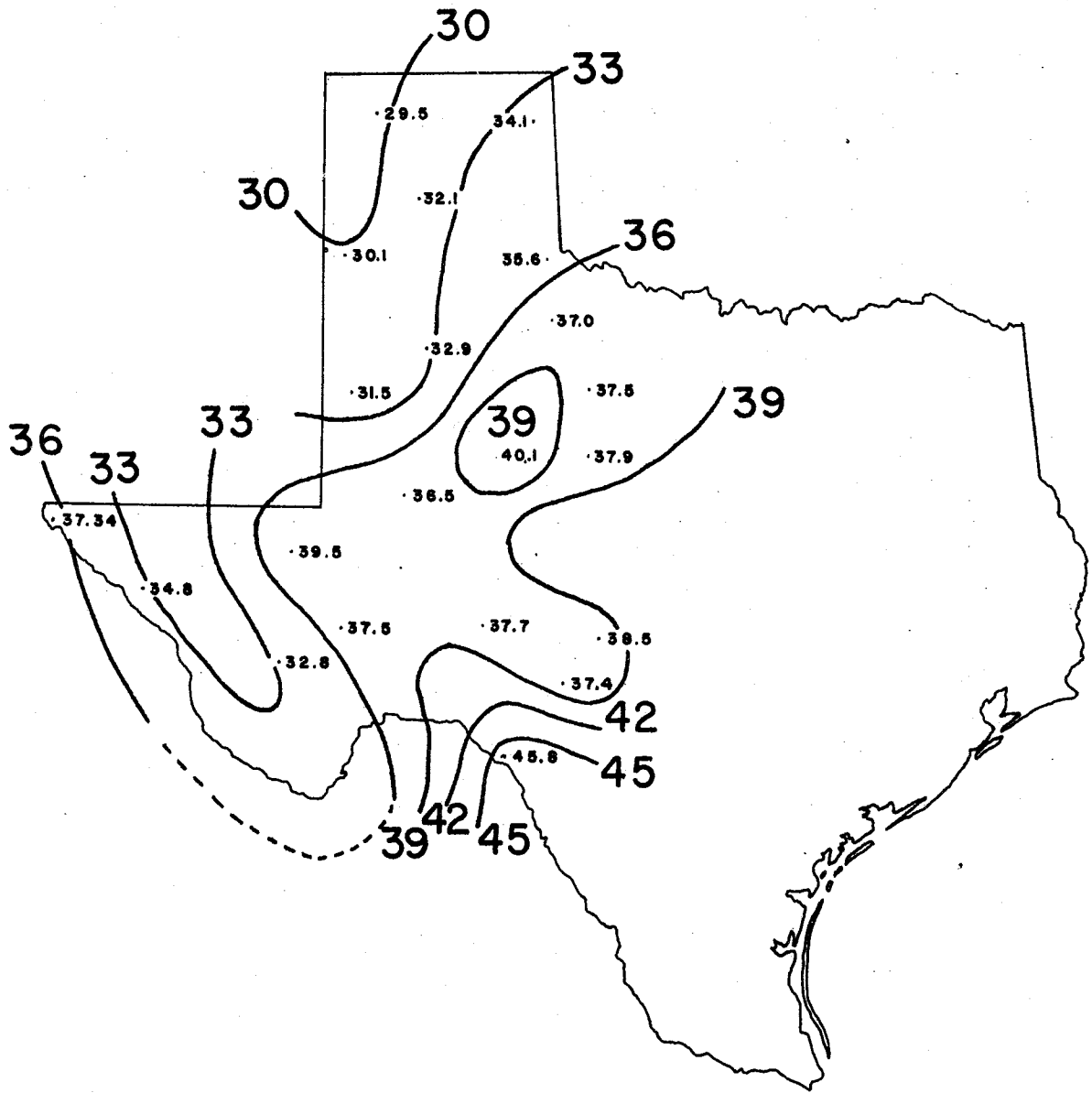


FIG. IA. - AVERAGE ANNUAL POTENTIAL EVAPOTRANSPIRATION, 1966-1970.

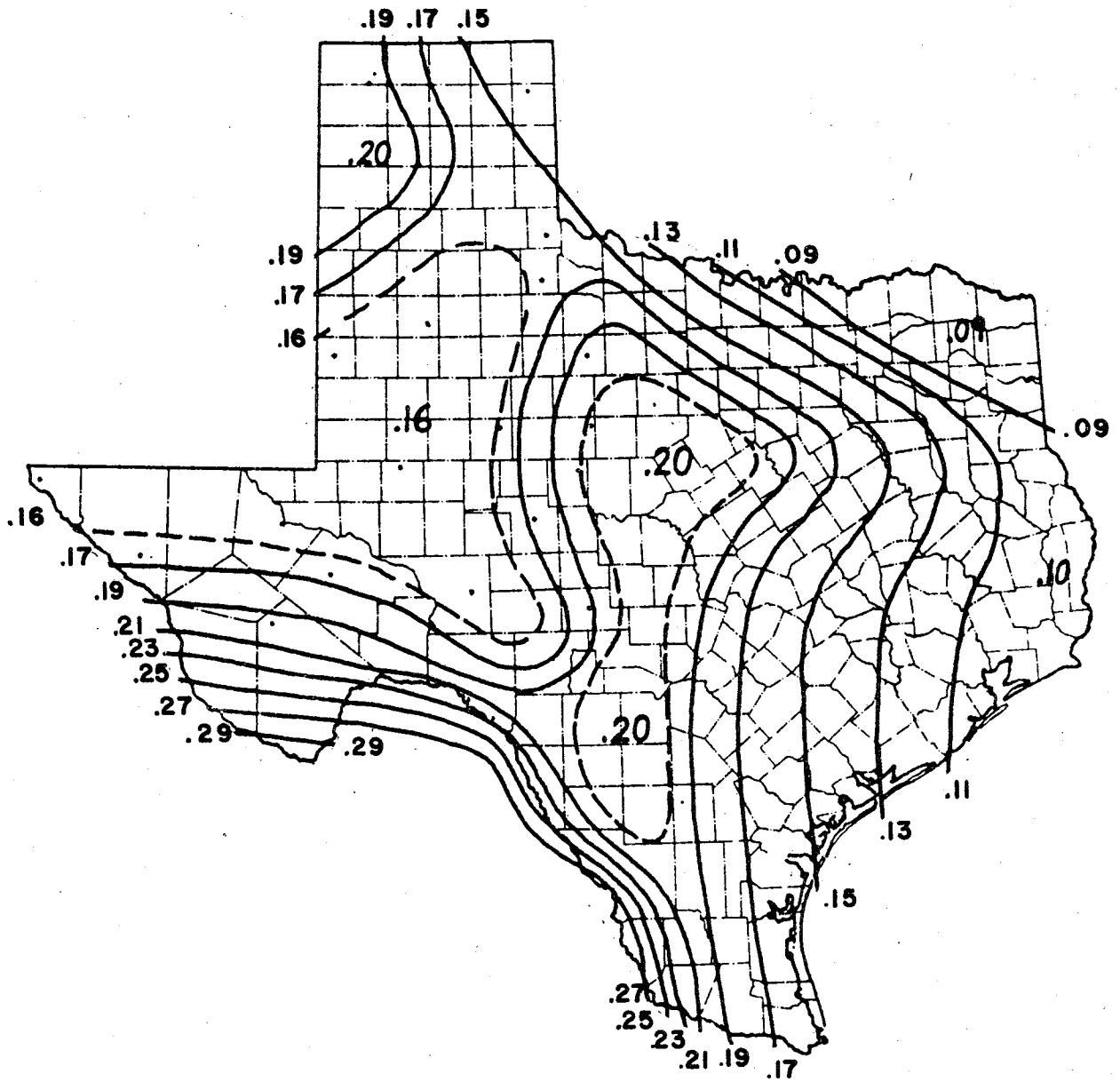


FIG.IB.— SLOPE OF THE REGRESSION LINE
AFTER MOE AND GRIFFITHS. (23)

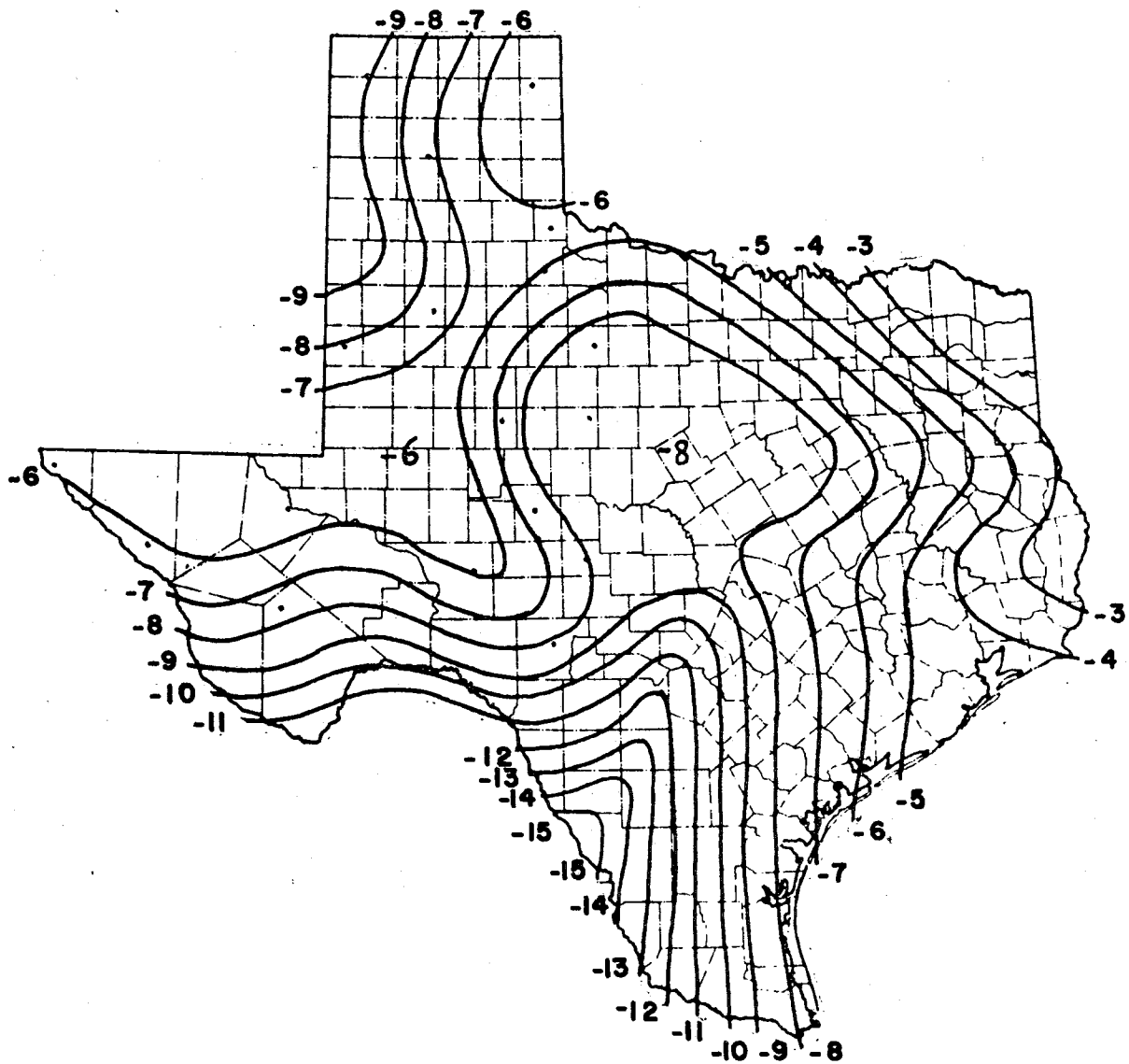


FIG. IC. — INTERCEPT OF THE REGRESSION LINE
AFTER MOE AND GRIFFITHS. (23)

to establish a relationship between potential evapotranspiration and Griffiths' evaporation, data for five years for the twenty-two cities in west Texas were assembled and used in calculating monthly values of evaporation and potential evapotranspiration. These values were used with the annual monthly mean temperature and the mean monthly temperature in a multiple regression analysis to determine whether a good correlation existed between the actual evaporation and the potential evapotranspiration.

Two analyses were conducted. The first utilized the entire data for the west Texas area to determine a single regression equation for the entire area. This equation took the form:

$$E_p = 0.7904 + E(0.0754T - 0.18197E - 2.65432)$$

where

E_p is the potential evapotranspiration in centimeters

E is the evaporation in inches from Griffiths,

T is the monthly average temperature in °F.

This regression gave a correlation coefficient R of 0.982 with a root mean square error of 0.674.

The second analysis was a regression analysis for each Highway Department District. The results for each District are as shown in Table CI. This table shows that for all but District 25 the same equation could be used from the regression analysis. This similarity along with the high correlation obtained for the general equation indicate that the potential evapotranspiration is directly and reliably determinable from west Texas weather data. Thus the moisture index, which is derived from the potential evapotranspiration may be utilized for the west Texas area to determine the suction in the base course beneath pavements.

TABLE C1. - REGRESSION ANALYSES BY DISTRICTS

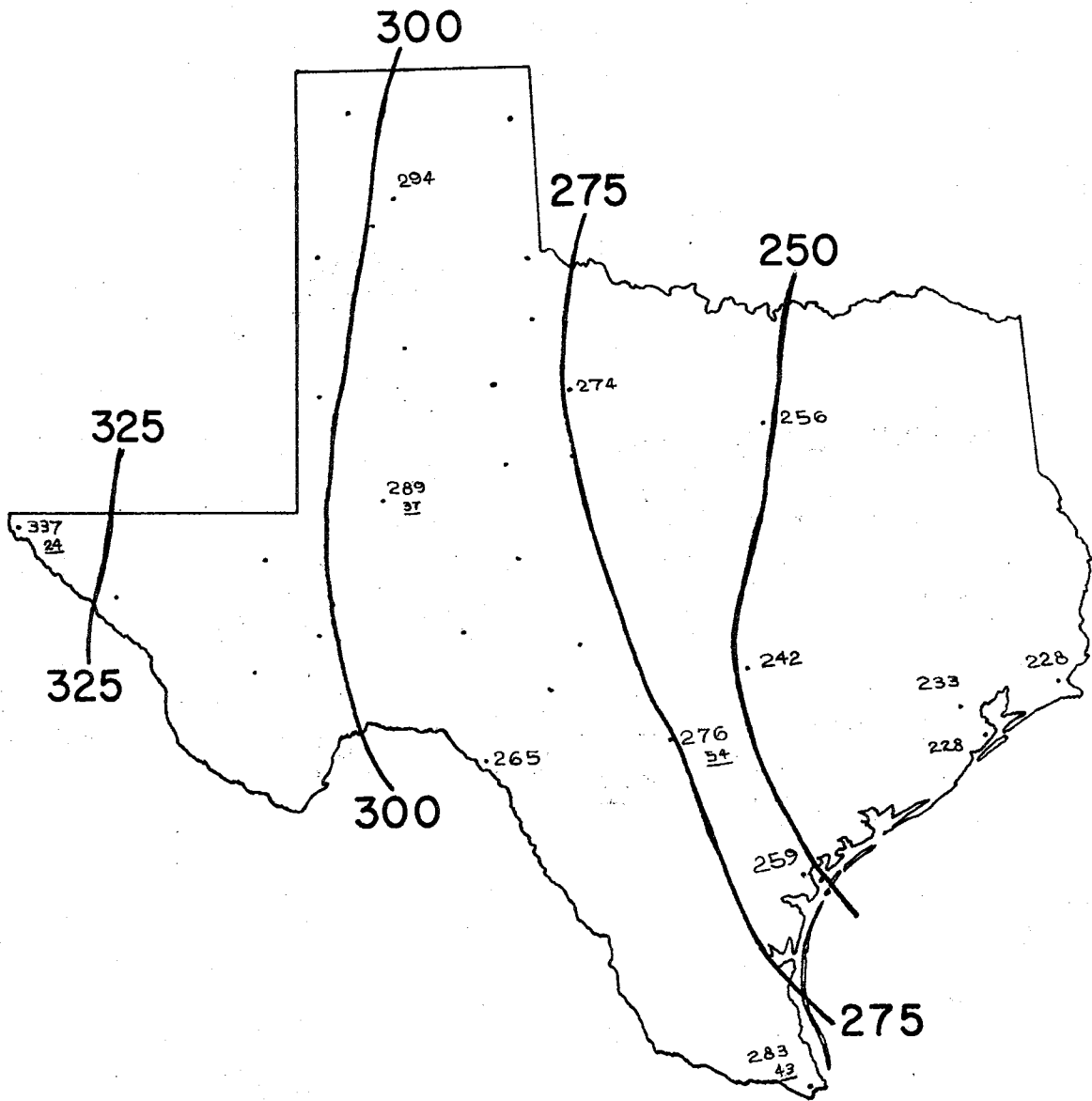
District	Regression Equation	R ²
4	$E_p = 0.20488 - 1.8967E_G - .21593(E_G)^2 + .071778(E_G)(T)$	0.989
5	$E_p = 0.39262 - 2.24715E_G - .193162(E_G)^2 + .0731604(E_G)(T)$	0.992
6	$E_p = 1.52664 - 2.82145E_G - 0.106024(E_G)^2 + .0670869(E_G)(T)$	0.993
7	$E_p = 1.34632 - 2.79638E_G - 0.120833(E_G)^2 + 0.0683771(E_G)(T)$	0.993
8	$E_p = 0.1621 - 2.96792E_G - 0.247517(E_G)^2 + 0.0877653(E_G)(T)$	0.992
22	$E_p = 2.89429 - 3.66597E_G - 0.119118(E_G)^2 + 0.0769816(E_G)(T)$	0.989
24	$E_p = 0.834901 - 2.27631E_G - 0.101327(E_G)^2 + 0.060737(E_G)(T)$	0.990
25	$E_p = 2.26029 - 1.5182E_G + 0.14306(E_G)^2 + 0.0032482(T)^2$	0.994
All	$E_p = 0.7904 - 2.65432E_g - 0.18197(E_G)^2 + 0.0754(E_G)(T)$.982

APPENDIX II
MONTHLY VALUES OF MEAN DAILY SOLAR RADIATION

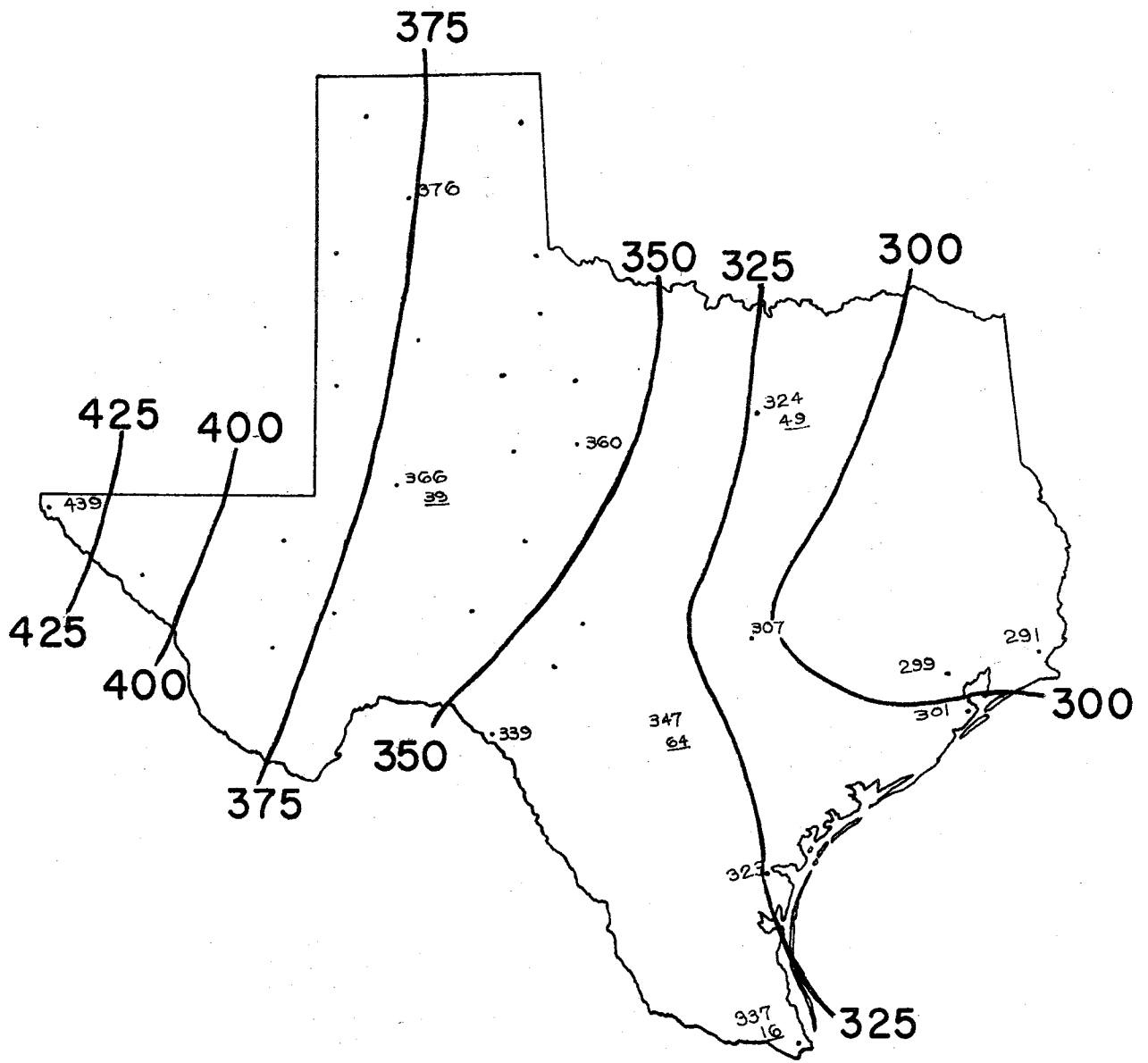
APPENDIX II

Mean Daily Solar Radiation for	Page
January	56
February	57
March	58
April	59
May	60
June	61
July	62
August	63
September	64
October	65
November	66
December	67

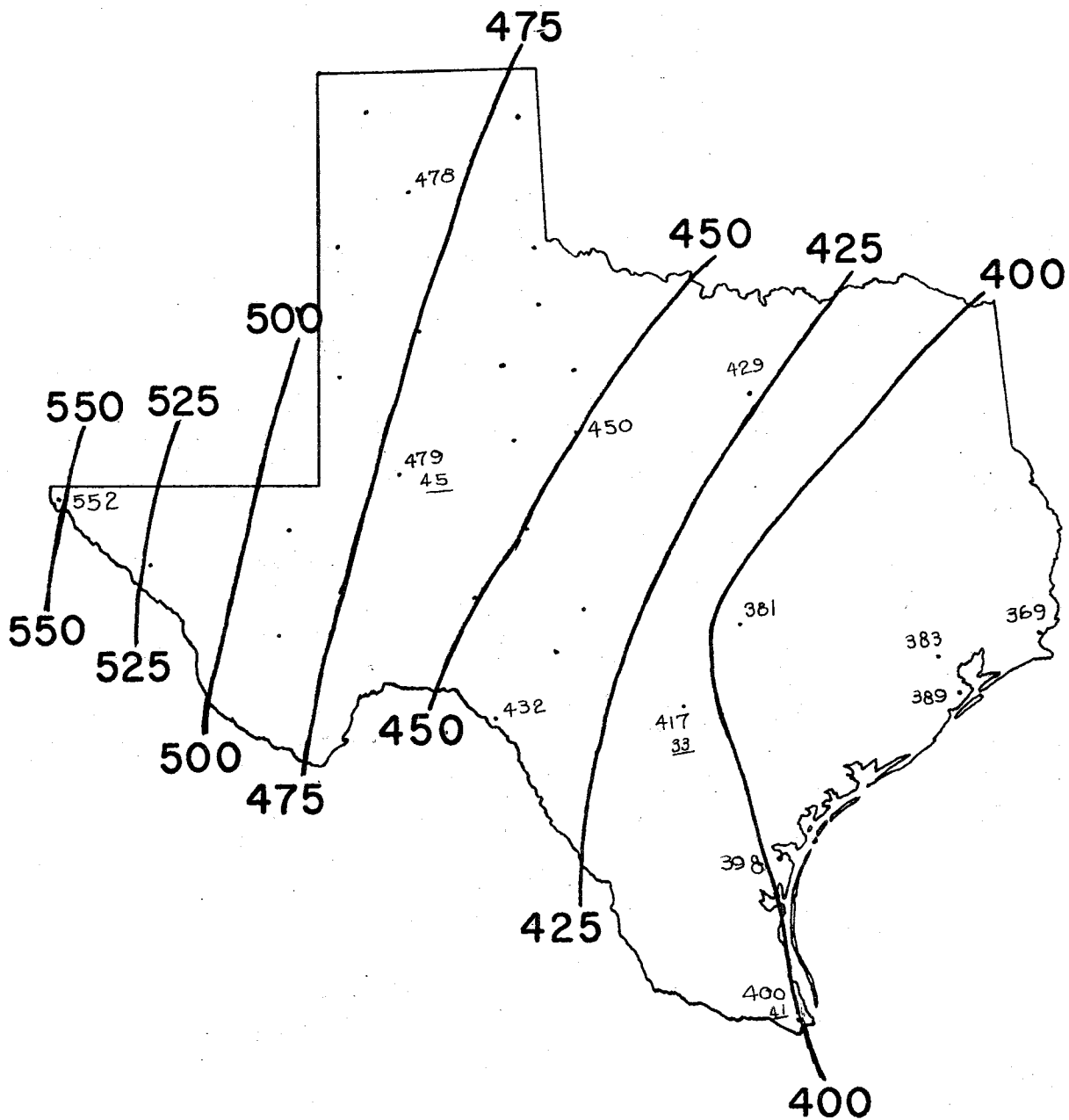
As given in Reference 16.



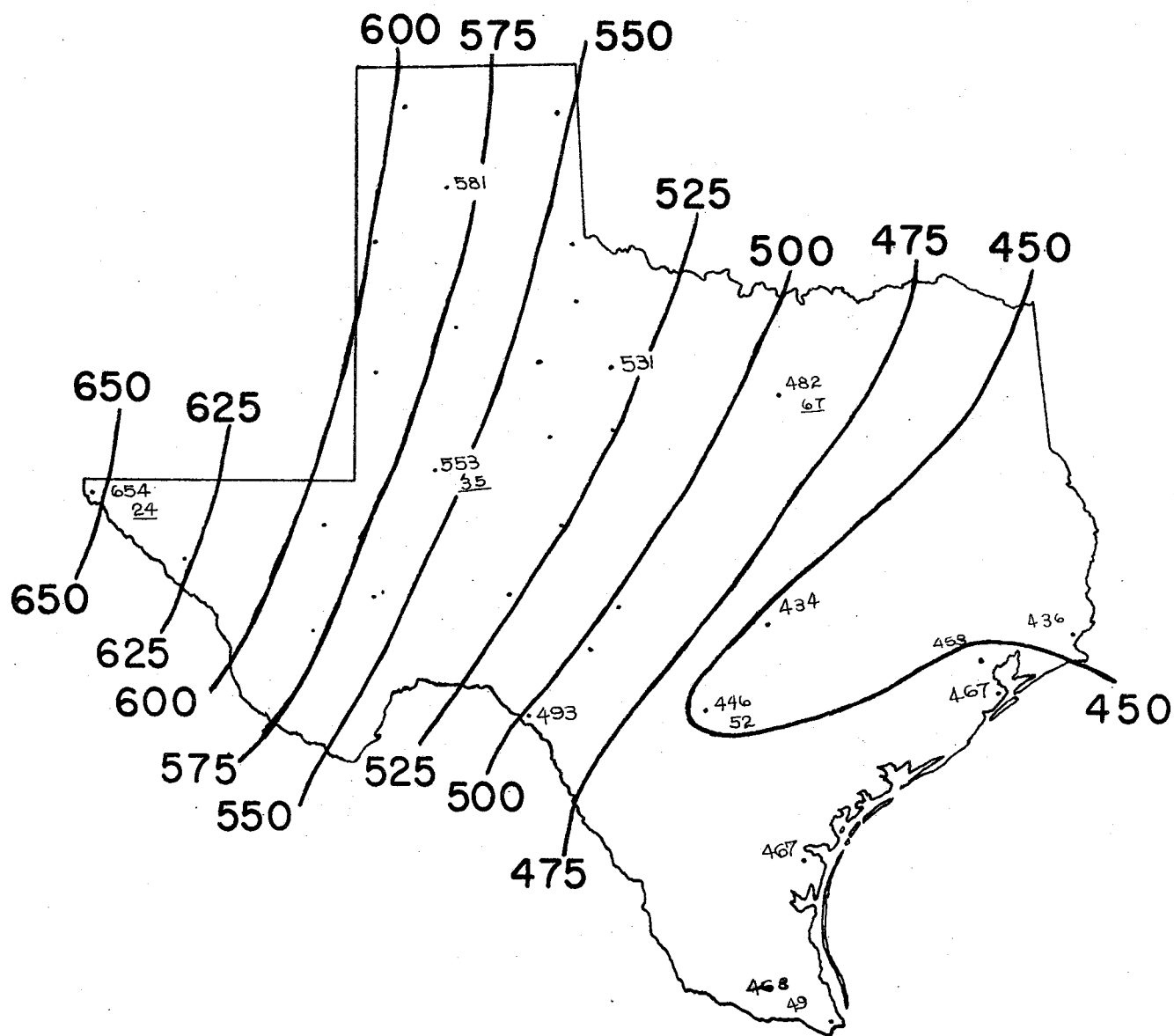
Mean Daily Solar Radiation
 For January in Langleys per Day.



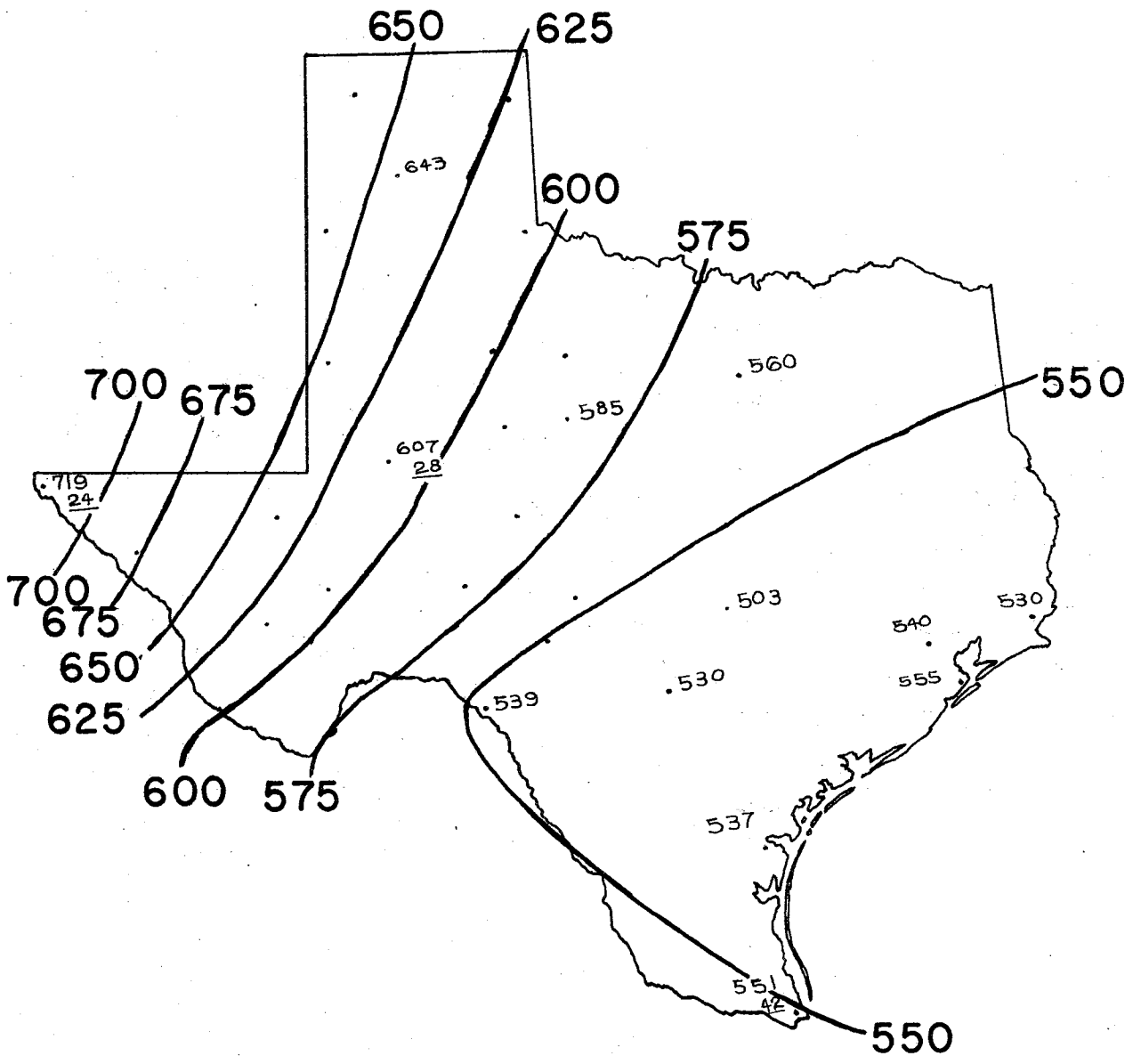
Mean Daily Solar Radiation
 For February in Langleys per Day.



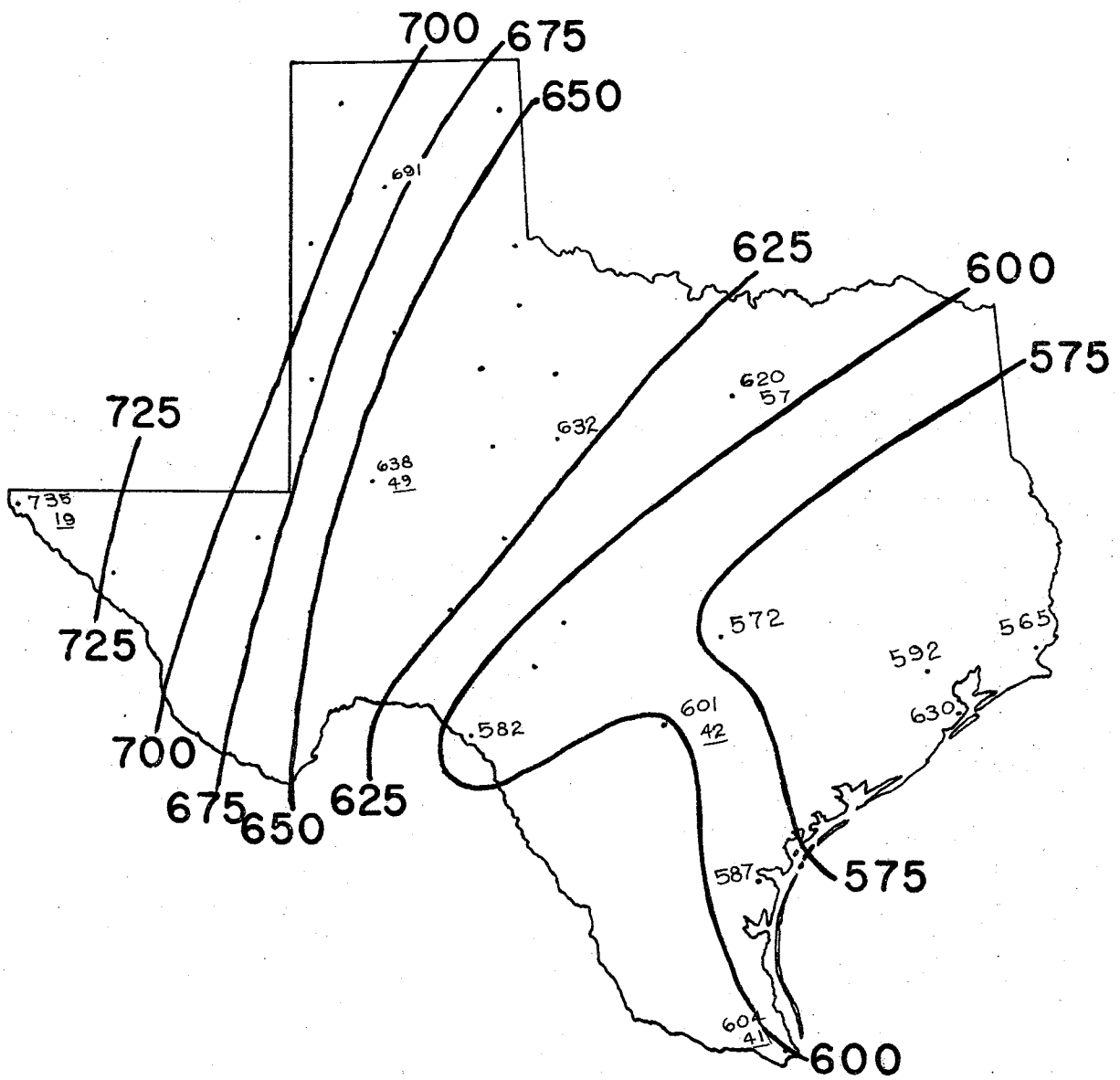
Mean Daily Solar Radiation
 For March in Langleys per Day.



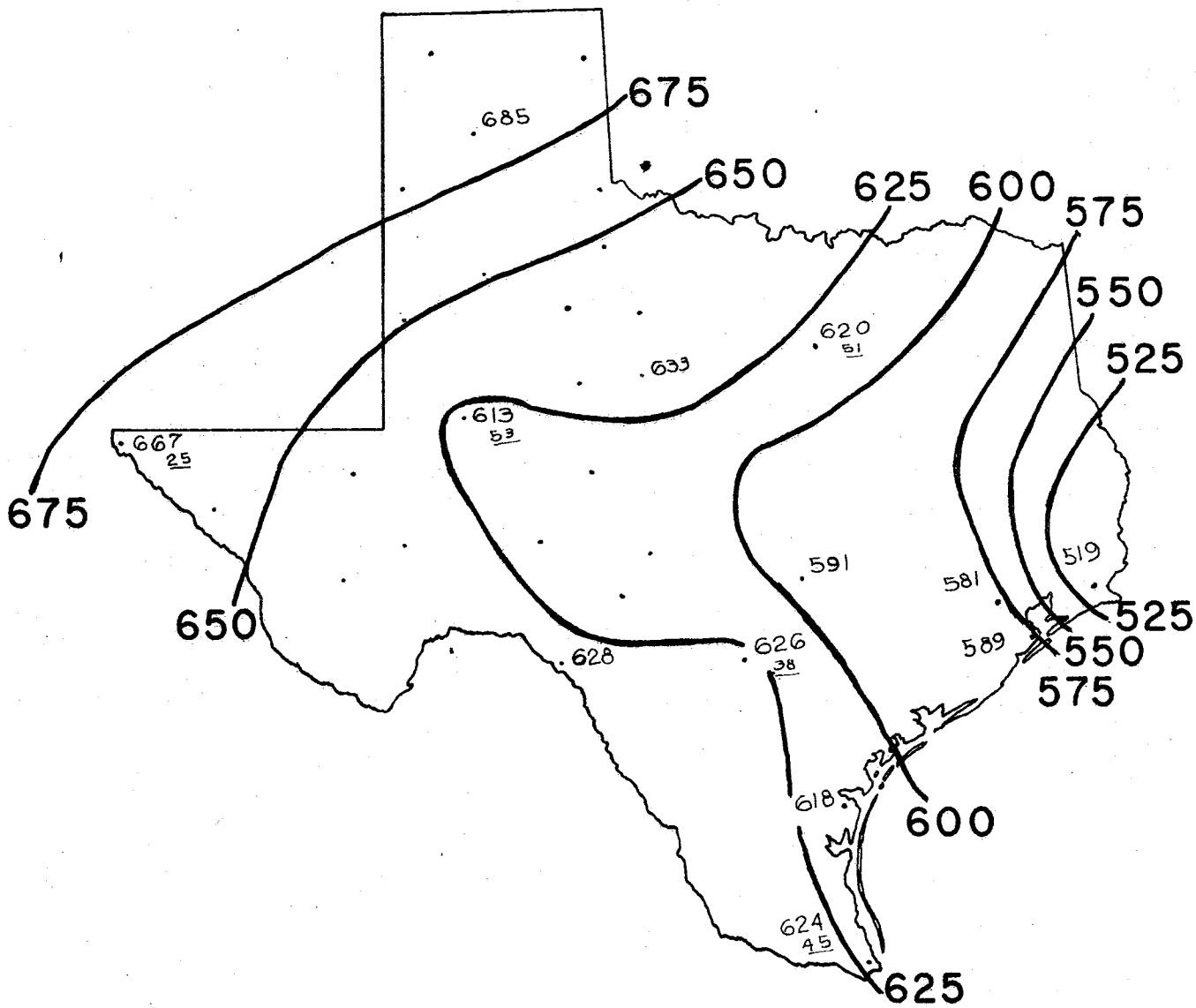
Mean Daily Solar Radiation
 For April in Langleys per Day.



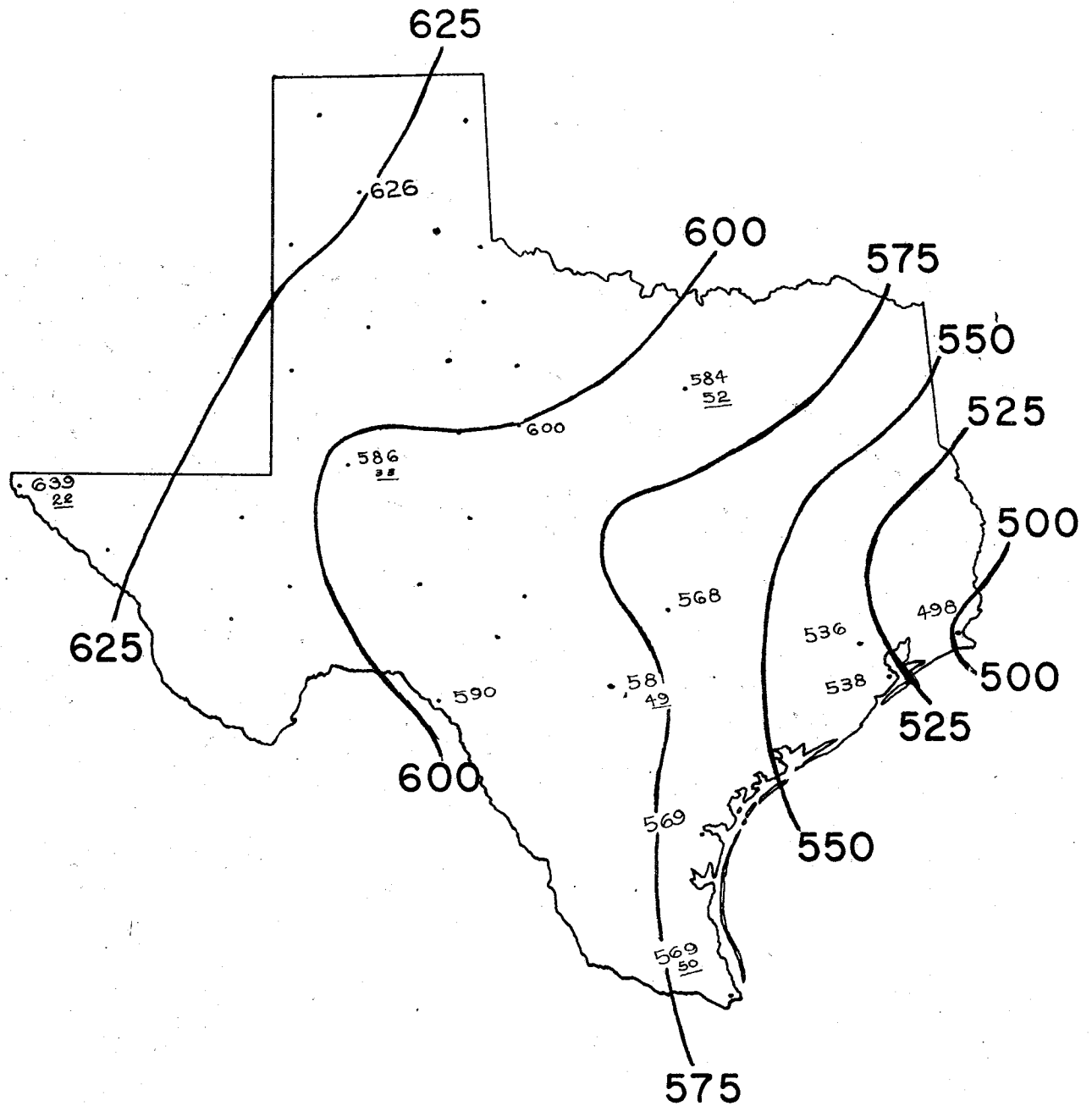
Mean Daily Solar Radiation
 For May in Langleys per Day.



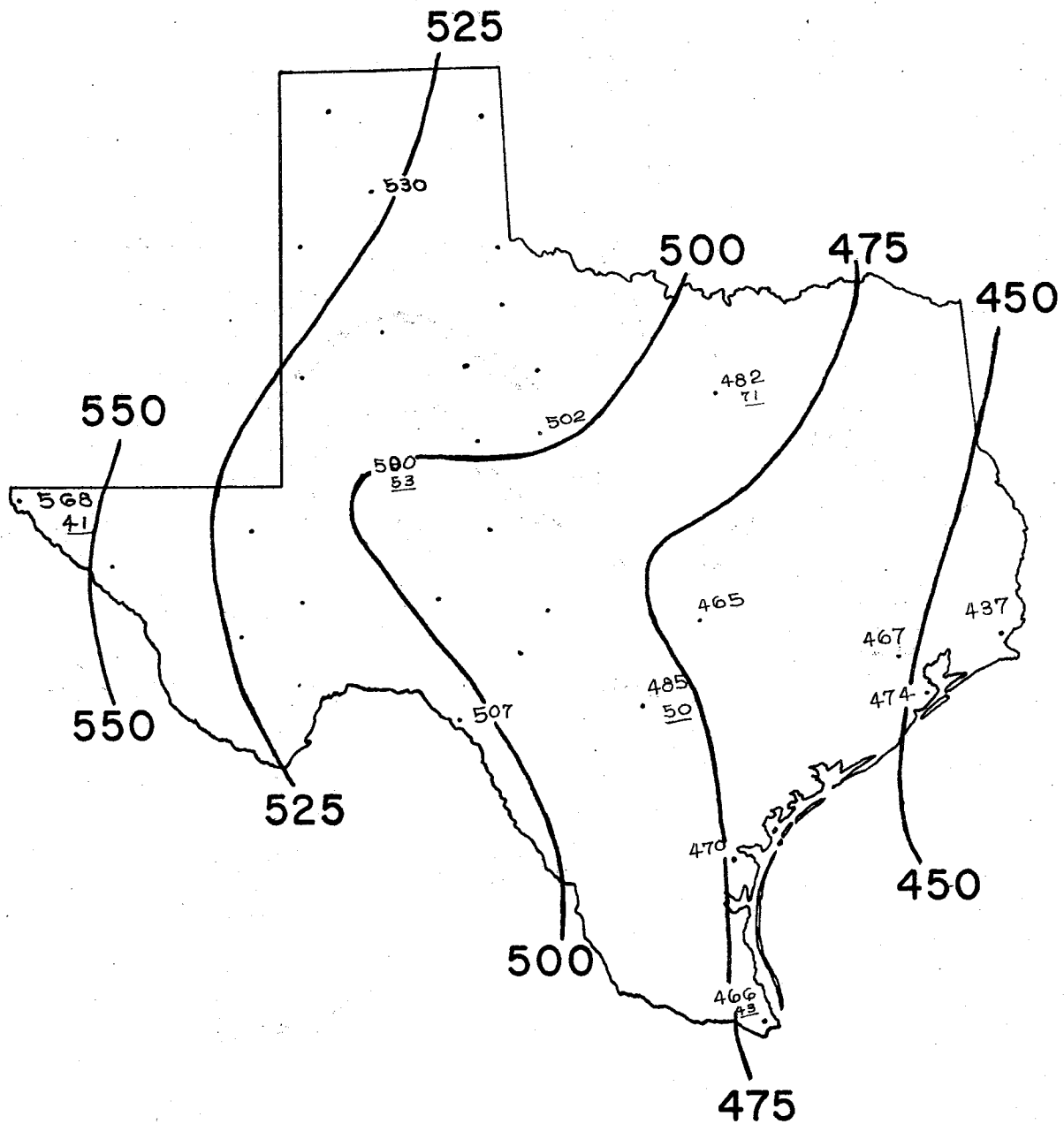
Mean Daily Solar Radiation
 For June in Langleys per Day.



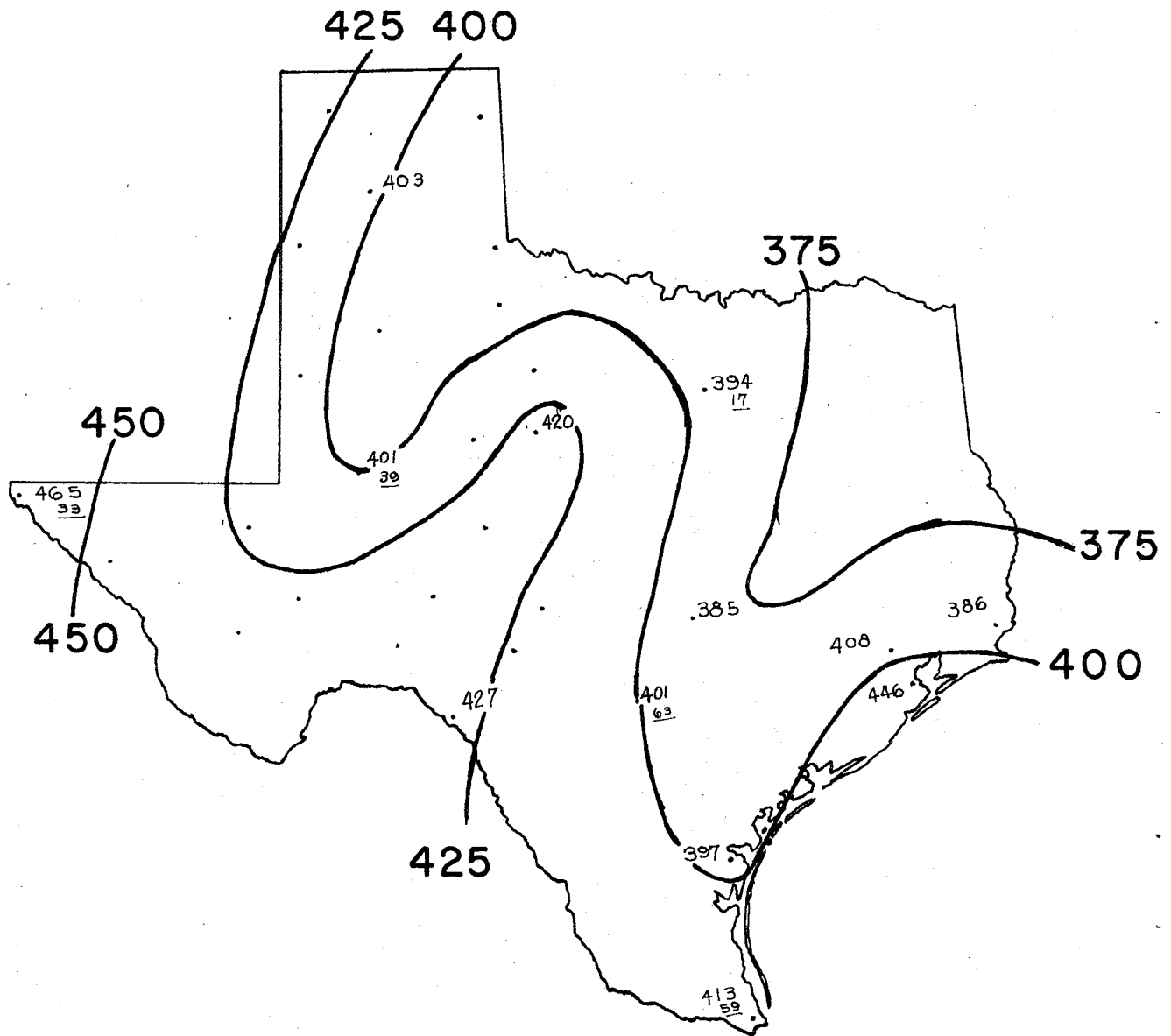
Mean Daily Solar Radiation
 For July in Langley per Day.



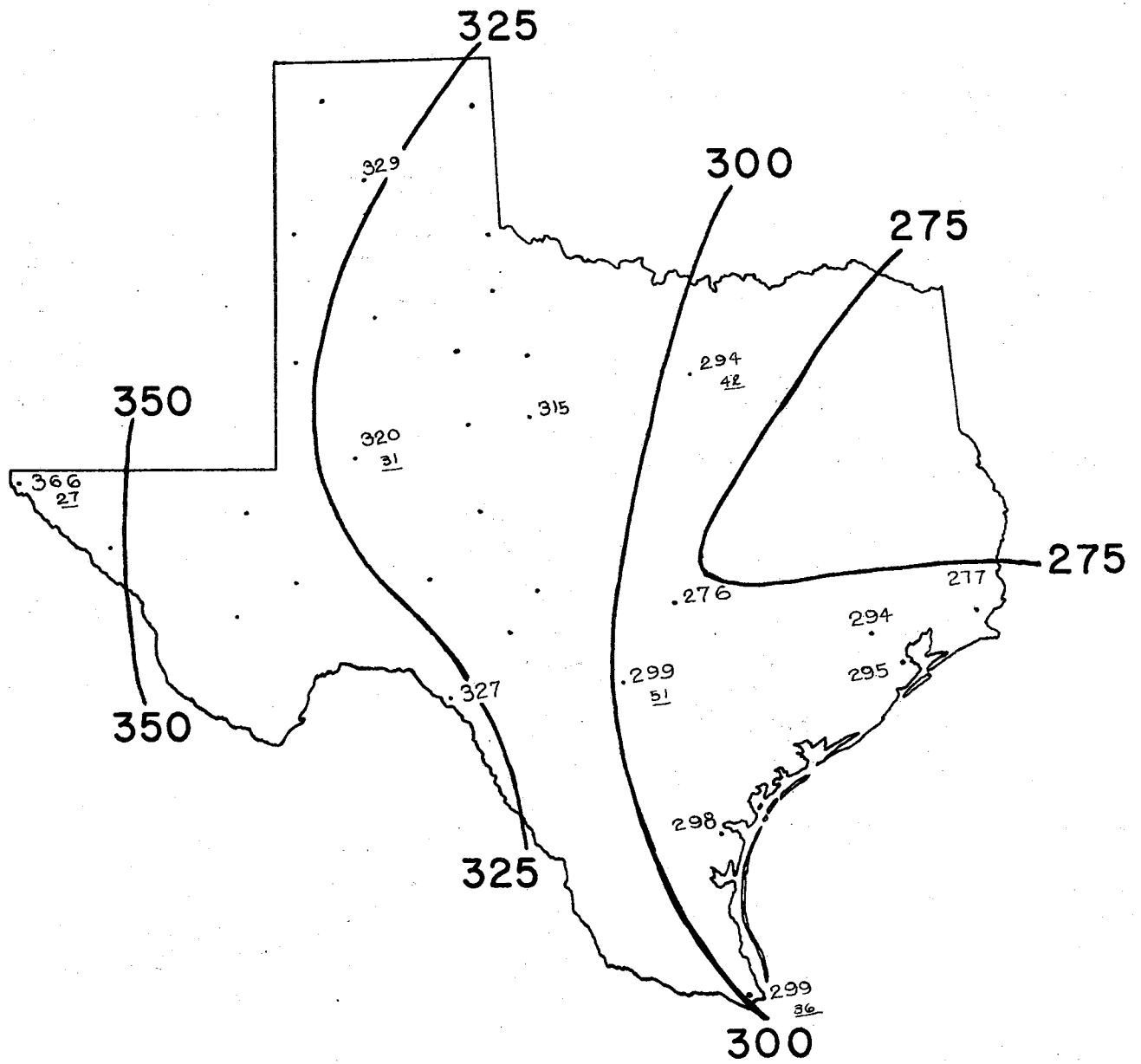
Mean Daily Solar Radiation
 For August in Langleys per Day.



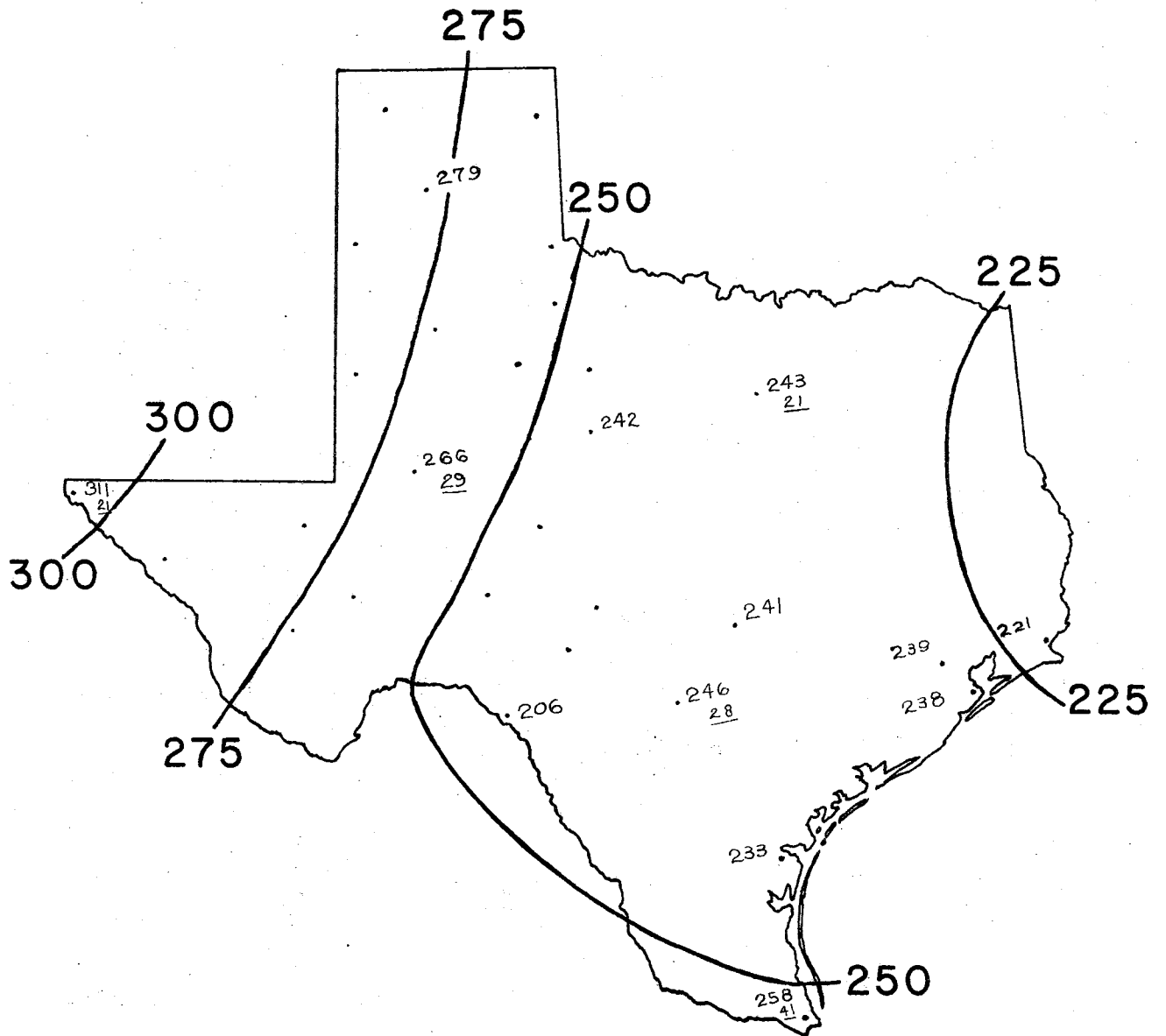
Mean Daily Solar Radiation
 For September in Langley's per Day.



Mean Daily Solar Radiation
 For October in Langleys per Day.



Mean Daily Solar Radiation
 For November in Langley's per Day.



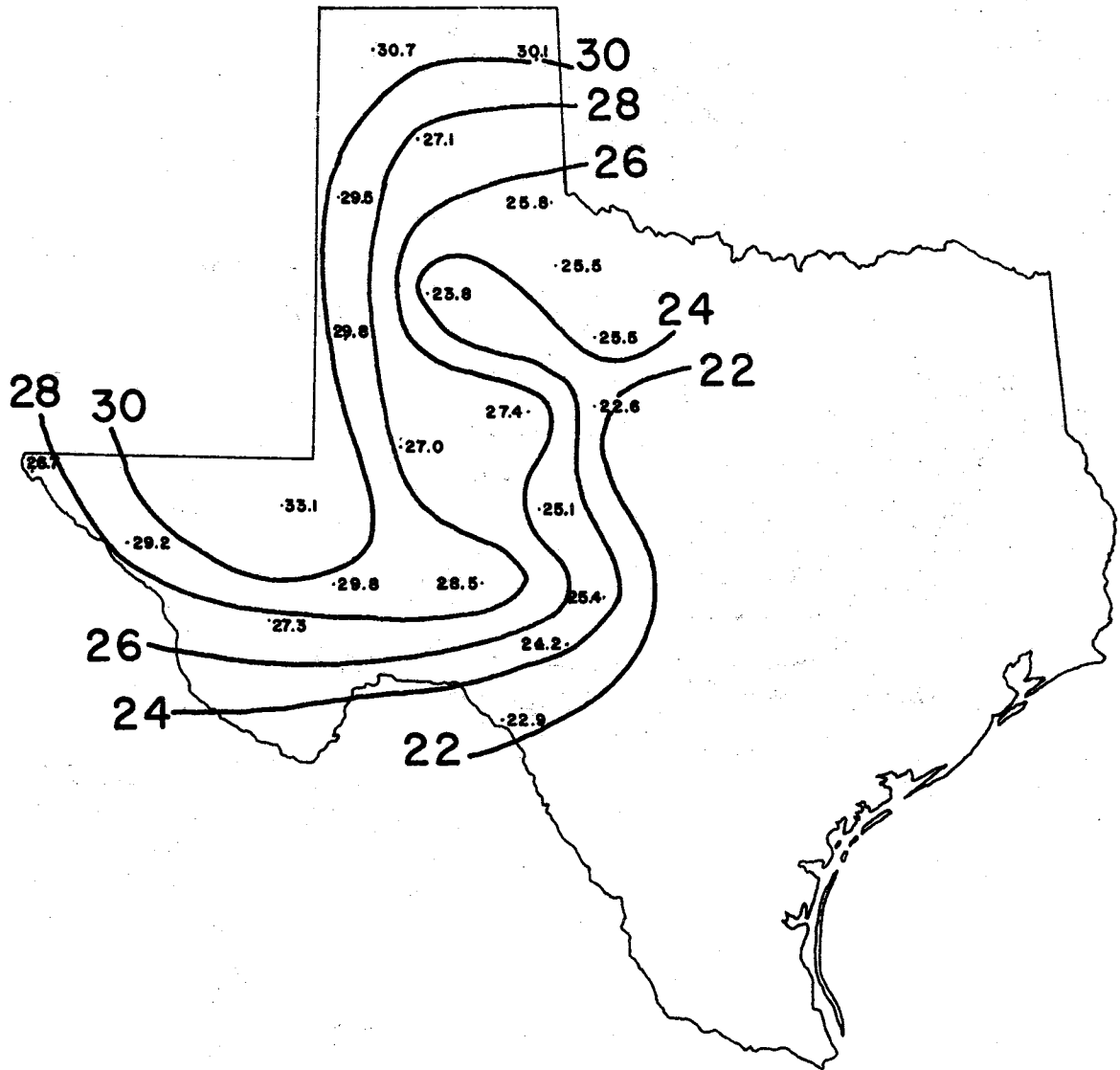
Mean Daily Solar Radiation
 For December in Langleys per Day.

APPENDIX III
YEARLY DAILY TEMPERATURE RANGES

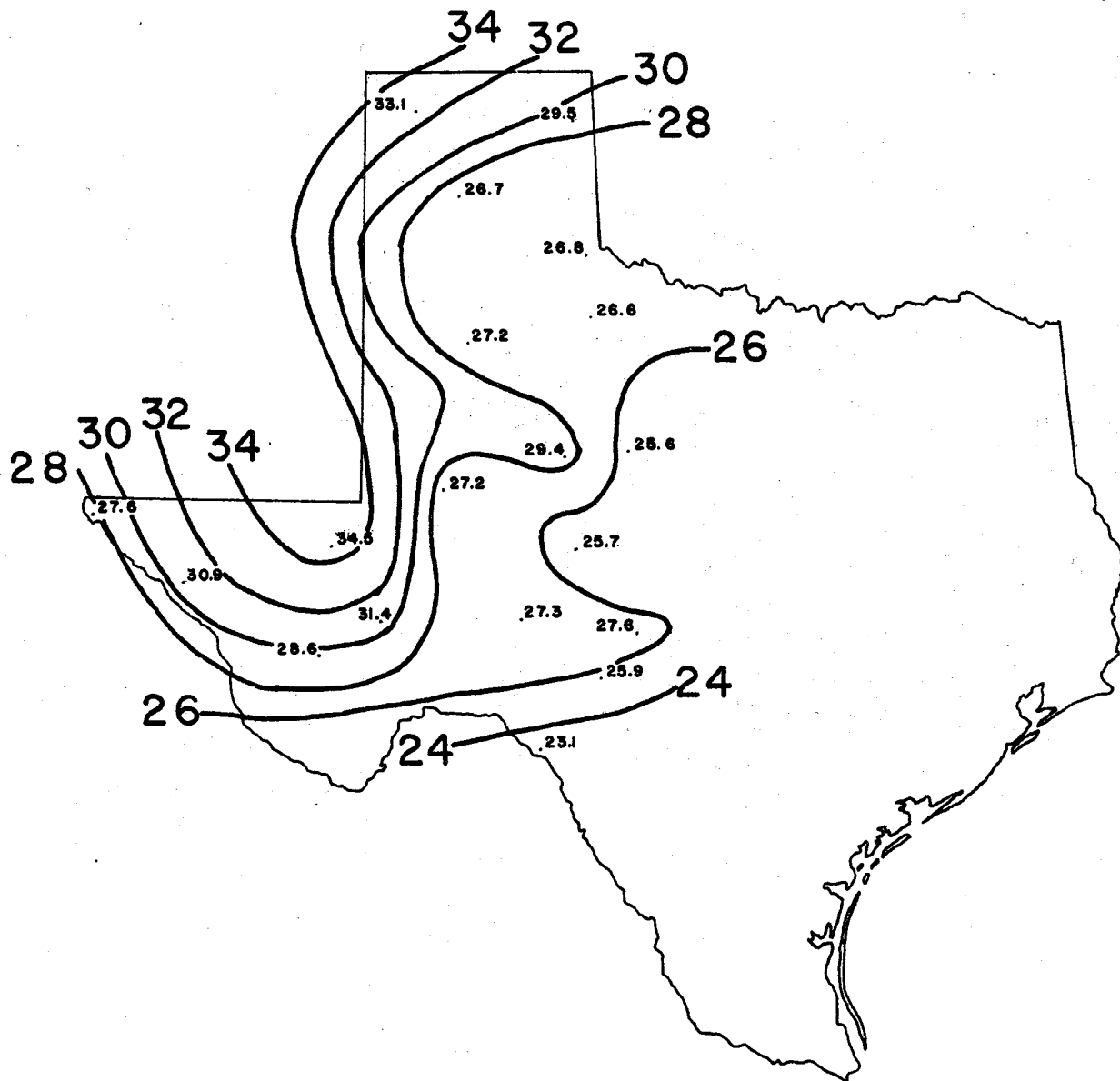
APPENDIX III

Daily Temperature Ranges for the Year	Page
1966	70
1967	71
1968	72
1969	73
1970	74

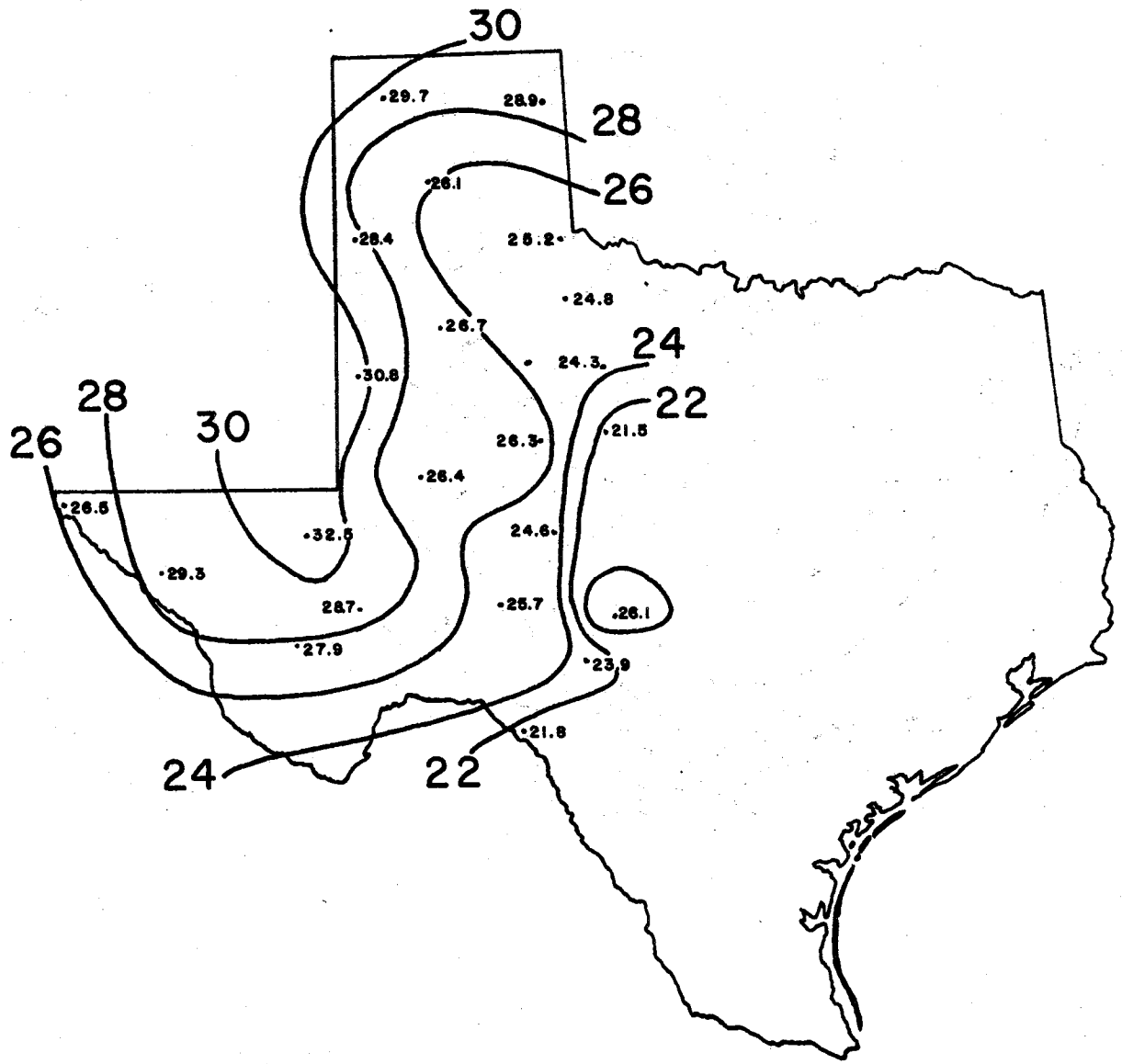
As compiled from U.S. Weather Bureau data.



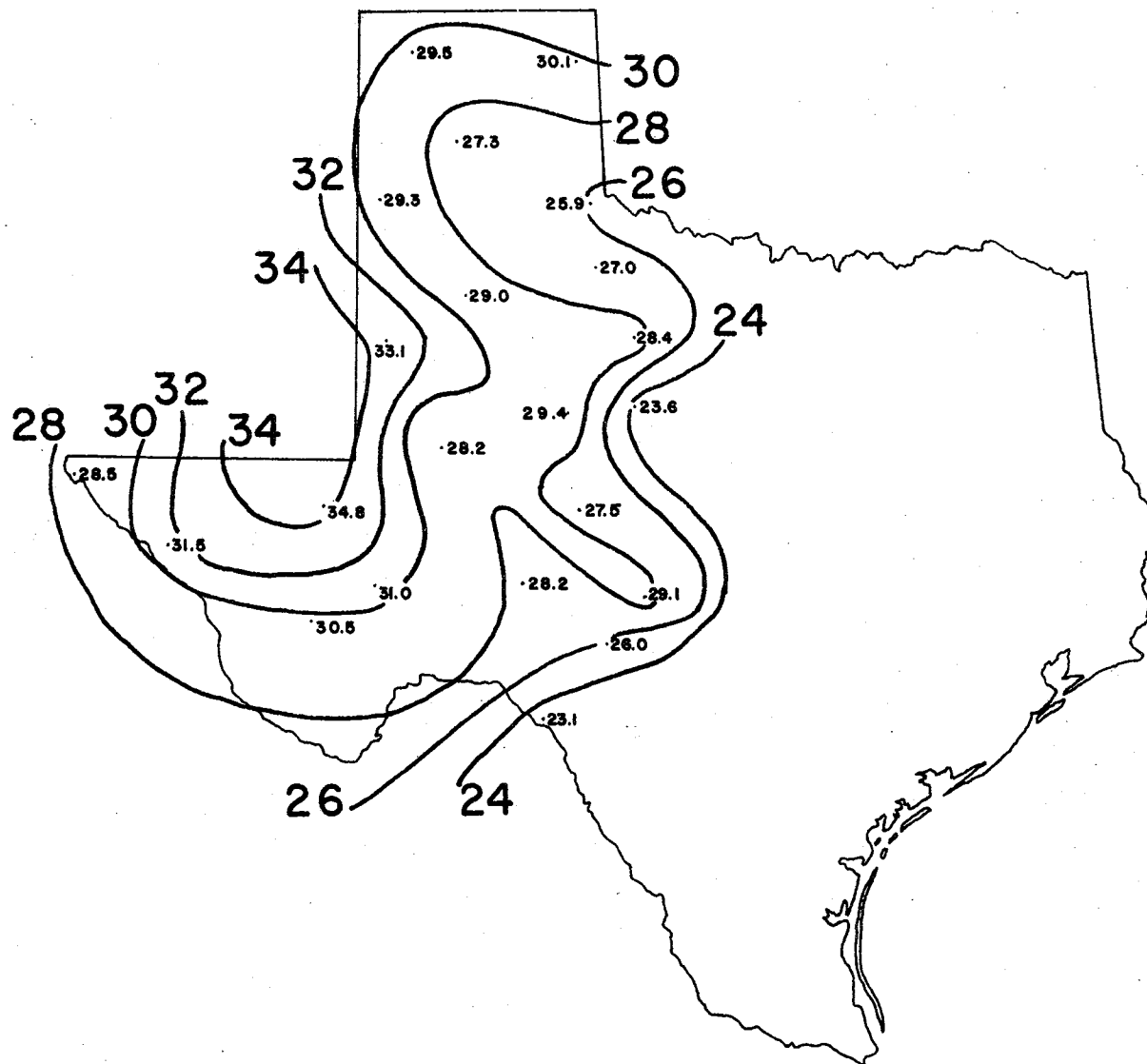
Mean Annual Daily Temperature Range
for 1966



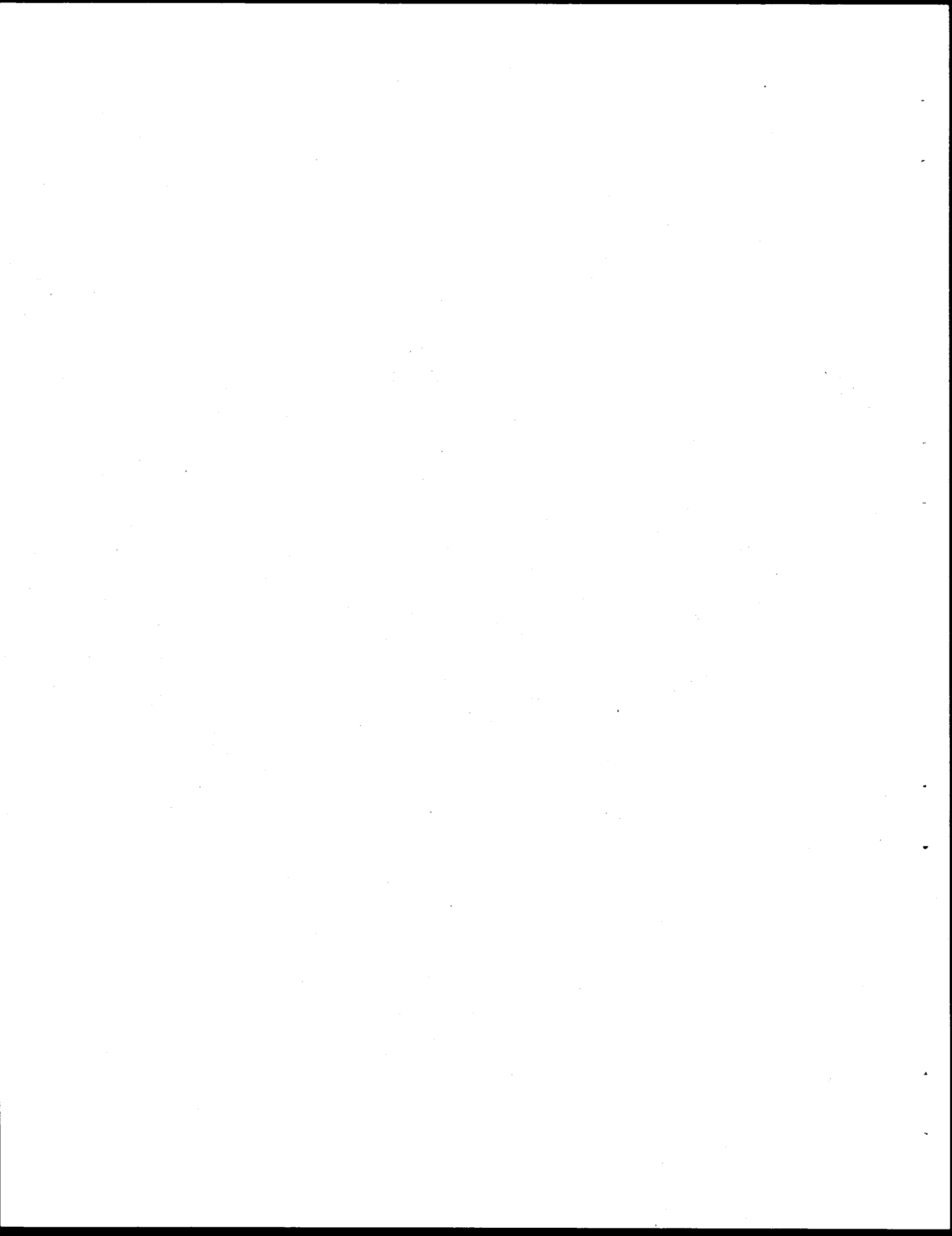
Mean Annual Daily Temperature Range
for 1967



Mean Annual Daily Temperature Range
for 1968



Mean Annual Daily Temperature Range
for 1970

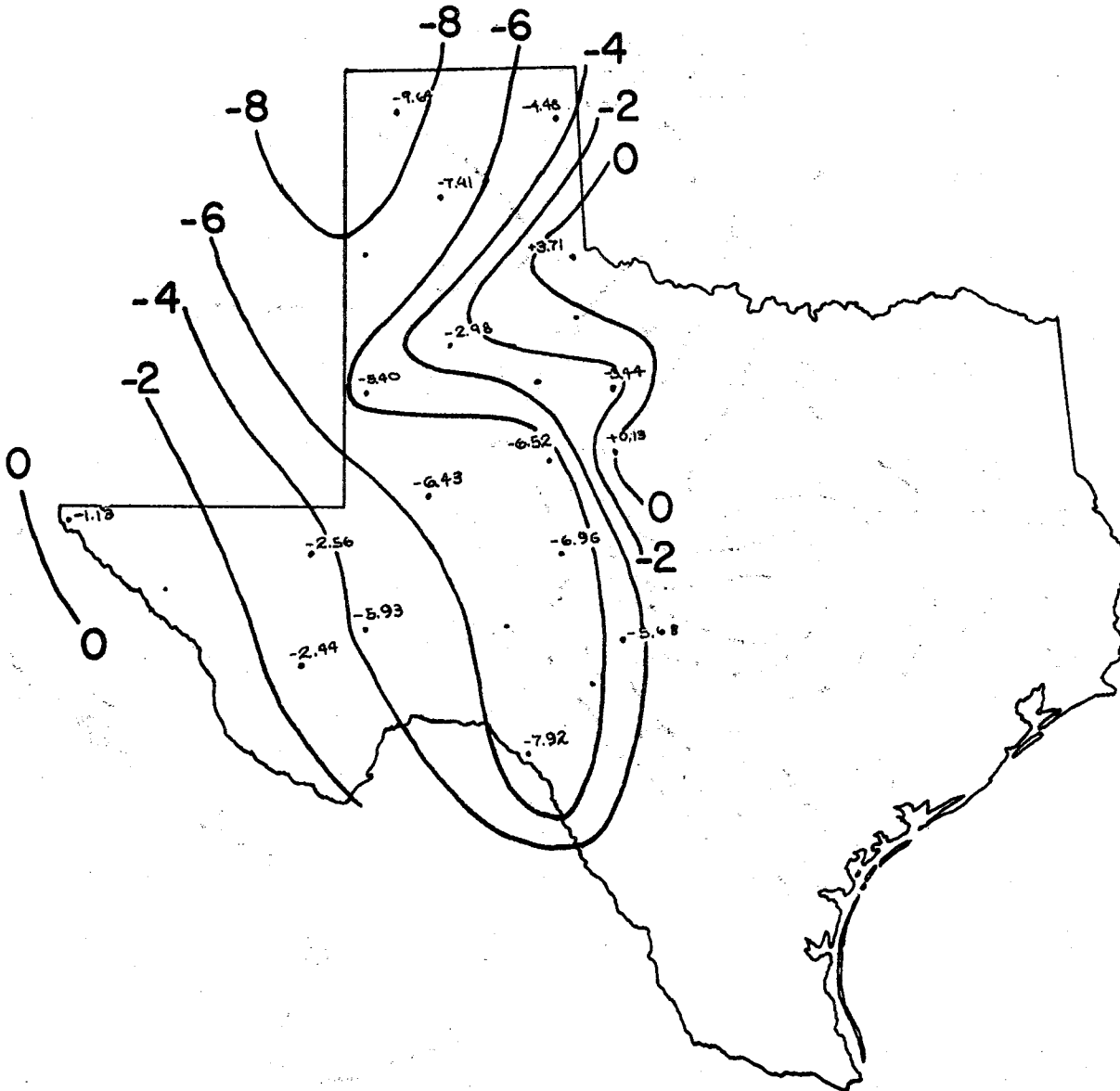


APPENDIX IV
DEPARTURE FROM LONG TERM MEAN PRECIPITATION

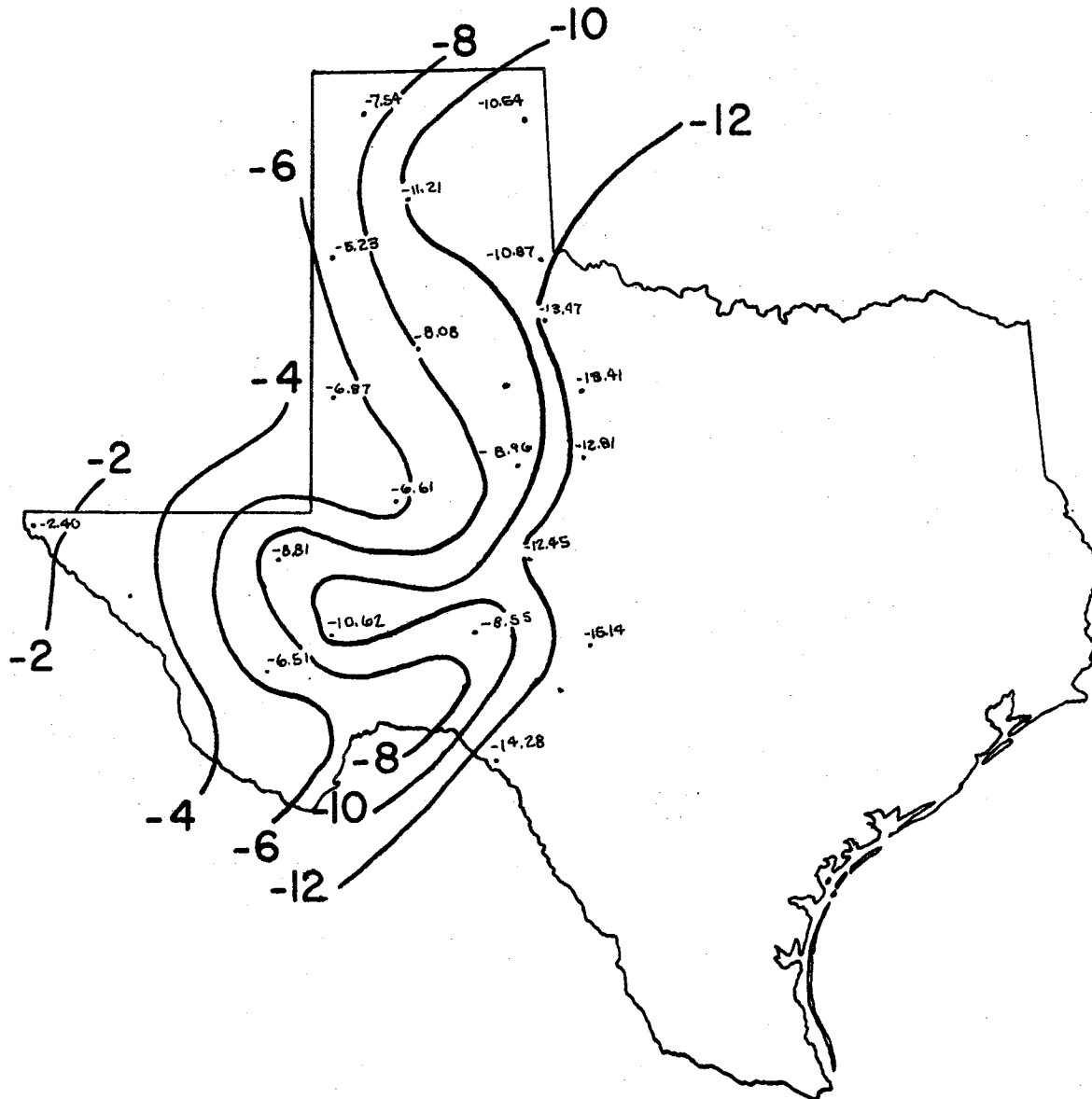
APPENDIX IV

Departure From the Long Term Mean Precipitation for the Year of	Page
1955	77
1956	78
1957	79
1958	80
1959	81
1960	82
1961	83
1962	84
1963	85
1964	86
1965	87
1966	88
1967	89
1968	90
1969	91
1970	92

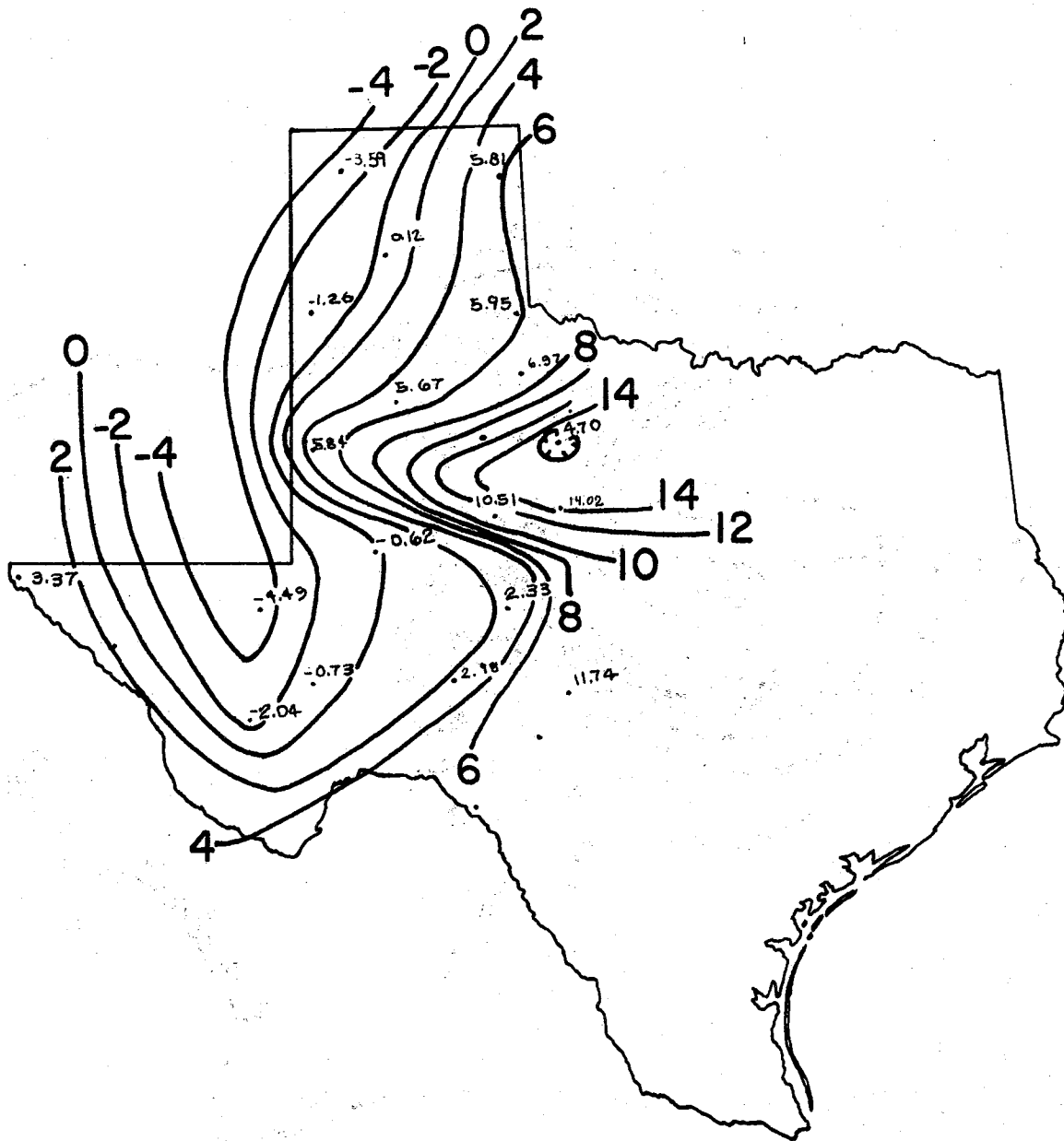
As compiled from U.S. Weather Bureau data.



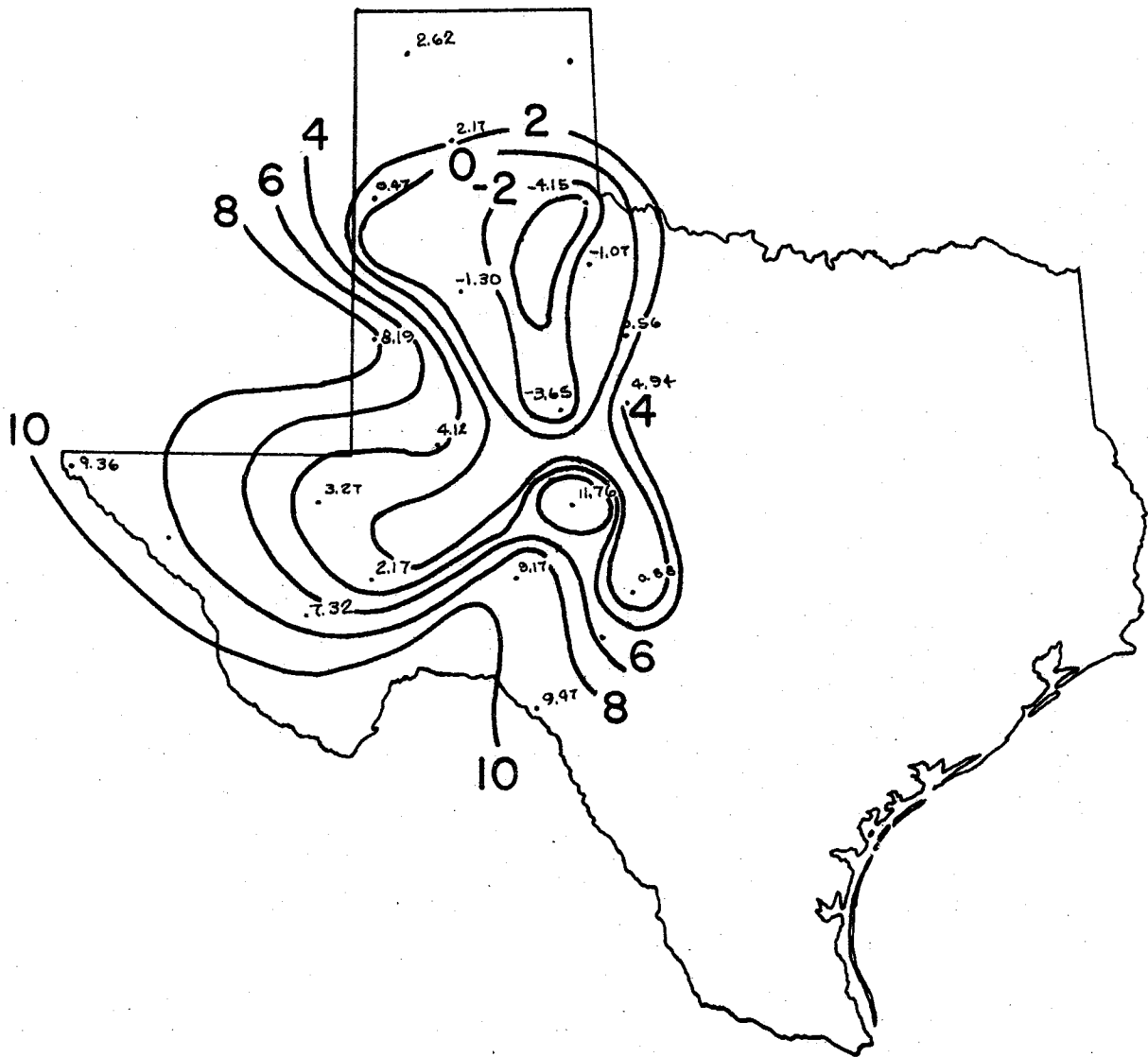
Departure From Long Term Mean Precipitation,
for the Year of 1955 in Inches of Water



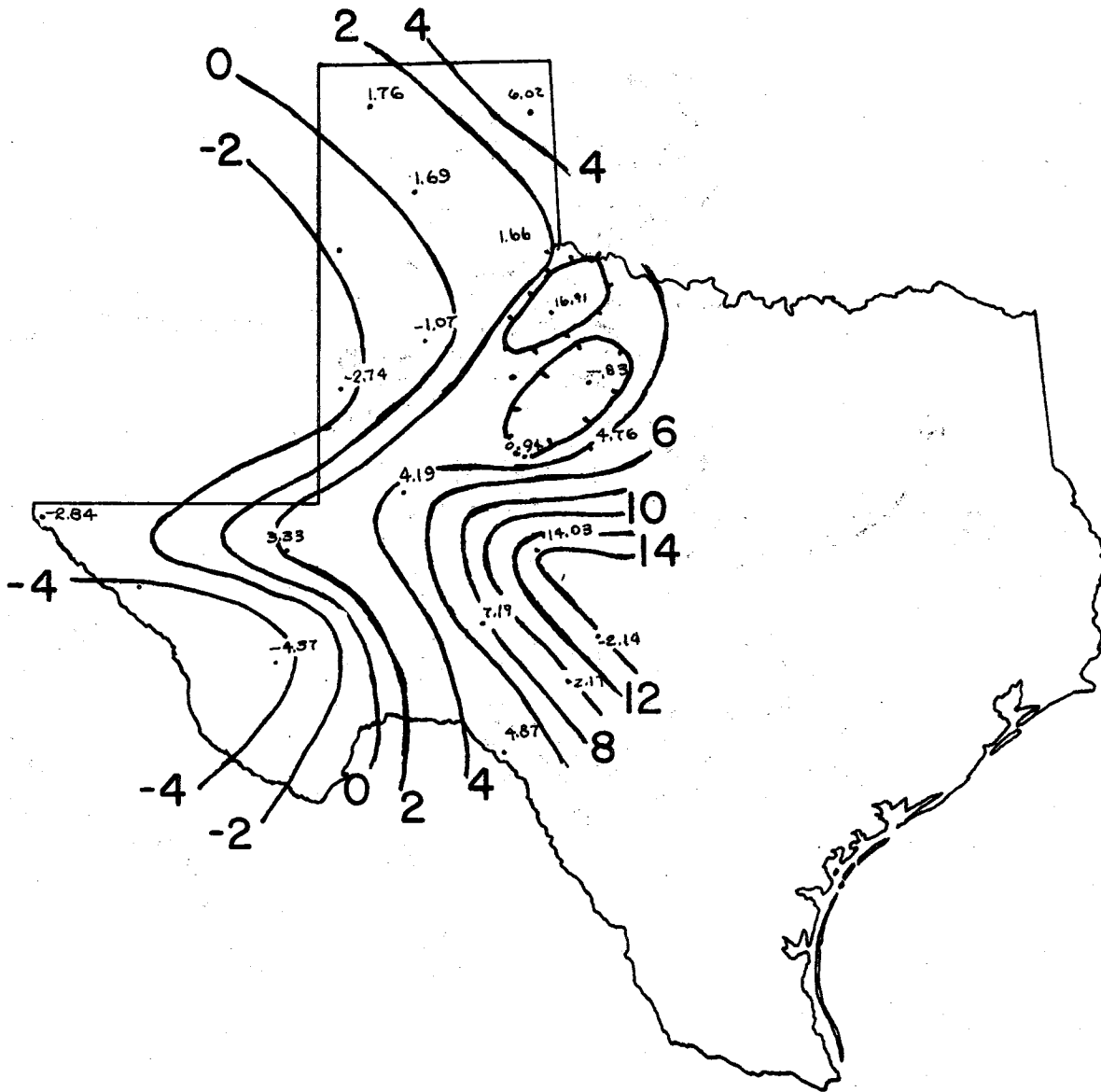
Departure From Long Term Mean Precipitation,
for the Year of 1956 in Inches of Water



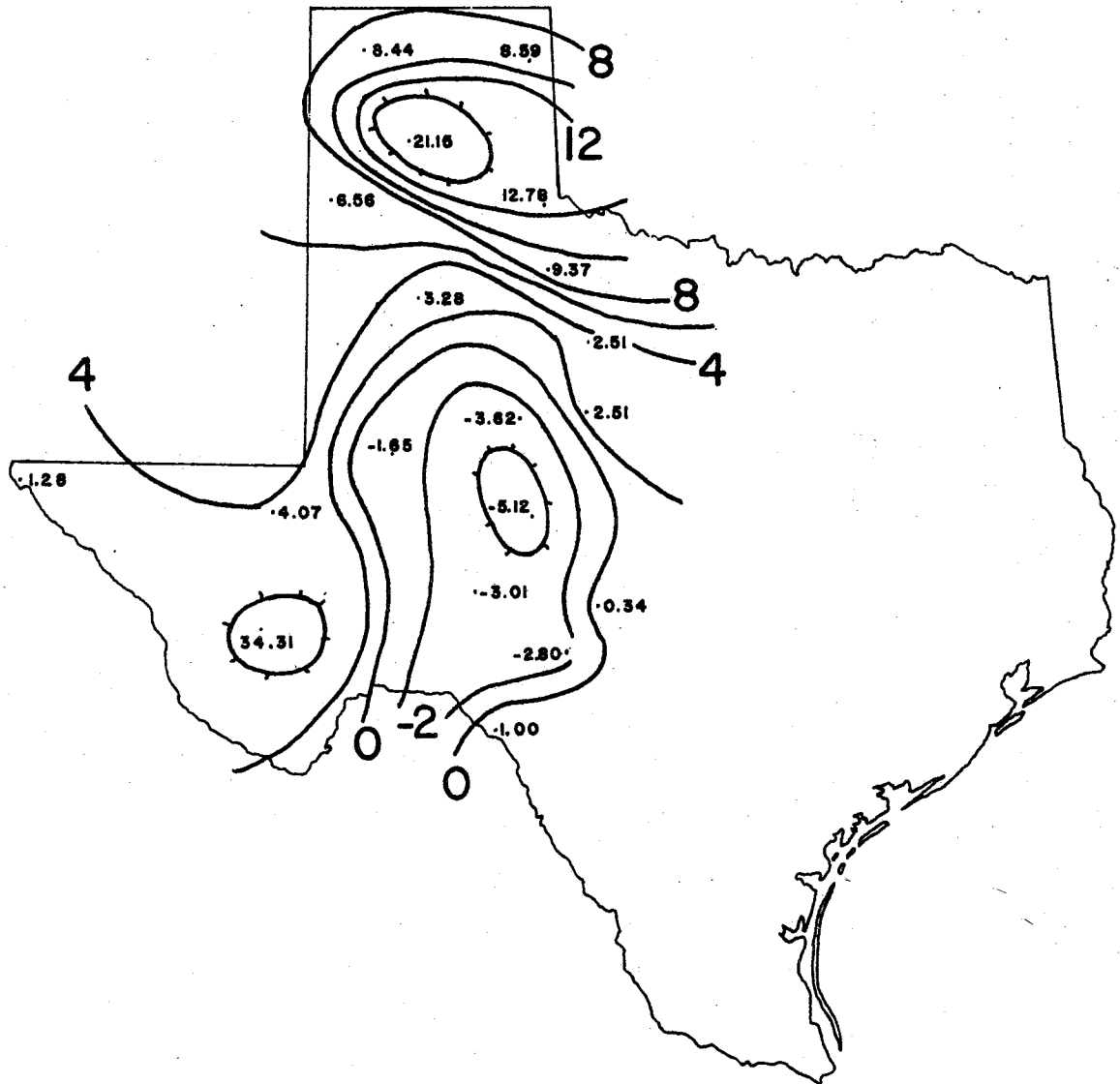
Departure From Long Term Mean Precipitation,
for the Year of 1957 in Inches of Water



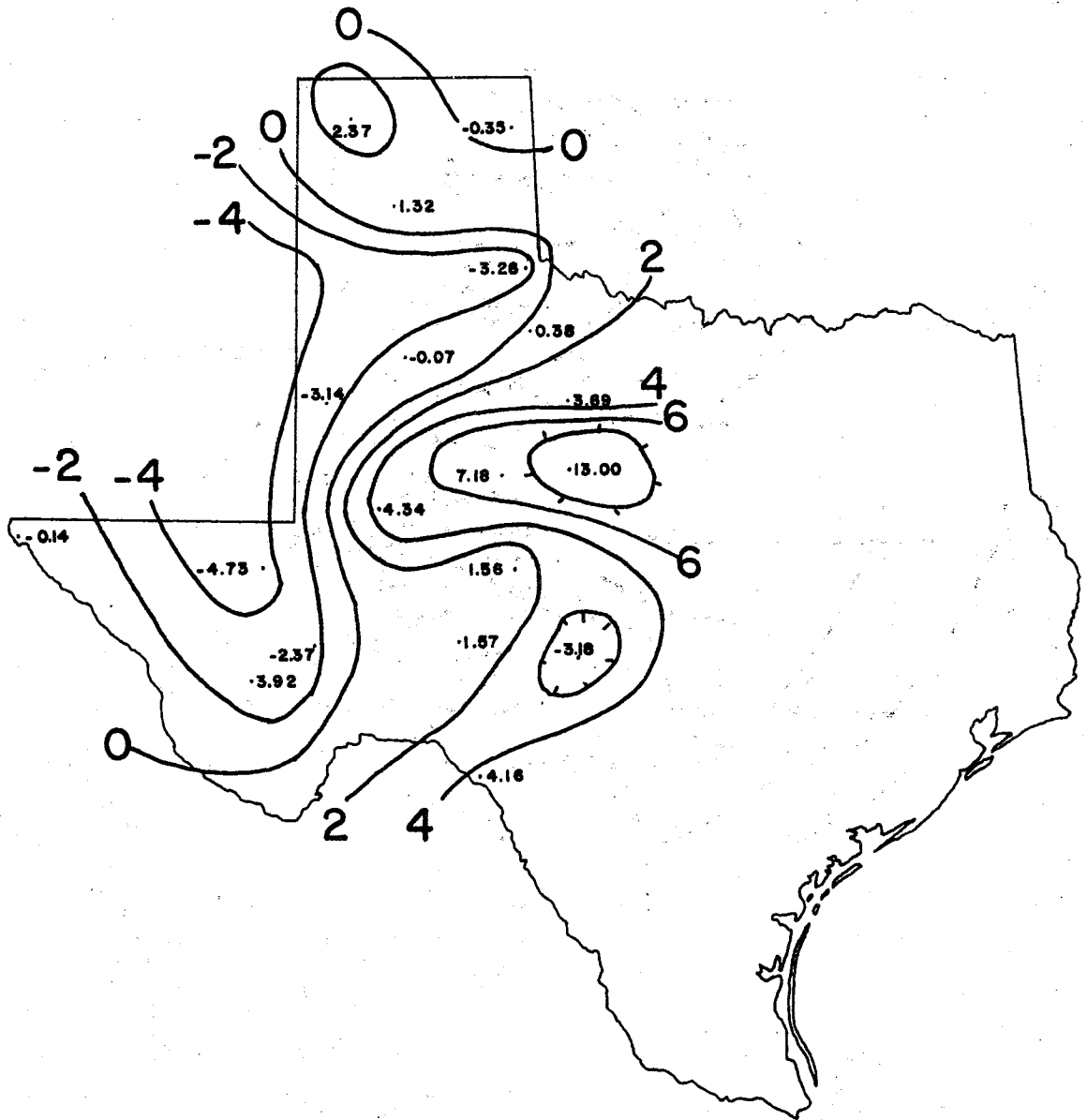
Departure From Long Term Mean Precipitation,
for the Year of 1958 in Inches of Water



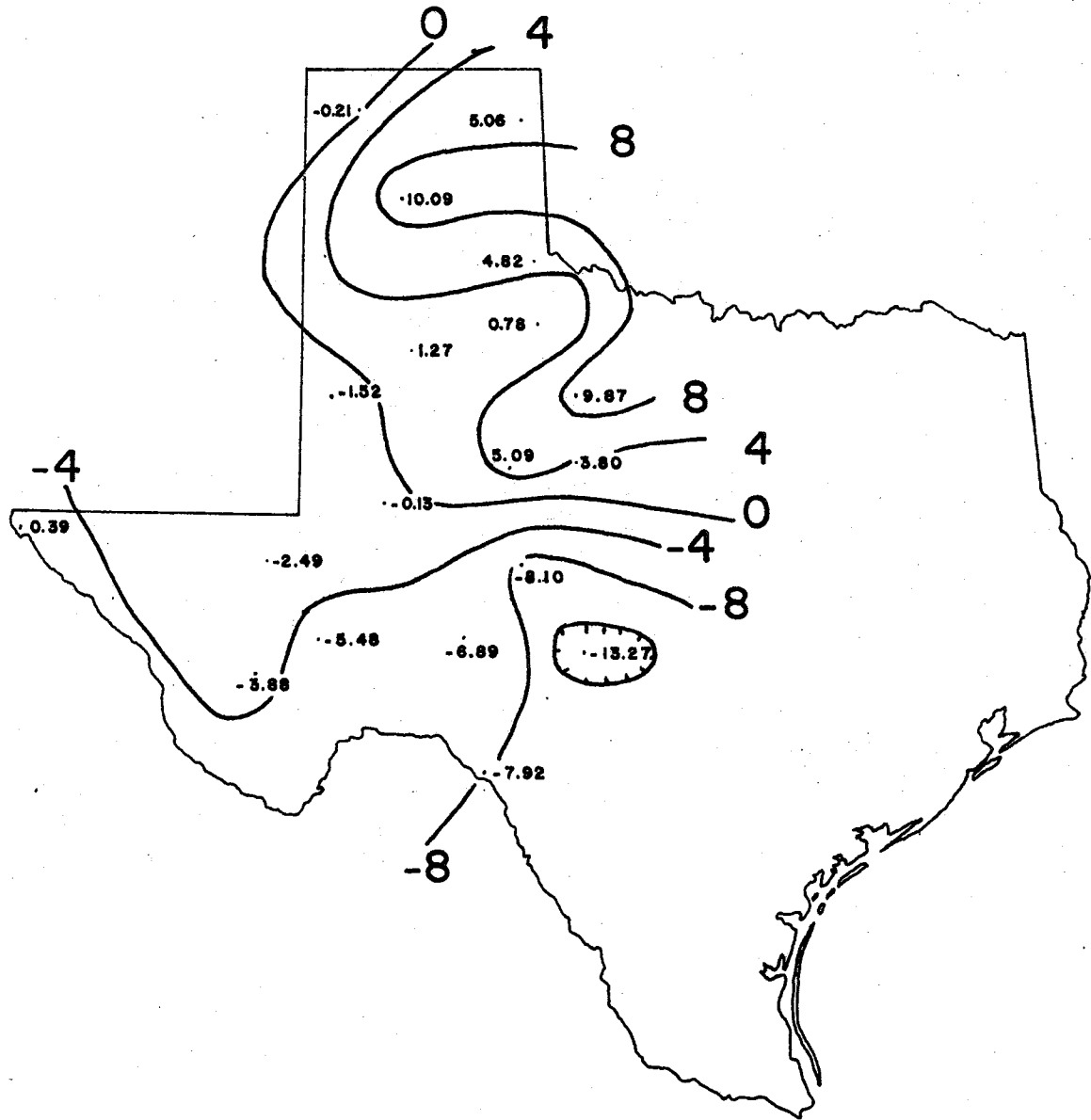
Departure From Long Term Mean Precipitation,
for the Year of 1959 in Inches of Water



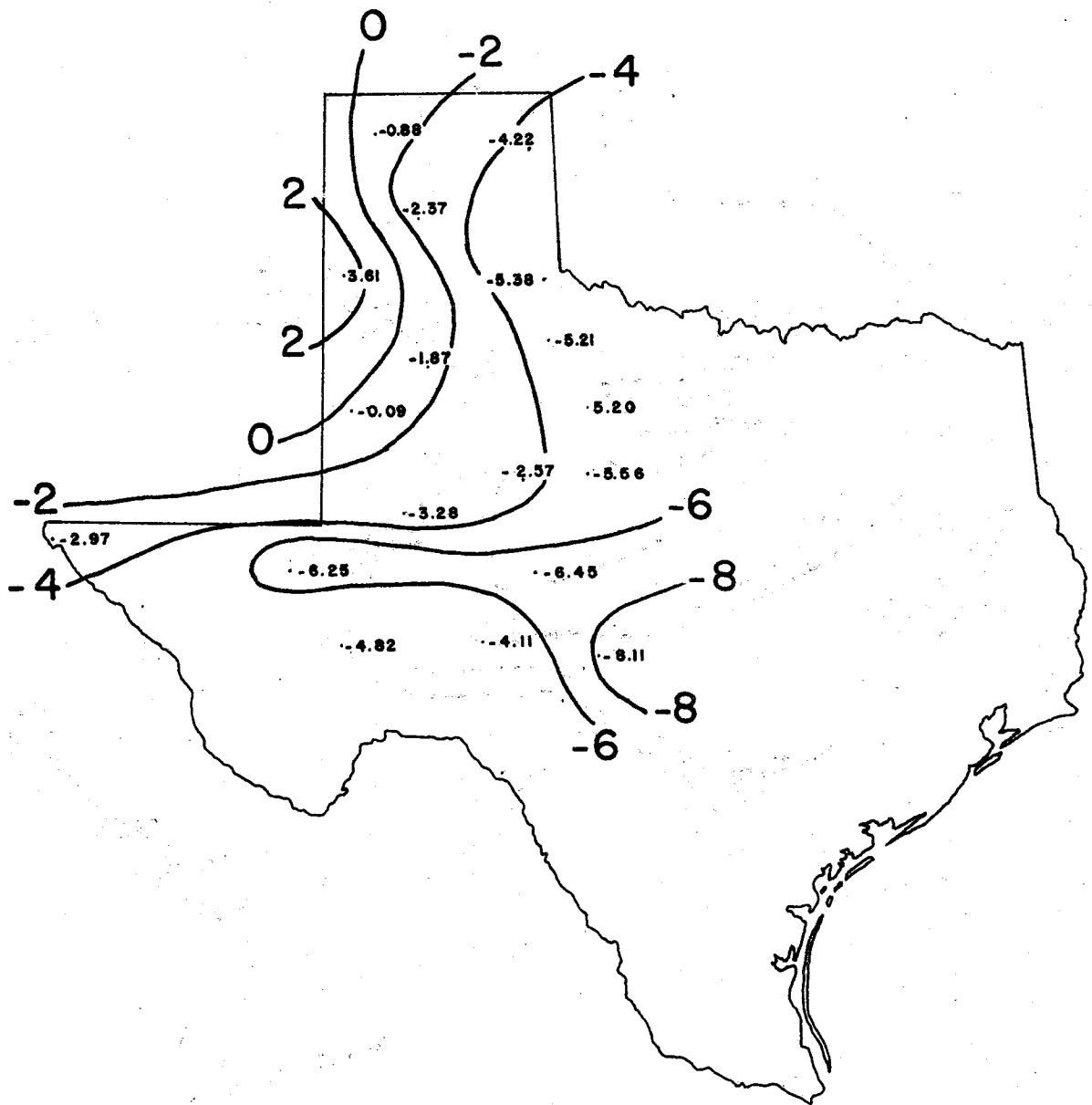
Departure From the Long Term Mean Precipitation
for the Year of 1960 in Inches of Water



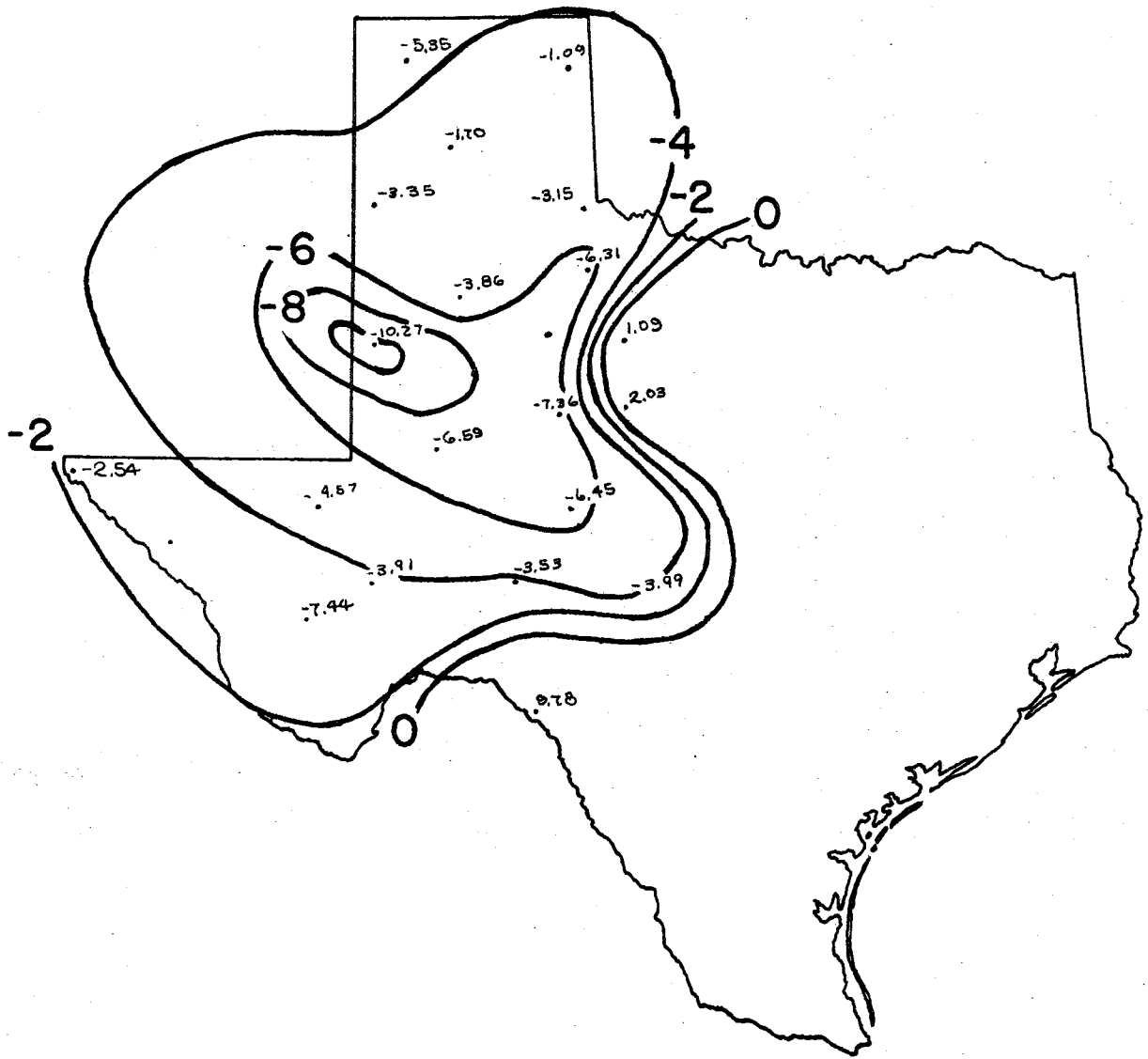
Departure From the Long Term Mean Precipitation
for the Year of 1961 in Inches of Water



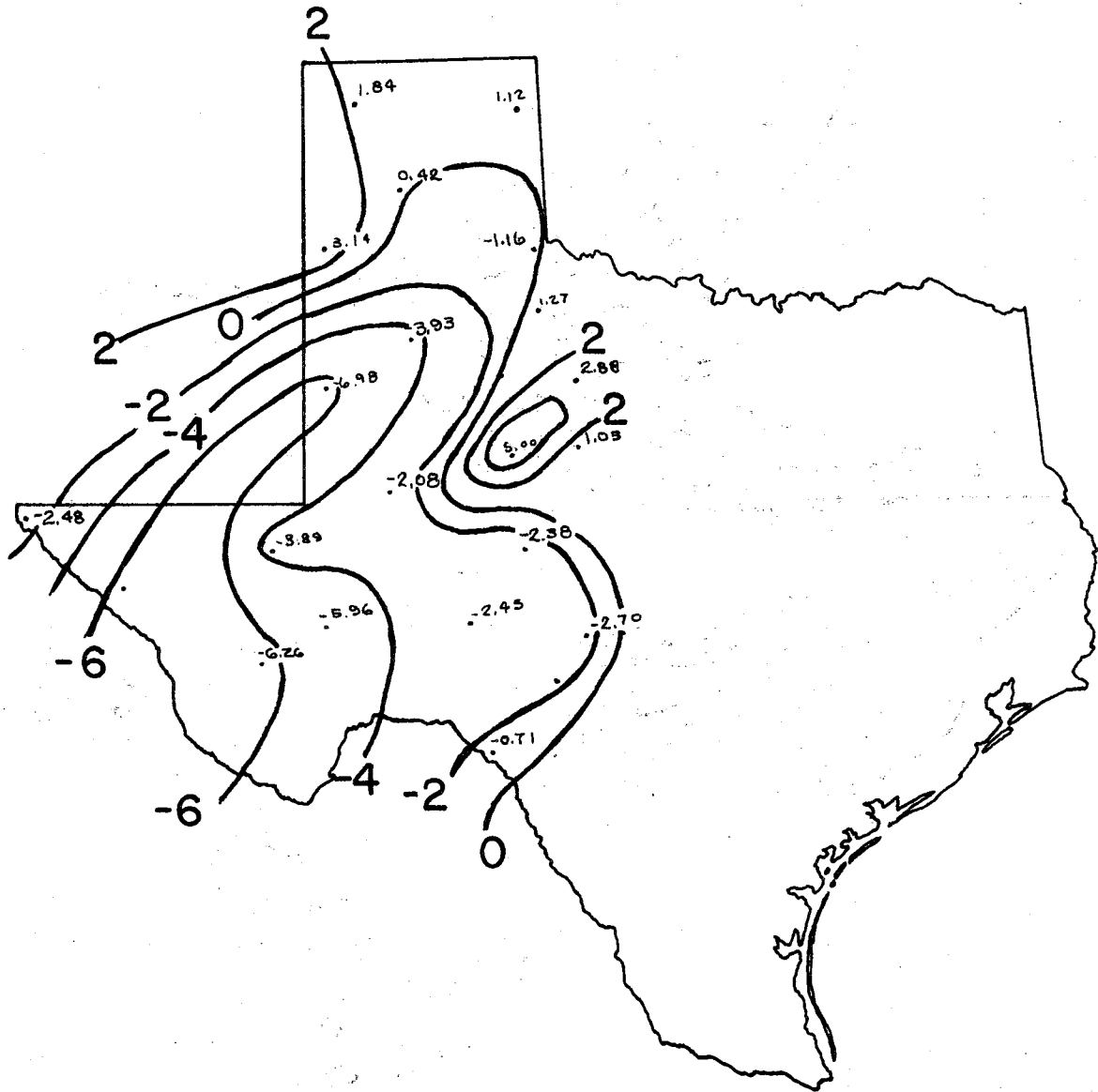
Departure From the Long Term Mean Precipitation
for the Year of 1961 in Inches of Water



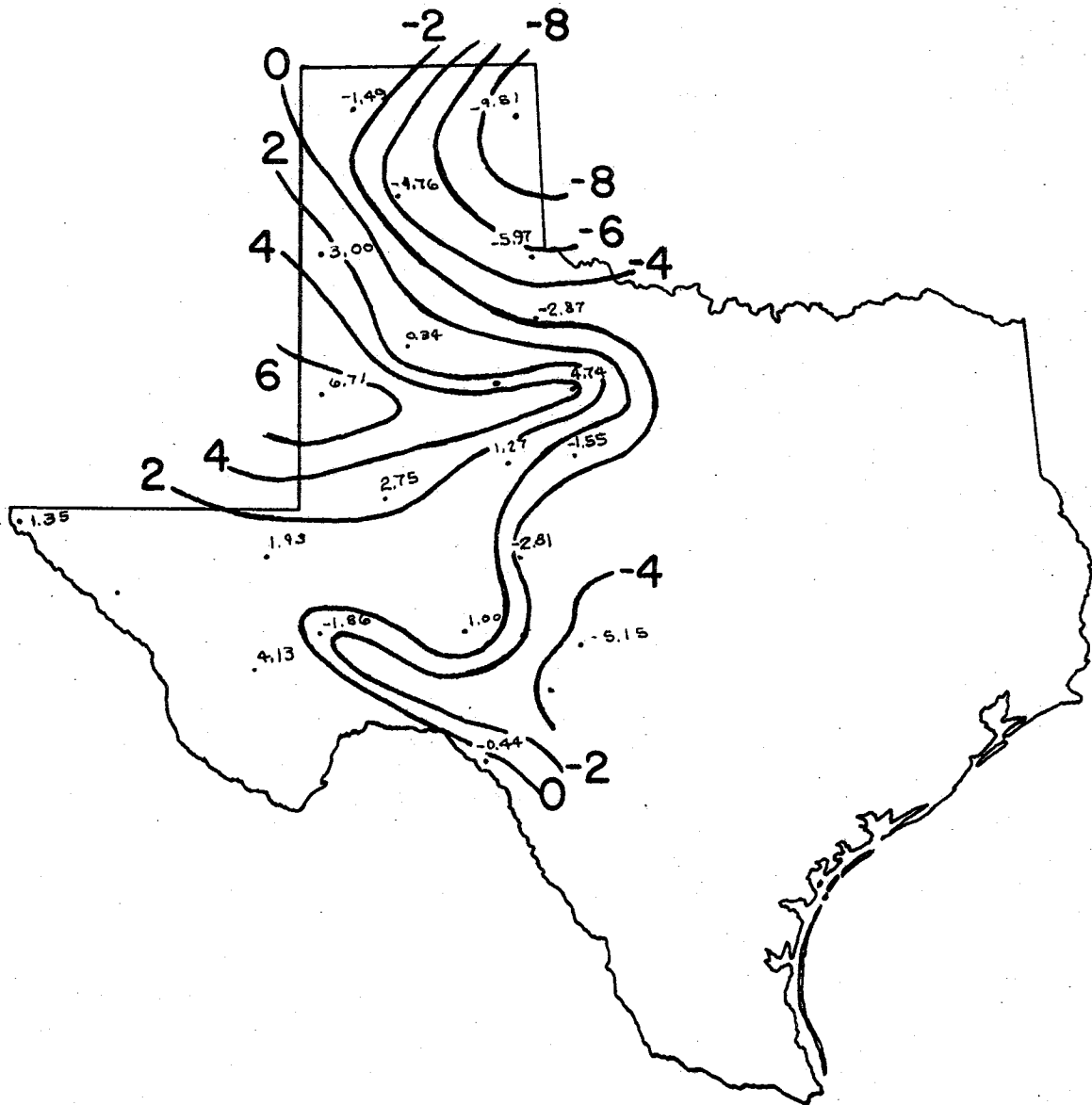
Departure From the Long Term Mean Precipitation
for the Year of 1961 in Inches of Water



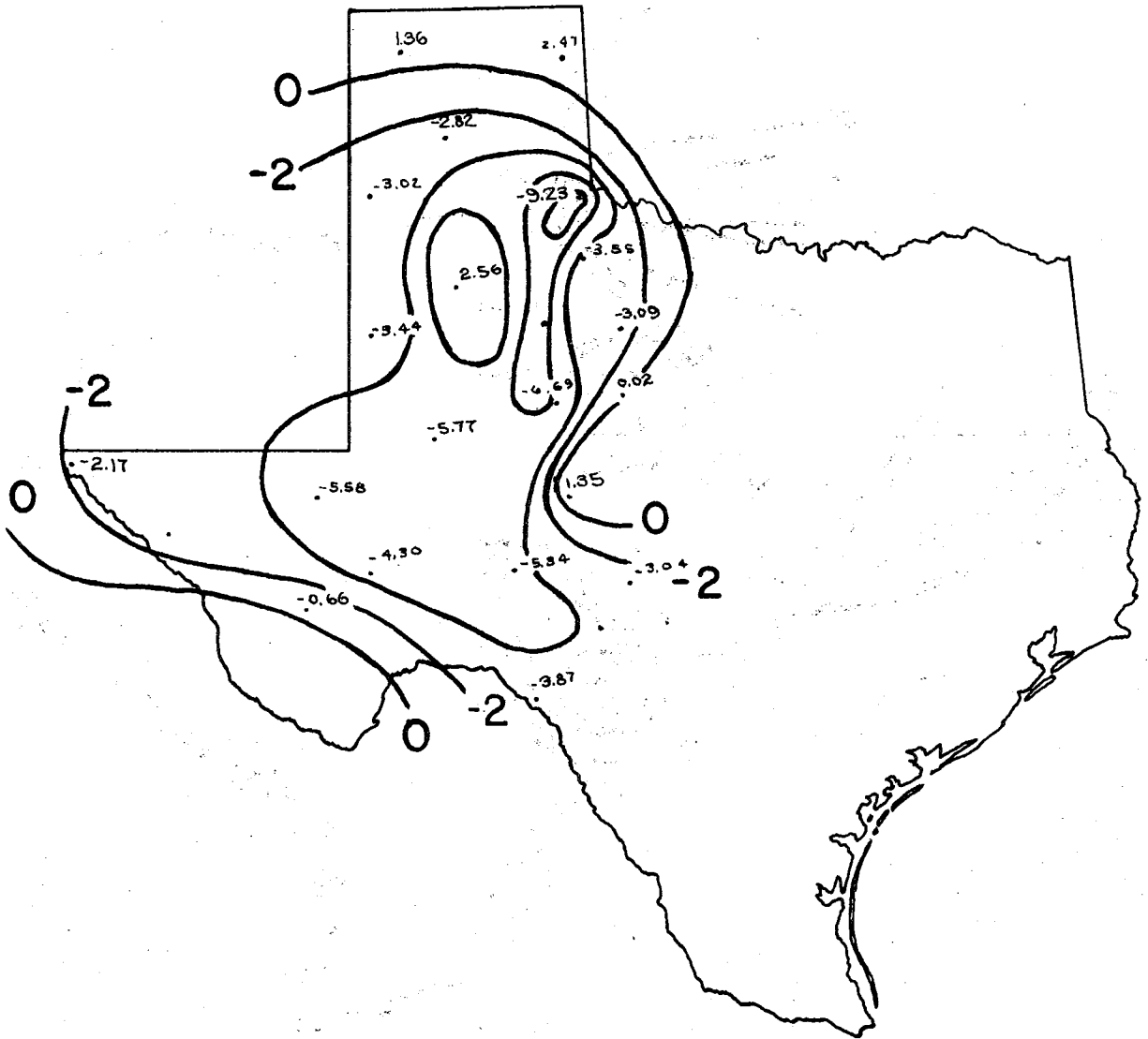
Departure From Long Term Mean Precipitation,
for the Year of 1964 in Inches of Water



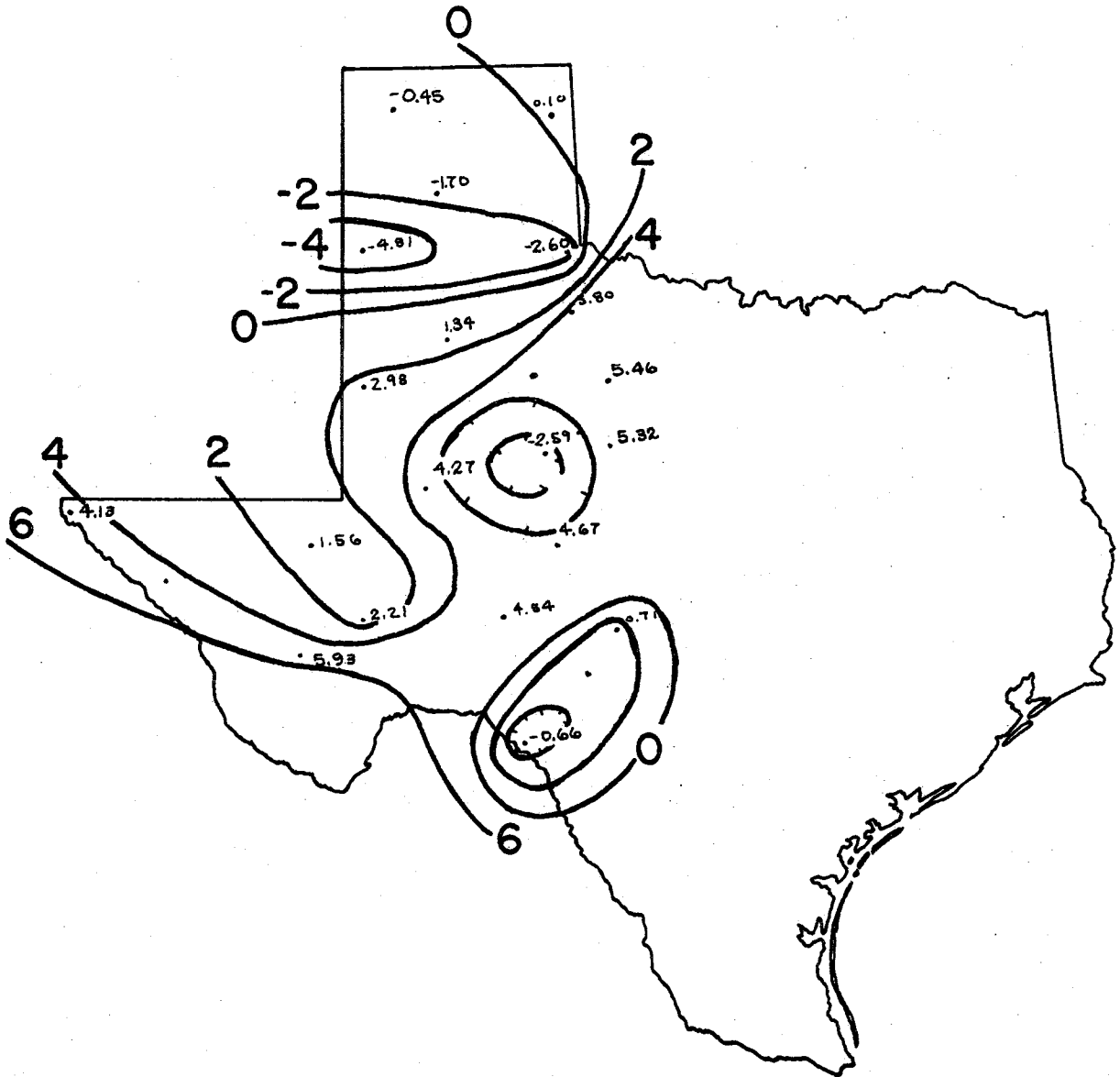
Departure From Long Term Mean Precipitation,
for the Year of 1965 in Inches of Water



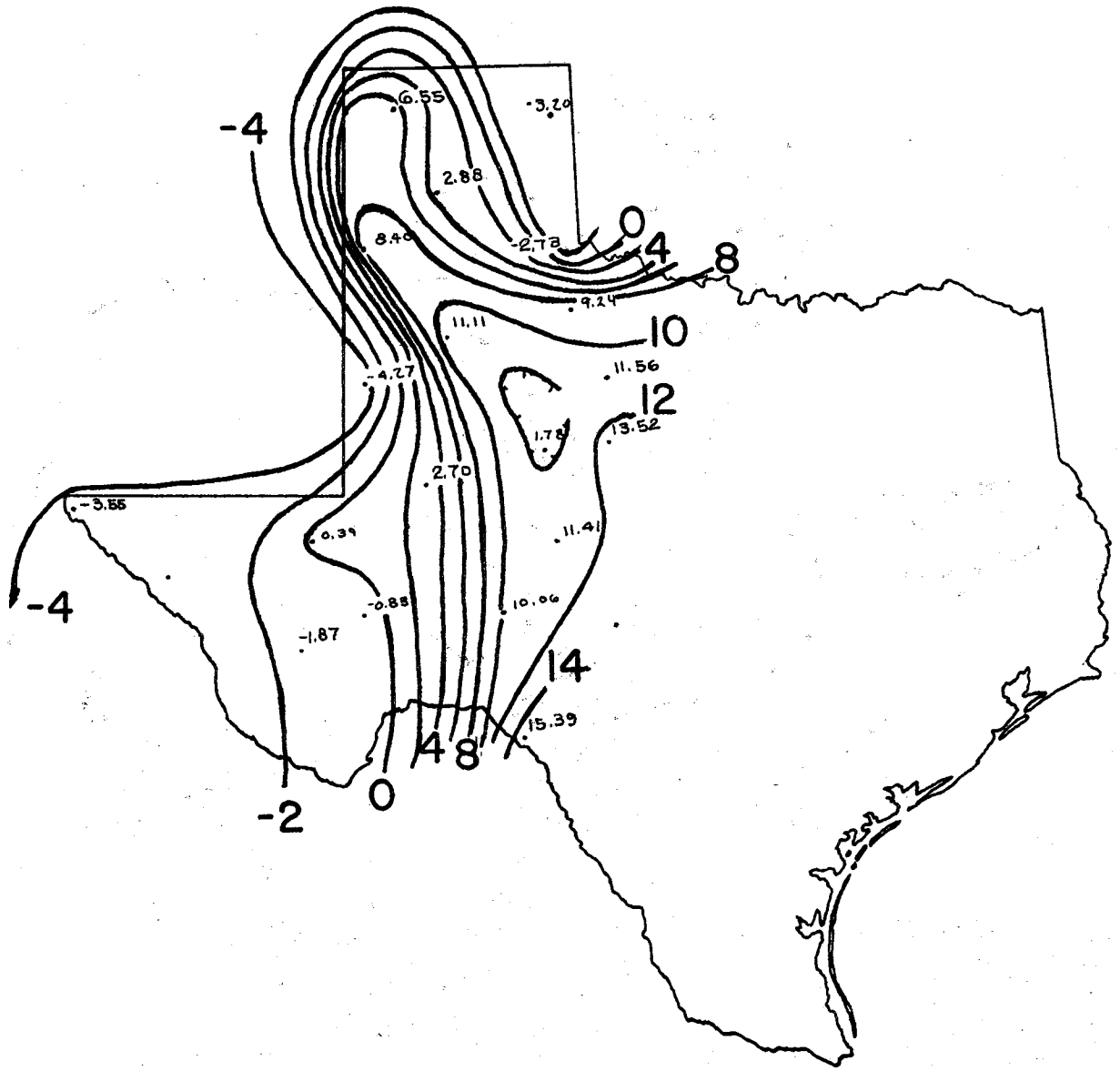
Departure From Long Term Mean Precipitation,
for the Year of 1966 in Inches of Water



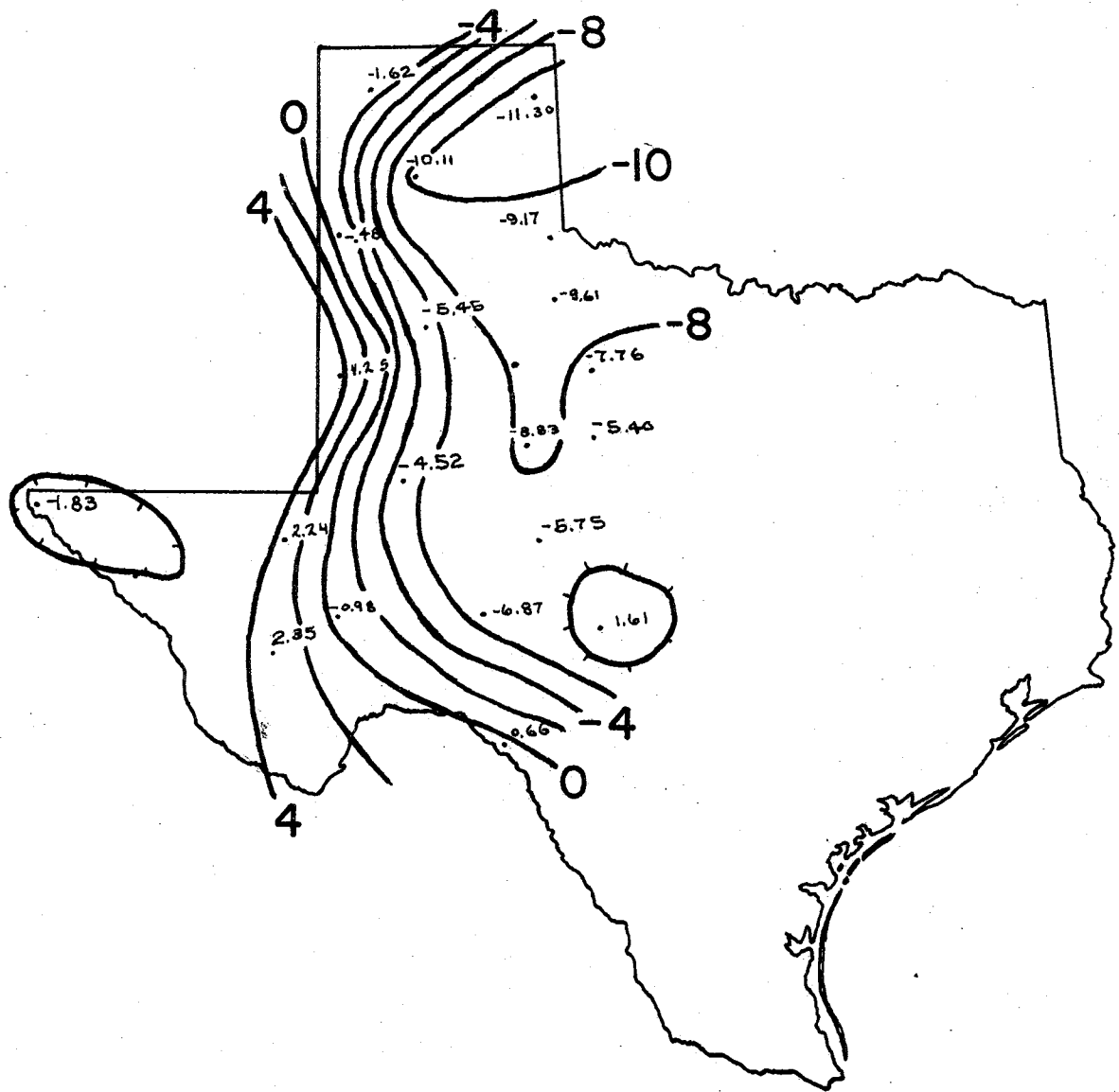
Departure From Long Term Mean Precipitation,
for the Year of 1967 in Inches of Water



Departure From Long Term Mean Precipitation,
for the Year of 1968 in Inches of Water



Departure From Long Term Mean Precipitation,
for the Year of 1969 in Inches of Water



Departure From Long Term Mean Precipitation,
for the Year of 1970 in Inches of Water