TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-84/56+249-6	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN CHARTS FOR THE DESIGN OF HMAC OVERLAYS ON PCC PAVEMENTS TO PREVENT REFLECTION CRACKING		5. Report Date November 1983 6. Performing Organization Code
7. Author(s) Alberto Mendoza Diaz and B. F. McCullough		8. Performing Organization Report No. Research Report 249-6
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin Austin, Texas 78712-1075		10. Work Unit No. 11. Contract or Grant No. Research Study 3-8-79-249
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763		13. Type of Report and Period Covered Interim 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration

Research Study Title: "Implementation of a Rigid Pavement Overlay Design System"

16. Abstract

The purpose of this study was to develop graphical procedures (design charts) for use in the design of Hot Mix Asphalt Concrete (HMAC) overlays on Portland Cement Concrete (PCC) pavements against reflection cracking, for implementation by the Texas State Department of Highways and Public Transportation for a range of specified local conditions. The final design procedure will be a hand solution method that will facilitate the overlay design process by substantially reducing the time and cost involved, particularly where computer facilities are difficult to access or estimating phases of the planning process do not permit a detailed analysis.

Regression equations were developed for the prediction of overlay life, that is a direct function of the repetition of tensile stresses generated in the overlay by the horizontal movements of the concrete slab at the joints or cracks when temperature drops occur. The choice of equations was made following multiple linear regression analysis of a fractional factorial of simulated observations which were output from the ARKRC-2 program. The form of the equations was selected on considerations of the variation of the independent variable with respect to certain significant factors, fundamentally based on experience. A theoretical model developed at the Center for Transportation Research was used to predict limiting values of vertical slab movements at the joints or cracks when subjected to wheel load applications. Some mathematical relationships were developed and converted into a design chart to predict the limiting values of vertical movements. Those joints exceeding these limiting values should be subjected to some type of repair before overlay rehabilitation to minimize the potential for vertical movement and avoid premature reflection cracking. A recommended procedure for the use of the design charts is presented along with some typical application examples.

17. Key Words rigid pavements, HMAC overlay, design charts, ARKRC-2, least squares, factorial experiment, variance, regression analysis, standard error for residuals, predicting accuracy	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	166	

Form DOT F 1700.7 (8-69)

DESIGN CHARTS FOR THE DESIGN OF HMAC OVERLAYS ON PCC PAVEMENTS TO PREVENT REFLECTION CRACKING

by

Alberto Mendoza Diaz
B. F. McCullough

Research Report 249-6

Implementation of a Rigid Pavemement Overlay Design System
Research Project 3-8-79-249

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November 1983

PREFACE

This is the sixth in the series of reports describing the work done in Project 249, "Implementation of a Rigid Pavement Overlay Design System." The study is being conducted at the Center for Transportation Research (CTR), The University of Texas at Austin, as part of a cooperative research program sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

This report presents the results of an analytical study undertaken to develop regression equations and design charts for use by the Texas State Department of Highways and Public Transportation as a supplementary tool in the design of Hot Mix Asphalt Concrete (HMAC) overlays on Portland Cement Concrete (PCC) pavements to prevent reflection cracking.

Many people have contributed to the completion of this report. Thanks are extended to Dr. W. R. Hudson and to all the CTR personnel.

A. Mendoza Diaz

B. F. McCullough

LIST OF REPORTS

Report No. 249-1, "Improvements to the Materials Characterization and Fatigue Life Prediction Methods of the Texas Rigid Pavement Overlay Design Procedure," by Arthur Taute, B. Frank McCullough, and W. Ronald Hudson, presents certain improvements to the Texas Rigid Pavement Overlay Design Procedure (RPOD2) with regard to materials characterization and fatigue life predictions. March 1981.

Report No. 249-2, "A Design System for Rigid Pavement Rehabilitation," by Stephen Seeds, B. Frank McCullough, and W. Ronald Hudson, describes the development, use and applicability of a Rigid Pavement Rehabilitation Design System, RPRDS, developed for use by the Texas State Department of Highways and Public Transportation. June 1981.

Report No. 249-3, "Void Detection and Grouting Process," by Francisco Torres and B. Frank McCullough, presents the results of an experiment and a theoretical analysis to determine an optimum procedure for detecting voids beneath CRC pavements. February 1982.

Report No. 249-4, "Effect of Environmental Factors and Loading Position on Dynaflect Deflections in Rigid Pavements," by Victor Torres-Verdin and B. Frank McCullough, discusses several of the factors that affect Dynaflect deflections in rigid pavements and provides a recommended procedure for Dynaflect deflections measurements which can be implemented in the rigid pavement overlay design procedures. February 1982.

Report No. 249-5, "Rigid Pavement Network Rehabilitation Scheduling Using Distress Quantities," by Manuel Gutierrez de Velasco and B. F. McCullough, presents the development and application of a computer program, PRP01, to prioritize and schedule a set of rigid pavements for rehabilitation within a specified time frame and budget constraints. August 1982.

Report No. 249-6, "Design Charts for the Design of HMAC Overlays on PCC Pavements to Prevent Reflection Cracking," by Alberto Mendoza Diaz and B. F. McCullough, presents the development of a series of regression equations and design charts for use by the Texas State Department of Highways and Public Transportation as a supplementary tool in the design of Hot Mix Asphalt Concrete Mix (HMAC) overlays on Portland Cement Concrete (PCC) pavements against reflection cracking. April 1983.

ABSTRACT

The purpose of this study was to develop graphical procedures (design charts) for use in the design of Hot Mix Asphalt Concrete (HMAC) overlays on Portland Cement Concrete (PCC) pavements against reflection cracking, for implementation by the Texas State Department of Highways and Public Transportation for a range of specified local conditions.

The final design procedure will be a hand solution method that will facilitate the overlay design process by substantially reducing the time and cost involved, particularly where computer facilities are difficult to access or estimating phases of the planning process do not permit a detailed analysis.

Regression equations were developed for the prediction of overlay life, that is a direct function of the repetition of tensile stresses generated in the overlay by the horizontal movements of the concrete slab at the joints or cracks when temperature drops occur. The choice of equations was made following multiple linear regression analysis of a fractional factorial of simulated observations which were output from the ARKRC-2 program. The form of the equations was selected on considerations of the variation of the independent variable with respect to certain significant factors, fundamentally based on experience.

A theoretical model developed at the Center for Transportation Research was used to predict limiting values of vertical slab movements at the joints or cracks when subjected to wheel load applications. Some mathematical relationships were developed and converted into a design chart to predict the limiting values of vertical movements. Those joints exceeding these limiting values should be subjected to some type of repair before overlay rehabilitation to minimize the potential for vertical movement and avoid premature reflection cracking.

A recommended procedure for the use of the design charts is presented along with some typical application examples.

KEYWORDS: Rigid Pavements, HMAC overlay, design charts, ARKRC-2, least squares, factorial experiment, variance, regression analysis, standard error for residuals, predicting accuracy.

SUMMARY

The ARKRC-2 computer program developed by Austin Research Engineers, Inc., the University of Arkansas, and the Arkansas State Highway and Transportation Department (Ref 1) from the original RFLCR programs developed for the FHWA provides a comprehensive procedure for the detailed analysis of the mechanisms directly related to the development of reflection cracking of HMAC overlays on PCC pavements. It accounts for the effect of the temperature variations that produce horizontal movements in the underlaying slab and tensile stresses in the overlay and the effect of vertical movements generated by wheel load applications producing shear stresses in the overlay. Using this program, simulated data were prepared for a selected range of values of input variables. Following analysis of variance and linear regression analysis a set of deterministic equations were developed to predict overlay life based on the repetition of tensile stresses produced by the thermally related horizontal movements of the concrete slab of the joints or cracks. Design charts were developed from these equations. For the vertical movements producing shear stresses in the overlay, two deterministic equations were developed to predict maximum deflection factors (a quantitative measure of relative slab movement at the cracks or joints). A design chart was prepared from these equations. Accuracy analyses were performed and safety factors were developed. Finally, a step-by-step procedure using charts was recommended and design examples were outlined.

IMPLEMENTATION STATEMENT

The design charts developed in this study are comprehensive, are easy to use, and allow the designer to analyze a series of feasible alternatives from an economic standpoint.

The procedure outlined in this study enables the designer to recommend a detailed design for the particular environmental conditions appropriate to the locality of the planned overlay section.

This design procedure should be incorporated into the Texas State Department of Highways and Public Transportation manual for the design of rigid pavement overlays.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

CHAPTER 2. ARKRC-2 PROGRAM DESCRIPTION

CHAPTER 3. SELECTION OF CONDITIONS FOR EQUATIONS

CHAPTER 4. DEVELOPMENT OF EQUATIONS

CHAPTER 5. ACCURACY ANALYSIS

CHAPTER 6. DESIGN PROCEDURE

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

APPENDICIES

CHAPTER 1. INTRODUCTION

BACKGROUND

Asphaltic concrete overlays represent the most widely used and accepted form of rehabilitation for improving performance in highways where generally new surfacing is required. Sometime after the overlaid section is opened to traffic, the cracks in the original pavement start to propagate to the surface of the overlay, leading to the appearance of the type of distress known as reflection cracking.

It is possible to design an overlay so that the expected amount of reflection cracking will be minimized. Various techniques have been available in the past for minimizing reflection cracking and many studies have been conducted in order to determine which are the most cost effective. These techniques have been exposed to a wide variety of environmental conditions; some states have used only one technique whereas most states have tried several. A summary of the rational experience on the fact is presented in References 1 and 4.

Reference 4 presents the results of experimental laboratory analysis substantiated with theoretical studies and actual field test projects conducted in several states. Systems with a demonstrated capability to retard reflection cracking of AC overlays on old PCC pavements include: thick AC overlays (6-inch) which are more effective than thin (2 or 4-inch) AC overlays where vertical movement is not excessive, prefabricated fabric membran strips and, interlayers of open-graded AC mixture (1 to 6-inch).

Reflection cracking was recognized as one of the principal forms of distress in resurfaced pavements at the 1932 annual meeting of the Highway Research Board. This led to a great deal of experimentation with various techniques for the control of reflection cracking, but even now the problem has not been solved. Most of the techniques used for preventing reflection cracking in overlays over PCC pavements are to a large degree based on experience gained from trial and error methods of in-service highways and have been of an empirical nature with no concentrated research effort.

In 1977, a part of a study conducted by the Federal Highway Administration was focused directly toward the task of developing design procedures for eliminating or reducing the reflection cracking of pavement overlays. The result of this effort was a computer program, called RFLCR-1, which could be used to determine if the distress mechanism of reflection cracking will occur in a specific overlay design. The program was intended for asphaltic concrete overlays and it characterized the existing concrete pavement through in-field measurements and calculated critical strains in the overlay for a specific design condition. The designer should compare these tensile and shear strains to the strains at which cracking would occur to determine if reflection cracking would occur.

In February 1982, the Arkansas State Highway and Transportation Department (AHTD) conducted a study in collaboration with the University of Arkansas and Austin Research Engineers, Inc. (Ref 1), to develop a comprehensive design procedure for predicting and minimizing reflection cracking in Arkansas for hot mix asphalt concrete (HMAC) overlays on portland cement concrete (PCC) pavements. The final design procedure consisted basically of a computer program, ARKRC-2, that considered both environmental and wheel loadings, and a series of tables, nomographs, and equations for inclusion in a design manual. The ARKRC-2 computer program was the result of an extensive study for the modification, improvement, and calibration of the original RFLCR-1 and follows basically the same methodology as RFLCR computer programs. ARKRC-2 is intended for direct application by AHTD for Arkansas conditions.

Recognizing the problem that reflection cracking represents when an HMAC overlay has been selected as an adequate measure of rehabilitation for a PCC pavement and the need for an adequate engineering design procedure for minimizing reflection cracking, it was decided to develop, for the prevailing conditions in Texas, equations and design aids similar to those published in the Arkansas study.

Although, usually, different methods are currently being used to solve the problem of reflection cracking in both states and ARKRC-2 is intended for direct application for the Arkansas conditions, the similar loading and environmental conditions under which pavements behave in both states and the similarity of construction procedures and material characteristics mean that the program can be used properly for Texas. Those techniques to minimize reflection cracking that can be simulated with ARKRC-2 as used in Arkansas and currently not used in Texas may be analyzed as new possible alternative solutions to the problem of reflection cracking in Texas.

OBJECTIVE AND SCOPE

The overall objective of this study is to develop a design charts for use in the design of hot mix asphalt concrete (HMAC) overlays on portland cement concrete (PCC) pavements for Texas.

From the ARKRC-2 computer program and with the aid of several analytical and statistical techniques, a set of deterministic equations will be derived to cover many types of pavements and environmental conditions in the state. The use of the deterministic equations will facilitate the overlay design process by substantially reducing the time and cost involved, particularly where computer facilities are difficult to access or estimating phases of the planning process do not permit a detailed analysis.

The final design procedure will be a hand solution method developed by considering the effects of certain significant factors while holding the less significant ones constant for the Texas conditions.

In the process of developing the design procedure, the relationships among the significant input variables related in the mathematical model used by ARKRC-2 to simulate the mechanisms of reflection cracking will be quantified to present them in the form of deterministic equations or design charts.

The objectives of this report will be accomplished through the development of the following chapters.

Chapter 2 describes briefly the use, application, and operation of the ARKRC-2 computer program; the meaning of all data; input variables, and the interpretation of the program output.

In Chapter 3 the number of equations to be developed is defined and also the set of conditions under which each equation is applicable is presented by substantially establishing a series of recommended values for the ARKRC-2 input variables.

Chapter 4 describes the procedure to develop the regression equations for the tensile strain criteria. The final regression equations are presented, as are the deterministic equations corresponding to the shear strain criteria. The development of design charts from the final equations is also outlined here.

Chapter 5 presents a detailed analysis of the accuracy of the regression equations as predictors of the ARKRC-2 program output. A kind of safety factor is also developed in this chapter, based on the standard error of the predictions.

Chapter 6 gives the development of a comprehensive and easy to use design procedure. Three levels in the detail of the analysis are proposed in the design procedure. The first two levels are computer based by directly running ARKRC-2, one with a series of design inputs generated through precise characterization and the other with a series of recommended values. The third is a less accurate but easier hand solution, which applies the design charts developed in Chapter 4. A design example is shown applying the design charts to check an actual overlaid section in one of the Texas regions and to select the most accurate and economical design alternative.

Chapter 7 presents the conclusions and recommendations derived from the present study.

CHAPTER 2. ARKRC-2 PROGRAM DESCRIPTION

This chapter is intended to provide a brief discussion of the use, application, and operation of the ARKRC-2 program, as well as a description of all data and input variables and an interpretation of the program output.

ARKRC-2 is the result of an extensive study oriented to the modification, improvement, and calibration of the original reflection cracking program, RFLCR-1, developed for the FHWA (Ref 2) in 1977. RFLCR-2, the second version, appeared later as the result of the correction of some minor coding errors in RFLCR-1, but is conceptually identical to RFLCR-1. ARKRC-2, developed specifically for Arkansas, follows the general RFLCR methodology.

USE AND APPLICATION

The primary objective of the ARKRC-2 program is to provide a procedure capable of analyzing the potential for reflection cracking in an asphalt concrete overlay placed on an existing concrete pavement. This capability permits an examination of a series of suitable alternatives, those most commonly used in Arkansas, so that the most cost effective overlay strategy can be selected.

The most effective techniques to minimize reflection cracking in Arkansas have been, commonly, the use of thicker overlays; the use of strain relieving interlayers, in particular the bond-breaker material known as SAMI (stress absorbing membrane interlayers); and the use of a cushion course, such as an asphalt treated open-graded course. All these techniques can be analyzed with ARKRC-2.

In Texas, the use of strain relieving interlayers (bond breakers) has not been a common practice though it represents one of the most effective techniques for jointed pavements, especially when used in combination with cushion courses.

Therefore, because the techniques analyzed by the ARKRC-2 model represent reasonable measures for minimizing reflection cracking and because the program was calibrated using overlaid sections in Arkansas and Texas the program can be used satisfactorily to develop the design aids.

OPERATION

The two basic mechanisms leading to the development of reflection cracking are (1) horizontal temperature-drop related movements of the underlying slab and (2) differential vertical movements which occur as a load moves across a discontinuity in the original pavement. The temperature drop related movements induce horizontal tensile strains in the overlay while differential vertical movements induce vertical shear strains in the overlay. ARKRC-2 analyzes the detrimental effects that temperature drops produce on overlays and provides a reasonable way to detect when the shear strains generated by vertical movements will exceed an allowable level.

A summarized flow chart of the ARKRC-2 computer program is shown in Fig 2.1. The steps of the program are described briefly here.

Block I summarizes the collection and input of data required by the program. This is discussed briefly later in this section and in great detail in the Arkansas study. A guide for data input is provided in Appendix A.

In the ARKRC-2 analysis and design procedure, reflection cracking developed in the overlay is directly attributed to fatigue or the accumulation of damage caused by the tensile strains loading cycles resulting

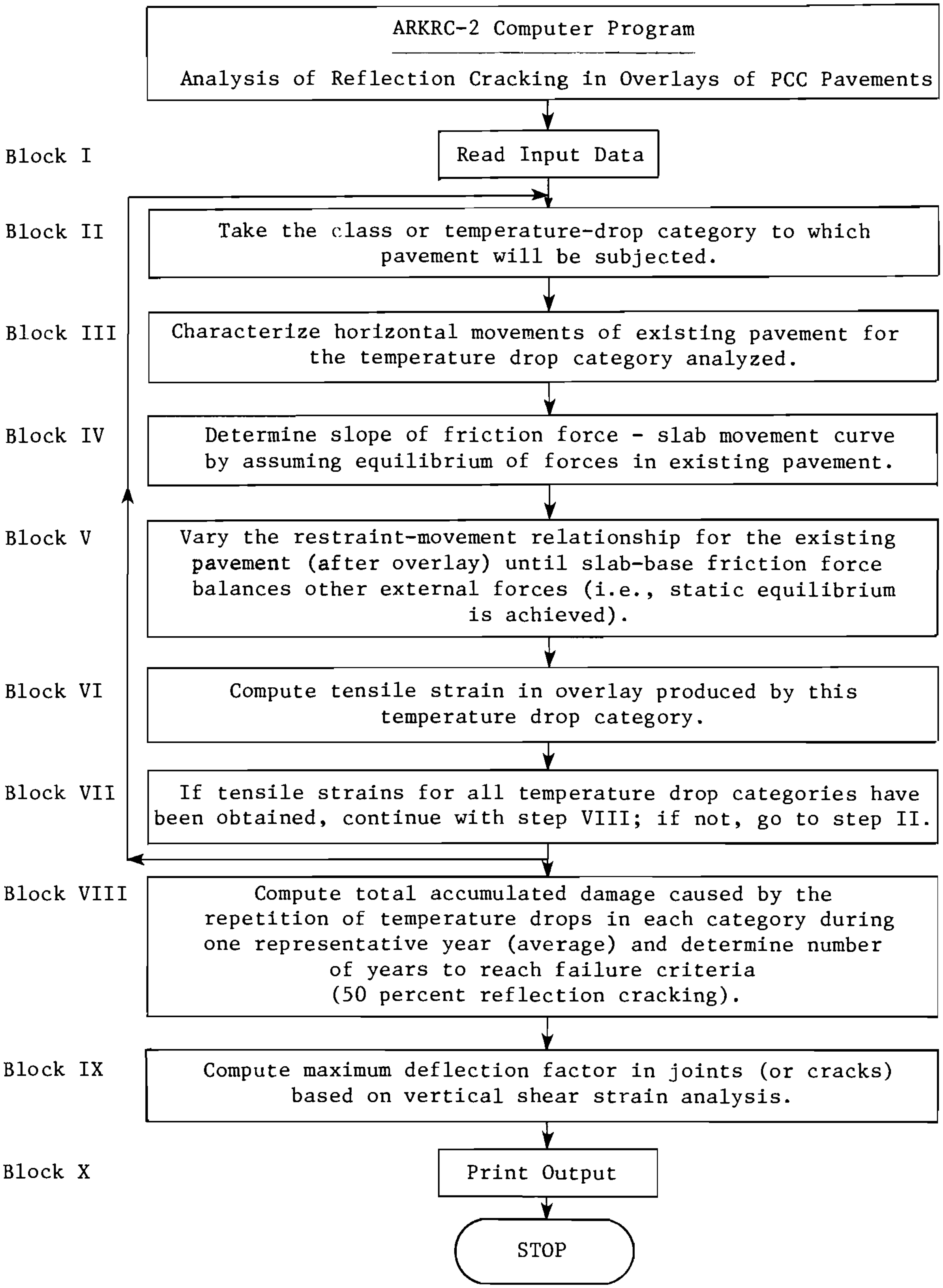


Fig 2.1. Flowchart of the major components of Arkansas Reflection Cracking Analysis Program, ARKRC-2.

from varying low-temperature drops. Miner's linear damage hypothesis was assumed applicable to the analysis of fatigue.

Research at the Texas Transportation Institute (TTI) showed that asphalt concrete is particularly susceptible to damage at temperatures below 50°F, and, therefore, 50°F was selected as a reference temperature for calculating the overlay tensile strains (Ref 8).

Information on the distribution of daily temperature drops for all climatic stations installed in Texas were provided by the National Climatic Center (Ref 7). The differences between 50°F and the daily minimum temperature were divided into 10 degree frequency ranges (classes or categories) and the average number of days during each year that the temperature dropped a certain magnitude below 50°F were assigned to the corresponding classes. Those days in which the temperature stayed above 50°F were not counted.

The seven temperature classes or categories referred to in Block II and considered in ARKRC-2 analysis are given in Table 2.1.

The program takes each temperature category successively and determines the corresponding strain values to be used later in the fatigue damage model.

Block III summarizes the characterization of the horizontal movement of the existing slab for a change in temperature. This part involves the use of a mathematical expression for the movement along the entire slab as a function of the magnitude of the temperature drop, length of slab, concrete thermal coefficient, and restraint coefficient, beta (β), which is indicative of the slab's movement relative to unrestrained thermal contraction.

TABLE 2.1. MINIMUM TEMPERATURE FREQUENCY RANGES (CLASSES)

Range of Temperature Drop (°F)	Range of Minimum Temperature (°F)	Average Temperature Drop Below 50° F
1 - 10	49 - 40	5
11 - 20	39 - 30	15
21 - 30	29 - 20	25
31 - 40	19 - 10	35
41 - 50	9 - 0	45
51 - 60	-1 - -10	55
61 - 70	-11 - -20	65

The restraint/movement relationship (beta function) is used in an iterative process to balance the forces generated by a temperature drop; it was originally defined in the RFLCR programs as having the following form:

$$\Delta x = \alpha c \cdot \Delta T \cdot (x - \beta x^{\beta}) \qquad (2.1)$$

where

α_C = concrete thermal coefficient (in./in./°F),

ΔT = temperature change (°F),

x = point along slab measured from midpoint of slab (in.),

β = restraint coefficient (beta), and

Δx = movement at point X (in.).

The range of beta is from zero to one. A zero value implies that slab movement is unrestrained and a value of one means that the slab is completely restrained against thermal movements.

The original equation does not accurately model actual slab movements under semi-restrained conditions and predicts higher movements near midslab than those observed in the field. Therefore, another equation was developed and incorporated into the ARKRC-2 program:

$$\Delta x = \alpha c \cdot \Delta T \cdot (1 - \beta) \cdot x \cdot \left(\frac{x}{\ell} \right)^{\beta} \qquad (2.2)$$

where most of the variables are the same as before and ℓ, the half-length of the slab (inches), has been introduced. This new equation has greater curvature and, therefore, predicts equal or less movement all along the slab.

Block IV summarizes the part of the process where the slope of the friction force versus the slab movement curve for the existing pavement is determined. This step is required in order to determine the influence of the slab base friction after overlay. When a decrease in slab temperature is experienced, the subbase friction acts as a restraint to contraction inducing concrete forces which reach a maximum at midslab. Through static equilibrium, the induced forces in concrete must balance with the steel reinforcement forces and the frictional forces on the slab underside. But these frictional forces follow a linear behavior similar to that shown in Fig 2.2 until reaching a point of sliding from which there is little change in frictional force with movement. Equilibrium must be achieved first and then the slope, m, of the frictional force versus slab movement obtained. This slope must be corrected by the overburden after overlay and used to estimate the total friction force acting after overlay.

In Block V, the program attempts to balance the forces generated by a temperature drop that occurs after overlay by varying the after overlay restraint coefficient, β_B .

One of the most common preventive measures for reflection cracking in Arkansas has been the use of an open-graded course to act as an intermediate layer between the original PCC slab and the asphalt concrete overlay. The resilient characteristics of the intermediate layer reduce the tensile strains that develop in the overlay due to the temperature related horizontal movements of the underlying concrete slab. The RFLCR programs do not consider the reduction in the tensile strains and the effects that it has on the horizontal forces generated in the layers. To include these effects

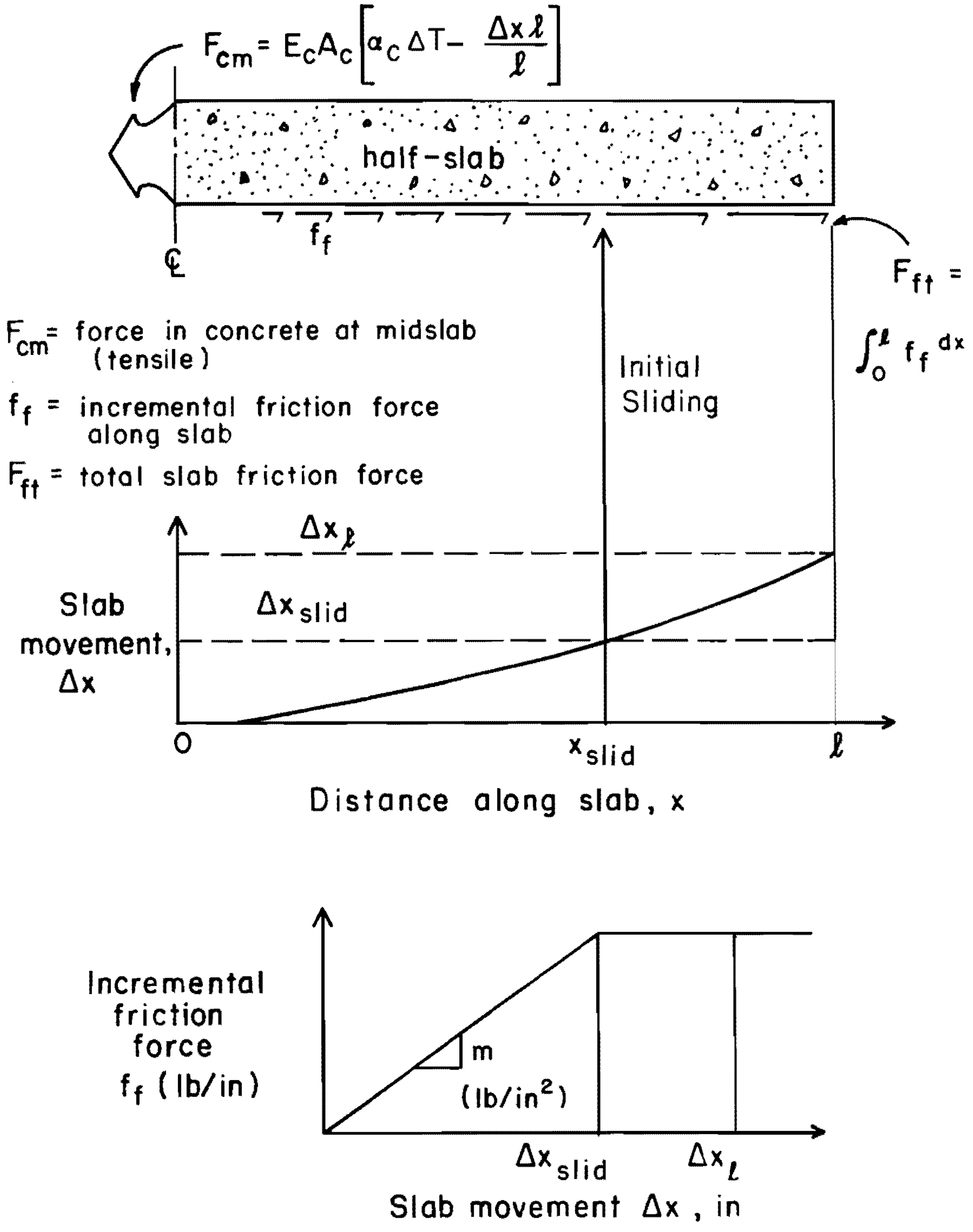


Fig 2.2. Illustration of the process for determining the slope of the friction curve, m (after Ref 1).

in ARKRC-2 analysis, the maximum tensile strain, f_{max} , developed at the bottom of the intermediate layer was reduced by a strain reduction factor, f_{IL} . In Fig 2.3, the position of layers in the pavement and the reduction of the horizontal strains are shown. The strain transferred to the overlay, ε_{OV} , can be obtained by

$$\varepsilon_{OV} = f_{IL} \cdot \varepsilon_{max} \qquad (2.3)$$

An equation to determine f_{IL} in terms of the layer and overlay thicknesses and their respective creep moduli was developed by means of finite element techniques and linear regression analysis.

Another reduction in the horizontal strains takes place between the bottom and the top of the overlay and includes this effect in the analysis, the same type of solution given to the intermediate layer was applied to this case. From the horizontal strain at the bottom of the overlay, ε_{OV} , applying a strain reduction factor, f_{OV} , the strain at the top of the overlay (ε_{TOP}) can be determined:

$$\varepsilon_{TOP} = f_{OV} \cdot \varepsilon_{OV} \qquad (2.4)$$

Again, the equation to compute f_{OV} was determined using finite element techniques and linear regression analysis.

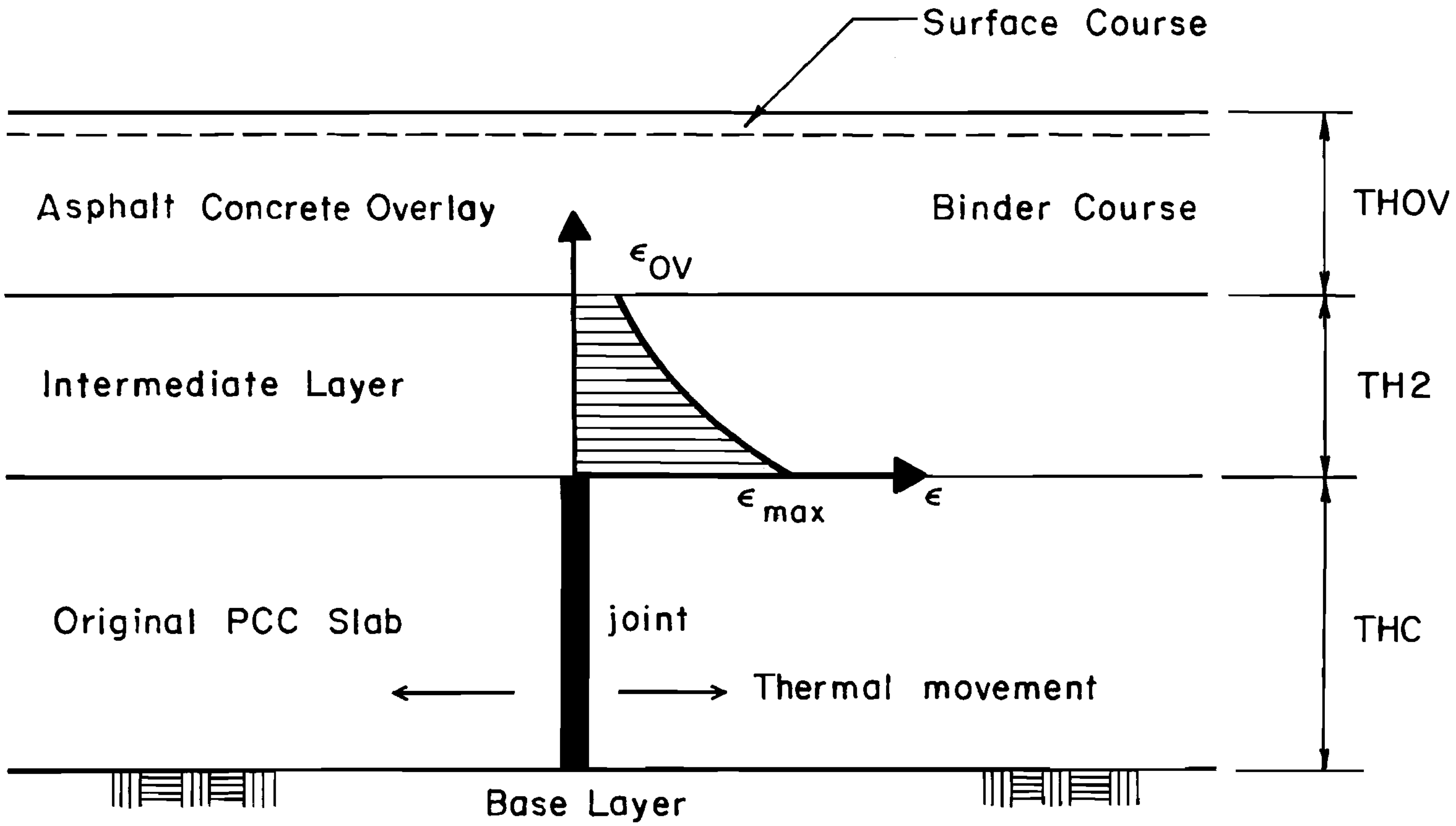


Fig 2.3. Illustraion of the reduction (or absorption) of horizontal strain by a low stiffness intermediate layer (after Ref 1).

With the maximum and minimum strains at the bottom and top, respectively, of each layer, a specific strain distribution between these values can be assumed, and, by means of an integration, the forces acting in these layers under a given temperature drop can be determined.

In Block VI, after the force carried by the overlay at the joint or crack is determined from the balance of forces of Block V, the maximum tensile strain generated in the overlay at the joint is computed.

Block VII indicates that the maximum tensile strain generated in the overlay must be determined for all temperature drop categories. The procedure marked from Block II to VII must be repeated for the seven temperature drop classes mentioned in the description of Block II.

Block VIII summarizes the process utilized in the ARKRC-2 program to compute the total accumulated damage caused by the repetition of the temperature drops in each category during one average year and the number of years that the overlaid section will be in service until 50 percent of reflection cracking will appear (failure criteria). The procedure is based on the fatigue damage model following Miner's hypothesis. A fatigue equation is used to determine the total number of cycles or repetitions of a certain tensile strain, $(N_T)_i$, that the overlay can resist before reaching failure criteria. The fatigue equation is of the form

$$N_T = a_1 (\varepsilon_T)^{a_2} \qquad (2.5)$$

where

a_1, a_2 = calibration or regression coefficient and

ε_T = tensile strain in overlay.

The fatigue coefficients, a_1 and a_2, were determined by a calibration process based on a series of surveys and performance studies of overlaid sections in Arkansas and Texas. An expression dependent upon the creep modulus of the overlay was obtained for a_1.

The fatigue coefficients obtained were

$$a_1 = 8.072 \times 10^{-4} \times (EOV)^{-1.118} \tag{2.6}$$

where

EOV = asphalt concrete overlay creep modulus, psi,

and

a_2 = -3.70

N_T is computed for all tensile strains corresponding to the different temperature drop categories.

Next, the incremental damage, d_i, produced during an average year by the repetition of each given strain level is computed by

$$d_i = \frac{n_i}{(N_T)_i} \tag{2.7}$$

where

n_i = average number of days during the year in which overlay is subjected to the $(\varepsilon_T)_i$ strain level; obtained from the temperature data provided by the NCC.

The total damage (in one year) produced on the overlay by the repetition of strain cycles of all temperature drop classes can be accumulated according to Miner's hypothesis:

$$D = \sum_{i=1}^{7} d_i = \sum_{i=1}^{7} \frac{n_i}{(N_T)_i} \qquad (2.8)$$

Finally, the total number of years for the overlay to reach 50 percent in reflection cracking (failure criterion) can be computed as

$$Y_T = 1.0/D \qquad (2.9)$$

If the number of years, Y, to reach a level of reflection cracking other than 50 percent is desired, the probabilistic principles developed by Darter and Hudson for the design of flexible pavement systems (Ref 11) can be applied. The following extrapolation function, which assumes that the distribution of reflection cracking is log-normally distributed, can be used:

$$Y_{T50} = Y/SD^{z} \qquad (2.10)$$

where

Y_{T50} = overlay age of 50 percent reflection cracking, years;

Y = overlay age at time of survey (years);

SD = standard deviation of log-normal distribution assumed from experience to be equal to 1.585; and

z = standard normal variate depending on the percentage of reflection cracking actually observed in overlay section.

In Block IX the maximum deflection factor to be used in the shear strain analysis is obtained. This procedure is an improved and more realistic approach than the one in the RFLCR programs, and consists of making field deflection measurements prior to overlay placement on a number of joints or cracks in a given design section by loading one side of each joint (or crack) and measuring the deflections on both loaded and unloaded sides. The Dynaflect device may be used for these measurements. The deflection factor for each joint, F_w, can be computed as

$$F_w = \frac{w_1 - w_u}{w_1 + w_u} \tag{2.11}$$

where

w_1 = deflection on load side and

w_u = deflection on unloaded side.

Figures 2.4 and 2.5 show the location of the Dynaflect load and geophones in order to determine the required deflection values.

The ARKRC-2 uses a model that determines the maximum shear strain, γ_{OV}, to which the overlay can be subjected so that it can resist N_T repetitions of the design 18-kip equivalent single axle load producing that maximum shear strain, in terms of the dynamic modulus of the overlay material, EDV, and the total number N_T of 18-kip ESAL that can be expected in the design lane in the overlay direction for the design period. The expression derived is

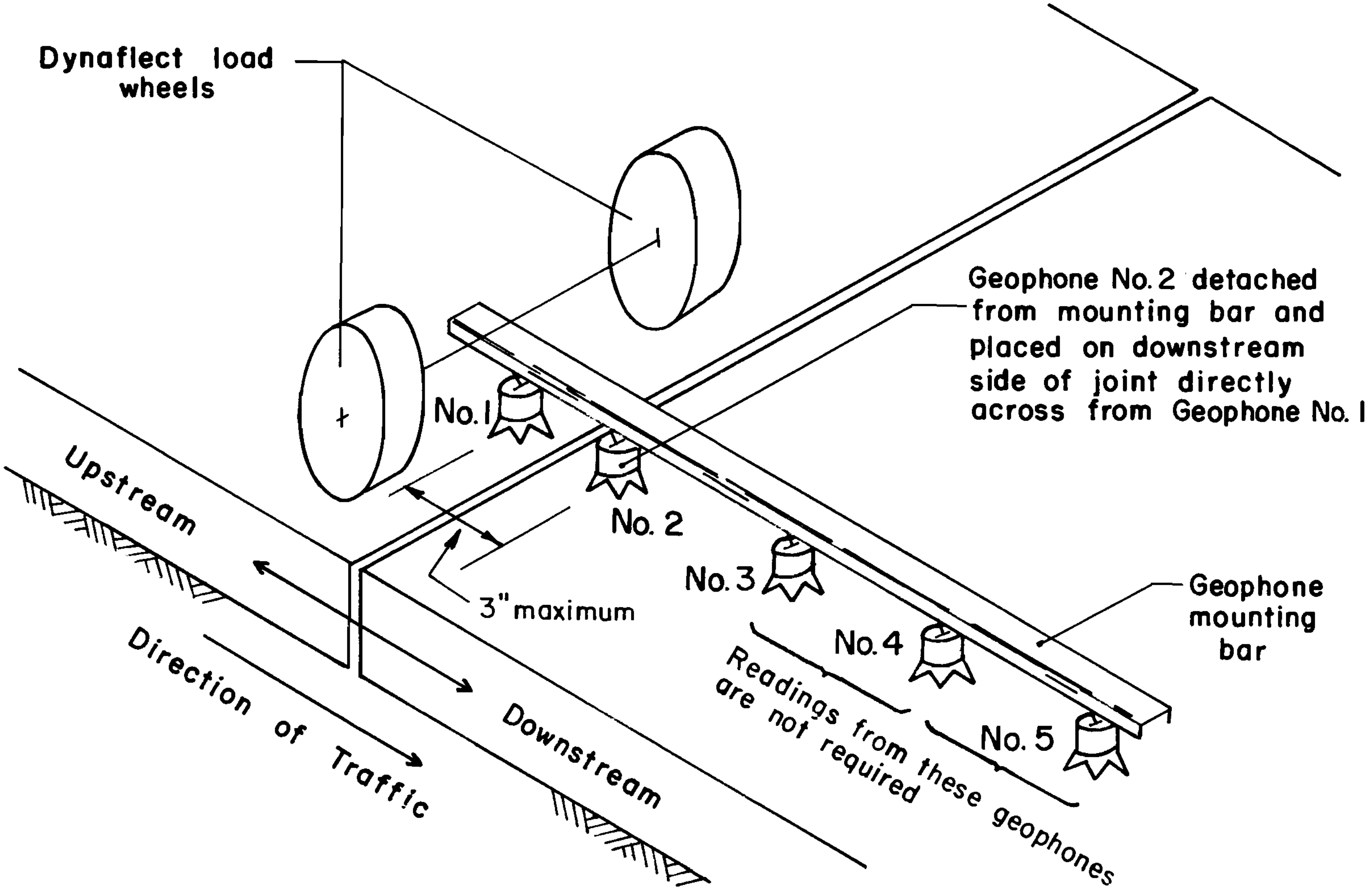


Fig 2.4. Required positioning of Dynaflect load wheels and geophones for load transfer deflection measurements (after Ref 1).

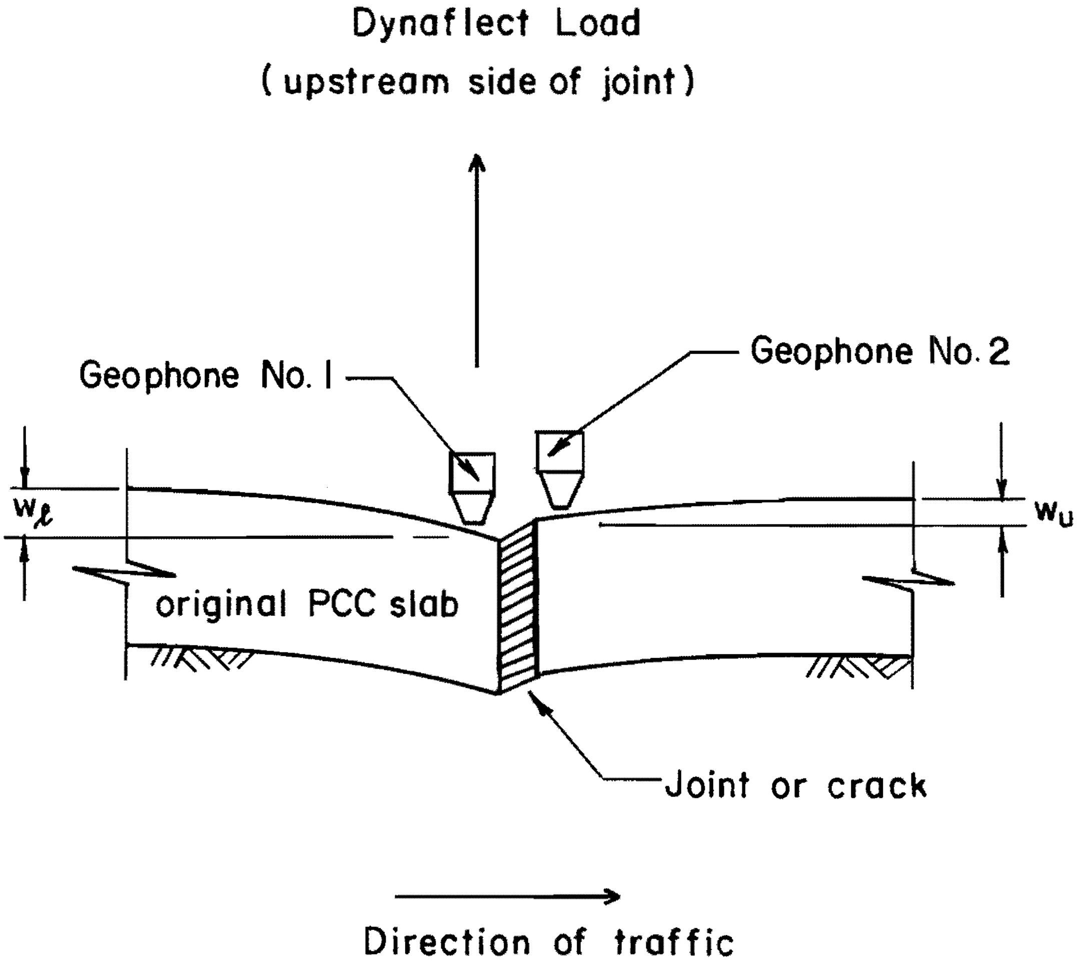


Fig 2.5. Illustration of Dynaflect deflection load and geophone configuration for determining required deflection values (after Ref 1).

$$\gamma_{OV} = 0.7587\ (EDV)^{-0.3022}\ (N_T)^{-0.2703} \qquad (2.12)$$

Next, an expression is developed to obtain the maximum allowable deflection factor, F_w, as a function of the maximum shear strain, γ_{OV}:

$$F_w = 7.123 \times 10^{-3} \cdot \gamma_{OV} \cdot (EDV \cdot THOV + 0.963 \cdot ED2 \cdot TH2) \qquad (2.13)$$

where

EDV = overlay dynamic modulus, psi;

THOV = overlay thickness, inches;

ED2 = intermediate layer dynamic modulus, inches; and

TH2 = intermediate layer thickness, inches.

Both expressions were derived from a theoretical analysis of the shear stress generated in the overlay due to the application of a vertical load on one side of the joint or crack and considering the load transfer along the joint as characterized by the field deflection measurements. Then, the overlay shear strain is determined from the shear stress and related to tensile strain with a relationship derived in the indirect tensile test (Ref 12) that permits the use of the tensile strain fatigue equation mentioned in the Block VIII description. For the theoretical background leading to the development of these formulas, the reader is referred to Reference 1.

In summary, by specifying the design 18-kip ESAL traffic, a critical deflection factor, F_w , based on the above cited equations is computed and published in the output program and this value must not be exceeded by the actual deflection factors of each joint (or crack) obtained from the field deflection measurements for the particular section being designed. Those joints (or cracks) whose deflection factors exceed the maximum deflection factor obtained with ARKRC-2 should be undersealed or subjected to any other measure of rehabilitation before overlay placement so that premature reflection cracking will be avoided.

Block X summarizes the RFLCR output.

INPUT VARIABLES DESCRIPTION AND DATA SELECTION

This section is intended to provide a brief description of input variables for the ARKRC-2 computer program. Typical values for these variables for the prevailing condition in Texas are recommended.

The inputs of the program can be categorized in eight different types: problem description, existing concrete pavement characteristics, existing pavement reinforcement characteristics, existing pavement movement characteristics, asphalt concrete overlay characteristics, intermediate layer characteristics, design traffic, and yearly frequency of minimum temperatures.

Problem Description Input Variables

IPROB defines the number of the problem.

PRODES represents all descriptive information to identify the problem, e.g., project location, date, user's name, etc.

Existing Concrete Pavement Characteristics

PVTYPE identifies the existing pavement type: plain jointed (JCP), jointed reinforced (JRCP), or continuously reinforced (CRCP) concrete pavement.

UC refers to the condition of the existing concrete pavement, cracked (C) or uncracked (U). CRCP should always be considered cracked while jointed pavements should always be considered uncracked unless most of the slabs exhibit transverse cracking (on more than 20 percent of the total area of the pavement cracked).

SPACE defines the spacing between the joints of a jointed pavement or the average spacing between the cracks of a continuously reinforced pavement. This value is in the range of 10 to 60 feet in jointed and 3 to 9 feet in continuously reinforced pavements.

THC is the variable that defines the thickness (in inches) of the concrete slab. Most Texas rigid pavements have slab thicknesses ranging to 10 inches for jointed pavements and 8 inches for the continuously reinforced type.

EC defines the elastic modulus (in psi) of the existing concrete under long-term loading (creep) conditions. This creep modulus is generally significantly lower than an elastic modulus determined under short term or dynbamic loading conditions. Neville (Ref 13) conducted tests that indicate that the elastic modulus under creep conditions is approximately 80 percent of the modulus determined under short term loading conditions for concretes with a compressive strength greater than 3,000 psi. The dynamic modulus is practically determined by the type of coarse aggregate used to prepare the concrete mix. Two types of aggregates have been commonly used in Texas for concrete mixes: crushed limestone and siliceous-calcareous gravel and sand.

Their corresponding dynamic moduli were obtained from a laboratory study (Ref 14) and converted into creep moudli. Since the difference between the creep moduli of the two aggregate mixes does not produce a significant variation in the design solution, an average value of 4.5×10^6 psi is suggested for this variable.

ALFC is the variable that represents the thermal coefficient of the existing concrete (in./in./°F). An average value of 4×10^{-6} in./in./°F is recommended based on Ref 14.

DENSC represents the density or unit weight (in pcf) of the existing concrete so that the effect of the increased overlay overburden on the friction between the base layer and the slab can be accounted for. A recommended value of this parameter for normal weight concrete is 145 pcf.

DS identifies the point on a slab-base friction force versus movement where sliding occurs. This value must be fixed based on the type of base or subbase material underlying the slab. In cases where the subbase or base material is unknown, a conservative value of 0.02 inch can be selected for design purposes. A series of values suggested by Treybig et al (Ref 10) are presented in Table 2.2.

Existing Pavement Reinforcement Characteristics

This category represents the characteristics and properties of the longitudinal reinforcing steel in the existing concrete pavement. These data are required only if the existing pavement is CRCP or if the longitudinal reinforcement is continuous across the joints where the critical concrete movements occur.

TABLE 2.2. MOVEMENT BETWEEN THE CONCRETE SLAB AND UNDERLYING LAYER AT WHICH SLIDING OR A CONSTANT FRICTION FORCE OCCURS

Material	Movement at Sliding, inches
Polyethelene sheeting	0.02
Granular subbase	0.25
Sand	0.05
Sand asphalt	0.02
Plastic soil	0.05

BARD defines the diameter of the longitudinal reinforcing bars (in inches) used in the existing pavement. The standard CRCP cross section used in Texas (8 inches thick) is reinforced with No. 5 bars at 6.25-inch centers.

BARS refers to the average spacing (in inches) between the longitudinal reinforcing bars (6.25 inches).

ES defines the elastic modulus (in psi) of the steel reinforcement. A value of 30×10^6 psi is recommended to be used.

ALFS defines the thermal coefficient of the steel reinforcement. A value of 5×10^{-6} in./in./°F is recommended for use.

SMU is the variable which defines the bonding stress (in psi) between the concrete and steel. A typical value of 500 psi.

Existing Pavement Movement Characteristics

In order to characterize the potential of existing pavement for reflection cracking from the standpoint of the tensile strains generated by the thermally related horizontal movements, it is necessary to measure a series of horizontal movements as a function of air temperature for several joints (or cracks) in the existing PCC pavement. The recommended procedure for doing this is described in detail in the Arkansas Report (Ref 1). The collection of the horizontal movement data for the joints can be made with the sample form provided in Table 2.3. The grid at the bottom can be used to plot the data after they have been recorded. The "best-fit" straight line through the temperature data plotted on the grid must be drawn for all the joints or cracks being analyzed for the pavement section being designed. Those joints or cracks having the highest slope values will have the greatest potential for reflection cracking according to the temperature related horizontal movements.

TABLE 2.3. SAMPLE FORM FOR COLLECTING HORIZONTAL MOVEMENT DATA (AFTER REFERENCE 1)

REFLECTION CRACKING ANALYSIS DATA
HORIZONTAL SLAB MOVEMENTS

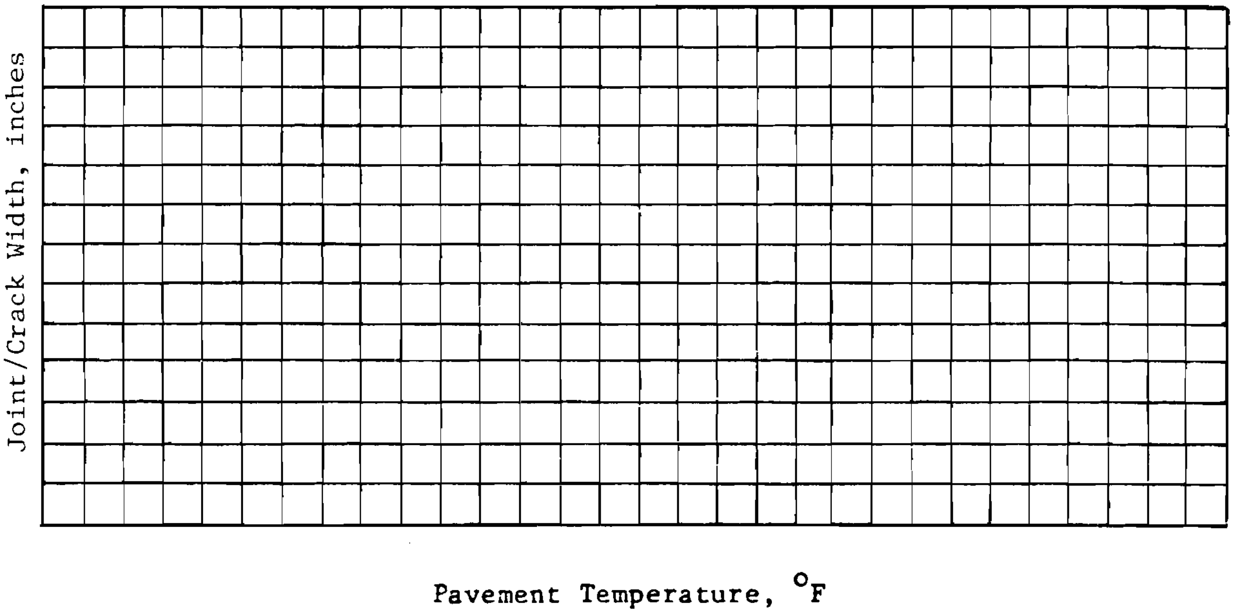
Project: ____________________

Location: ____________________

Joint/crack No. ____________________ Recorder ____________________

Slab Lengths: Upstream side ____________ Downstream side ____________

Measurement Number	Date	Time of Day	Pavement Temperature °F	Joint/Crack Width (inches)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				



One representative joint of the section being designed must be selected and two coordinates defining the "best-fit" line can be used as input data for ARKRC-2. The corresponding input variables of ARKRC-2 to define these two coordinates that characterize horizontal movements are:

TH which represents the temperature axis coordinate (in °F) of the selected point on the best fit line having the higher temperature,

WH which represents the joint (crack) width axis coordinate (in inches) of the best fit line corresponding to the higher temperature,

TL which represents the temperature axis coordinate (in °F) of the selected point on the best fit line having the lower temperature,

WL which represents the joint (crack) width axis coordinate (in inches) of the best fit line corresponding to the lower temperature, and

Tl which is a variable which identifies the minimum temperature that the existing concrete pavement has experienced since its construction. The variation of this variable for conditions in Texas has very little effect on the results of the design procedure; therefore, it is recommended that a value f 0°F be used for all problems.

The restraint coefficient, β (beta) or BP, is a measure of the restraint characteristics of the concrete slab against thermal movements; β is one of the most significant factors in the reflection cracking model used in ARKRC-2 and a variable that will figure indirectly in the equations for Texas. Values of β are computed by ARKRC-2 in terms of TH, WH, TL, and WL from the basic relationship

$$\beta = BP = 1 - \frac{WL - WH}{\alpha \cdot SPC \cdot (TH - TL)} \tag{2.14}$$

where

WL, WH, TH, and TL are as defined above,

α = concrete thermal coefficient, and

SPC = joint or crack spacing in feet,

and are published as a final result in the program output.

Asphalt Concrete Overlay Characteristics

THOV defines the thickness (in inches) of the asphalt concrete overlay. Typical values for this variable range from 1 to 6 inches. Increased overlay thickness is sometimes used as an effective technique to minimize reflection cracking by reducing the shear strains generated. This technique is not recommended due to the availability of more cost effective methods.

EOV is the variable used to define the effective creep modulus of the combined overlay layers. Procedures used to estimate the value of this variable for a Texas environmental design are described in the Arkansas report (Ref 1) in great detail and will not be discussed here. The procedure used in this study to estimate EOV for the design temperatures of the Texas environmental regions used the results of the Ring and Ball Softening Point Test (ASTM D36) and the Standard Penetration Test (ASTM D5). Using the Ring and Ball softening point temperature, TR & B, the penetration value, PEN, and the penetration test temperature, T, with Fig 2.6 the asphalt penetration index, PI, can be obtained. Then, with the design temperature for the given region, T_{DES}, the penetration index and a loading time of 3 hours (10800 seconds), and the Heukelom and Klomp nomograph presented in Fig 2.7, the stiffness modulus of the asphalt bitumen, δ_{ac}, can be determined. Finally, using the aggregate concentration in the mix, c_v, and with the nomograph in Fig 2.8, the stiffness modulus of the bituminous paving mixture, δ_{mix}

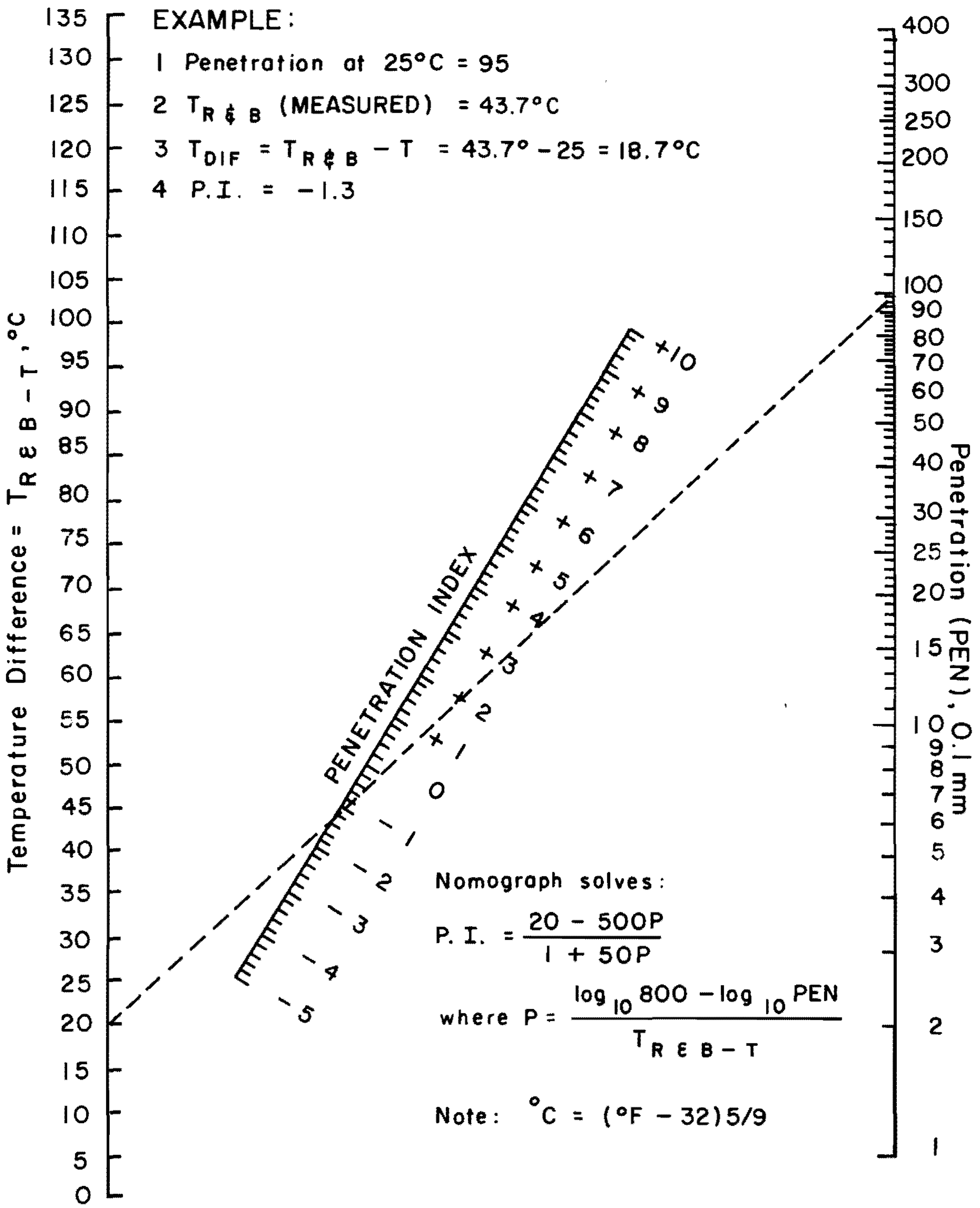


Fig 2.6. Nomograph for determining Pfeiffer and Van Dormaal's Penetration Index (Ref 11).

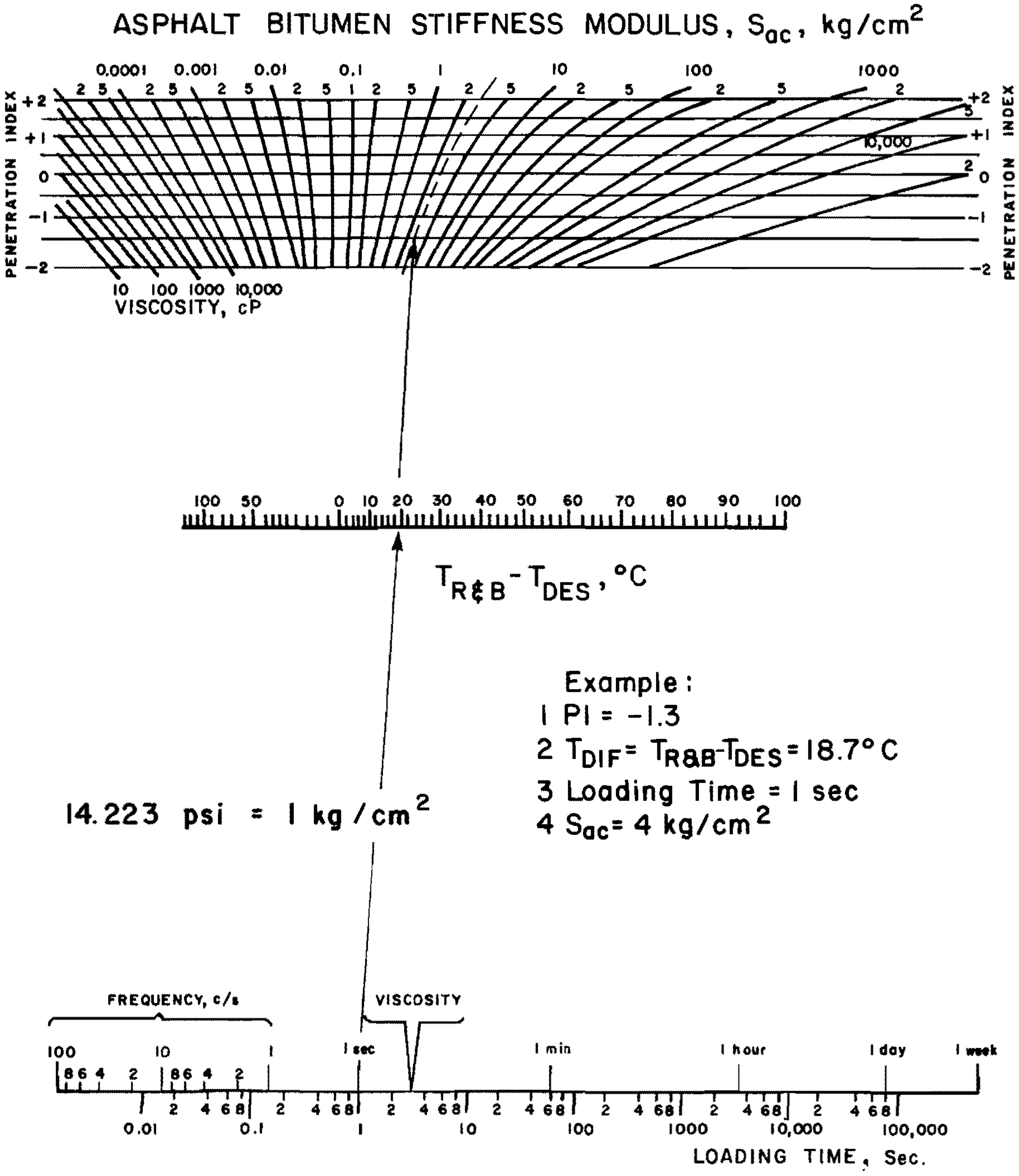


Fig 2.7. Nomograph for predicting the stiffness modulus of asphaltic bitumens (after Heukelom and Klomp) (Ref 11).

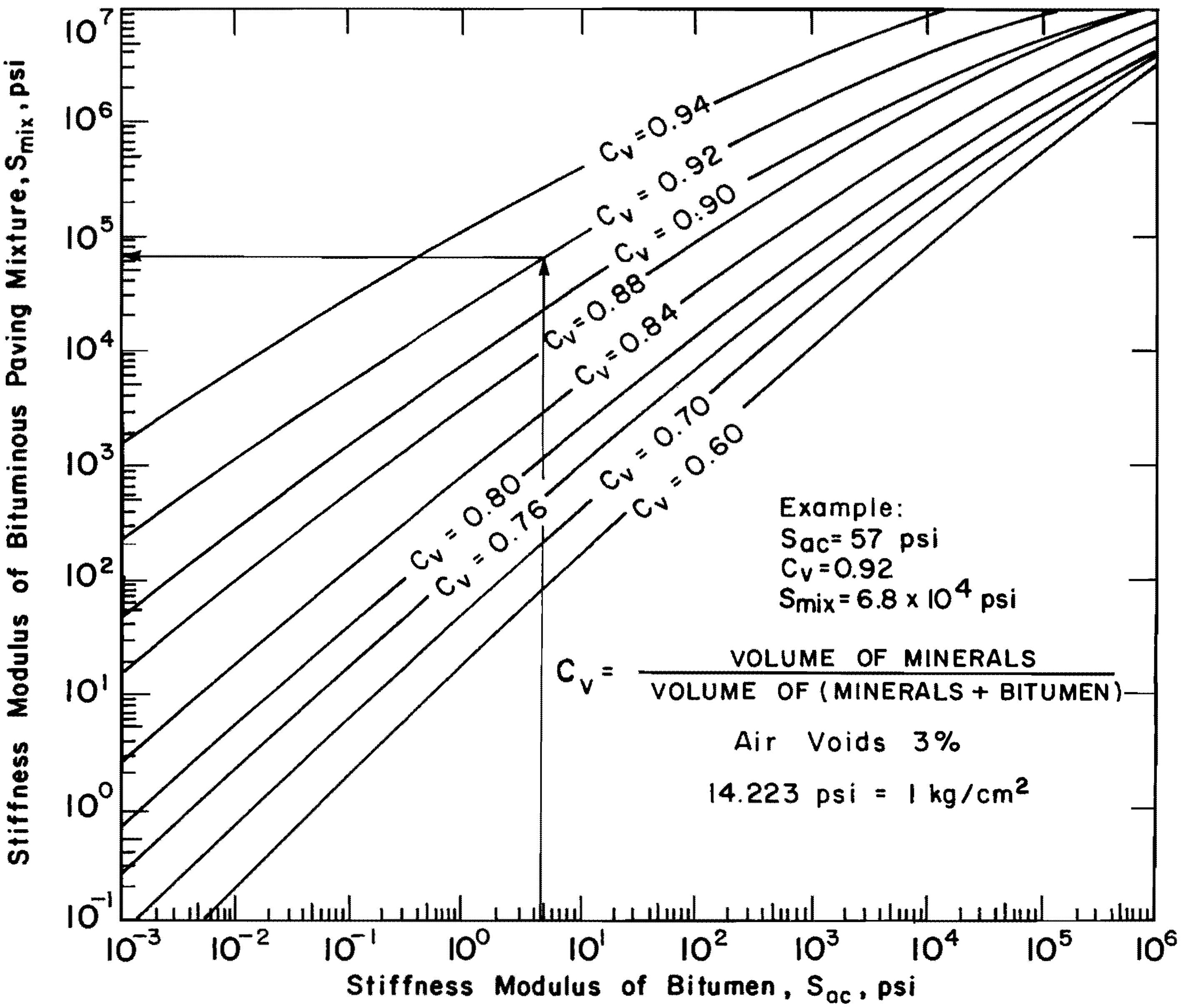


Fig 2.8. Relationships between moduli of stiffness of asphalt cements and paving mixtures containing the same asphalt cements (after Heukelom and Klomp) (Ref 20).

(equivalent to the overlay creep modulus), can be determined. The values of EOV for all Texas climatological regions were developed from the temperature data and the characteristics of asphalt bitumens provided by the Materials and Tests Division of the Texas State Department of Highways and Public Transportation. These values are reported in Chapter 3.

EDV represents the dynamic modulus of the asphalt concrete overlay. EDV can be determined by following the same procedure described above for EOV, and in this study a direct relationship between the two variables was assumed. Characteristic values for EDV for all Texas climatological regions are presented in Chapter 3.

ALFV is the variable that represents the thermal coefficient (in./in./°F) of the asphalt concrete. A value of 14.0×10^{-6} in./in./°F is typical of HMAC mixtures.

DENSOV is the density (in pcf) of the asphalt concrete overlay. A suggested value for this parameter is 140 pcf since the magnitude of this value is not very significant.

OVBS defines the overlay to existing concrete to increase surface bond-slip stress (in psi). If an intermediate or strain-absorbing layer is used, the value of OVBS must be between that of the intermediate layer and the concrete surface. A value of 250 psi was used in this study to represent the current practice in Texas of not making any special preparation of the existing pavement prior to overlay construction to increase bond-slip stress.

BBW is the variable which defines the width (in feet in the longitudinal direction) of a bond breaker placed over the existing joint (or crack) prior to overlay. Strips of the asphlat rubber bond breaker known as SANI up to one foot wide may be used along the joints of the existing pavement. The position of the bond breaker strip in the pavement discontinuity is shown in Fig 2.9.

The role of the bond breaker is to prevent formation of a bond between the overlay and existing concrete surface in the zone of the joints (or cracks) so that the horizontal movements induced in the concrete slab by the temperature drops do not transfer completely in the overlay and produce high tensile stresses in it.

Intermediate Layer Characteristic

One common technique in Arkansas to minimize reflection cracking in overlaid rigid pavements is the use of a cushion course, or intermediate layer between the existing pavement and the overlay, consisting of an open graded course with low asphalt content (approximately 3 percent) and with roughly 98 percent of the aggregate particles in the range of 0.38 to 2.5 inches (68 percent greater than 1.5 inches). ARKRC-2 permits the engineer to analyze the effect that an intermediate layer produces in internally absorbing some of the underlying slab movements.

TH2 is the variable which defines the thickness (in inches) of the intermediate layer. The intermediate layer used in Arkansas can not be less than 3 inches, since some of the aggregate particles are as large as 2.5 inches, and should not be greater than 5 to 6 inches, because of rutting and compaction problems.

E2 defines the creep modulus (in psi) of the intermediate layer. The Arkansas open-graded course has an approximate value of 5,000 psi.

ED2 represents the dynamic modulus (in psi of the intermediate layer. A value of 20,000 psi is recommended for the standard open-graded base course used in Arkansas.

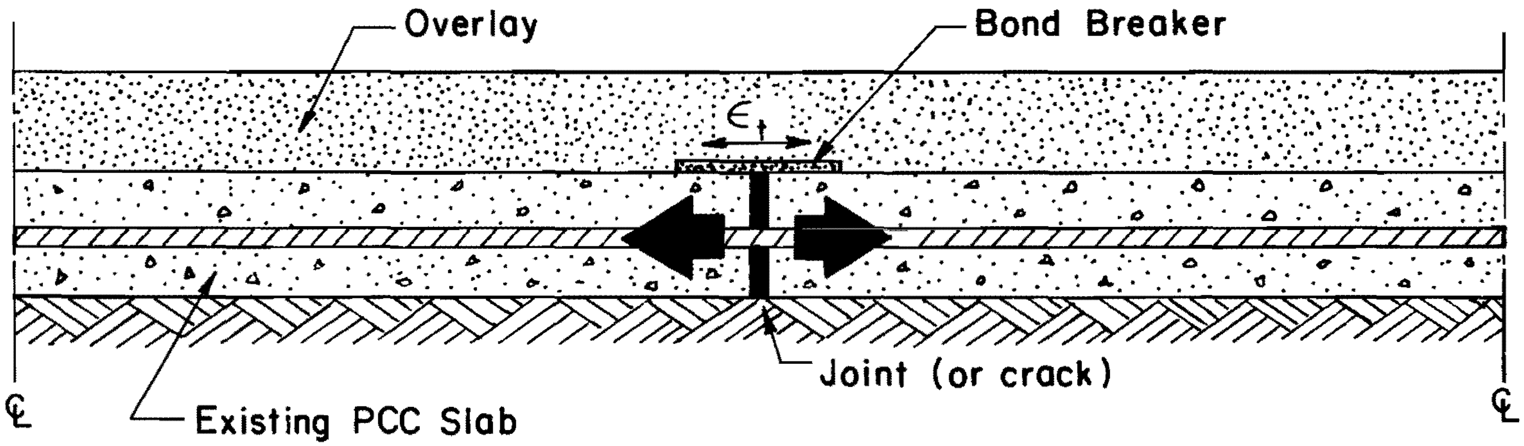


Fig 2.9. Position of bond breaker strip in the pavement discontinuity (after Ref 1).

ALF2 defines the coefficient of thermal expansion for the intermediate layer. A value of 20 x 10^{-6} in./in./°F is recommended for the open-graded course material used in Arkansas.

DENS2 is a variable which defines the density or unit weight (in pcf) of the intermediate layer material. A value of 120 pcf is recommended for the Arkansas open-graded course material.

Design Traffic

DTN18 represents the total number of 18-kip ESAL that are expected in the design lane in the overlay direction for the design period. Based on this value, the program will calculate the maximum allowable shear strain that can be repeated DTN18 times in the overlay before failure is reached, and the corresponding deflection factor. Those joints whose measured deflection factors are higher than the one reported in ARKRC-2 output will not be able to resist DTN18 repetitions of 18-kip ESAL due to deficient load transfer, and thus they should be corrected before overlay placement.

Yearly Frequency of Minimum Temperatures

DAY1 to DAY7 define the number of days in one year that the temperature descends below 50°F in ranges of magnitude from 10°F to 70°F, respectively.

With the temperature data obtained from the National Climatic Center (Ref 7), these variables can be defined for all climatological stations in Texas; based on them the climatological zones can be combined to form composite zones with similar temperature patterns, which is especially useful when the user is trying to develop the design aids with the hand solution procedure. Characteristic values for DAY1 to DAY7 for all climatological regions and composite zones are developed in Chapter 3.

ARKRC-2 OUTPUT DESCRIPTION

Basically the output of the ARKRC-2 computer program consists of two parts: the first is an echo-print of the input data and the second contains the results of the tensile and shear strain analyses.

From the tensile strain analysis, the total number of years that the overlay can be held in service before 50 percent reflection cracking will appear is obtained. This value does not necessarily represent the actual life of the overlay since any other distress mechanism, such as rutting, not considered in the ARKRC-2 model could make the overlay fail sooner.

Another important value reported in the ARKRC-2 program output is the maximum deflection factor, obtained from the shear strain analysis, which if plotted on the graph of field deflection factor (F_w) versus distance along the roadway for the particular section being designed, as shown in Fig 2.10, will permit detection of joints with poor load transfer that can cause premature reflection cracking.

An example of ARKRC-2 output is presented in Appendix A (Figs A.2 and A.3).

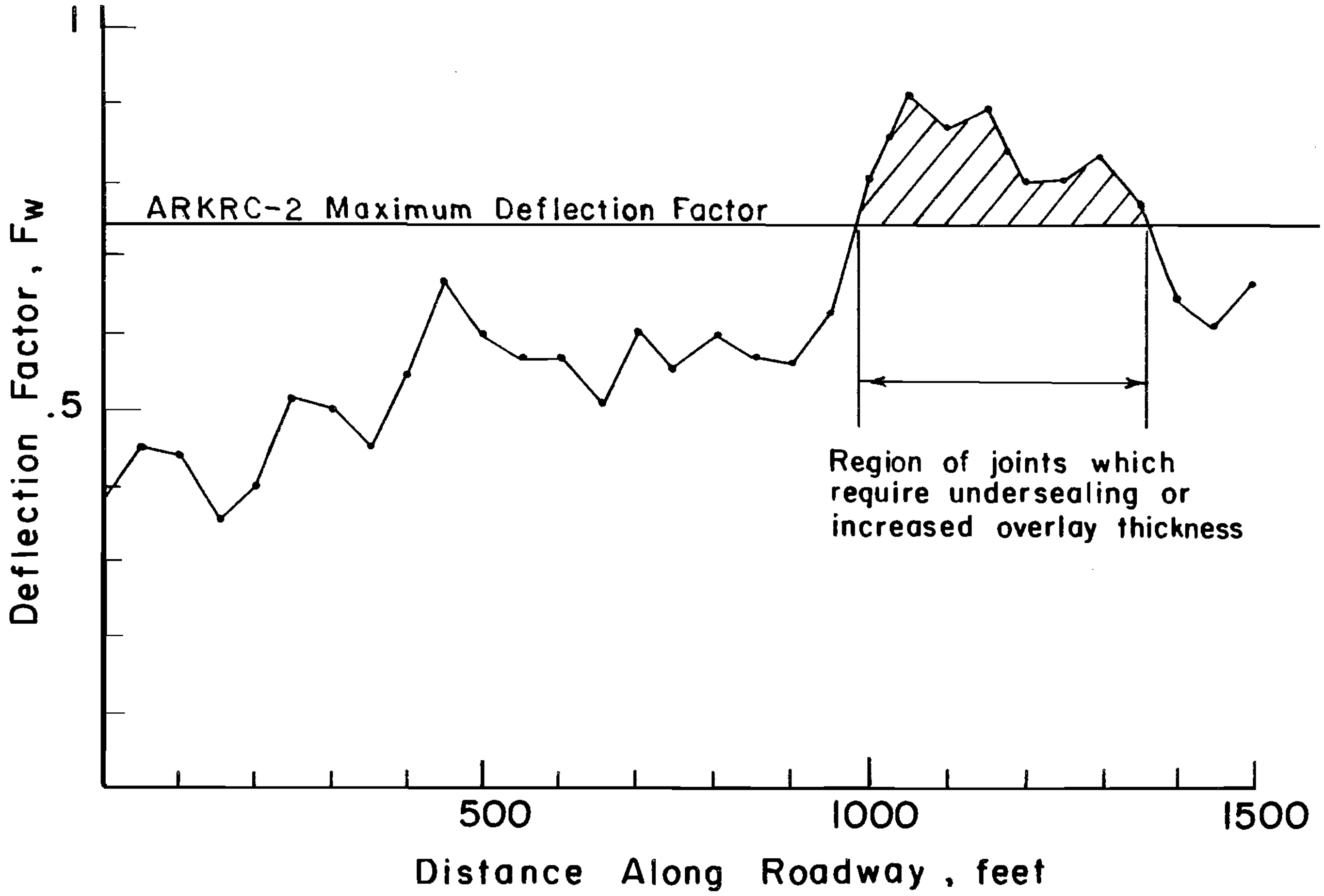


Fig 2.10. Graph of field deflection factors for 50-foot JCP illustrating application of ARKRC-2 maximum deflection factor in detecting joints which will cause premature reflection cracking in the overlay design considered (after Ref 1).

CHAPTER 3. SELECTION OF CONDITIONS FOR EQUATIONS

The development of deterministic equations from the ARKRC-2 model consists of generating observations through computer runs, processing the data, and making a statistical analysis of the data. Therefore, it was necessary from the beginning to define the number of equations and limit the set of conditions under which each equation is applicable.

The number of equations to be developed is determined, basically, by the type of rigid pavements currently in service in Texas and the climatological conditions prevailing in the state in terms of temperature characteristics.

This analysis is intended to cover the basic types of rigid portland cement concrete pavements: jointed (either JCP or JRCP) and continuously reinforced (CRCP).

On the other hand, the state can be divided into zones with similar trends in temperature characteristics. The first part of this chapter deals with the details of dividing the state into composite zones, and the second part refers to the selection of adequate values for the ARKRC-2 input variables, depending on the temperature characteristics of the composite zones.

COMPOSITE CLIMATOLOGICAL ZONES

Data about daily temperature changes were obtained from the National Climatic Center for the weather stations in the climatic regions into which the state is currently divided.

Figure 3.1 is a map of Texas showing the different climatic regions and the locations of the corresponding climatic stations. The criterion used to combine the climatic regions into composite zones with similar temperature characteristics was the magnitude of the difference between 50°F and the minimum temperature registered during each day, for those days with minimum temperatures below 50°F.

From the NCC records of minimum daily temperatures, the difference between 50°F and the minimum temperature recorded, was determined for each day. Then, based upon the magnitude, the day was assigned to a particular temperature drop class. The temperature drop classes selected were: 0-10°F, 11-20°F, 21-30°F, 31-40°F, 41-50°F, 61-70°F, and more than 71°F. After this was completed for each year considered, the average number of days per year for each temperature drop class was determined.

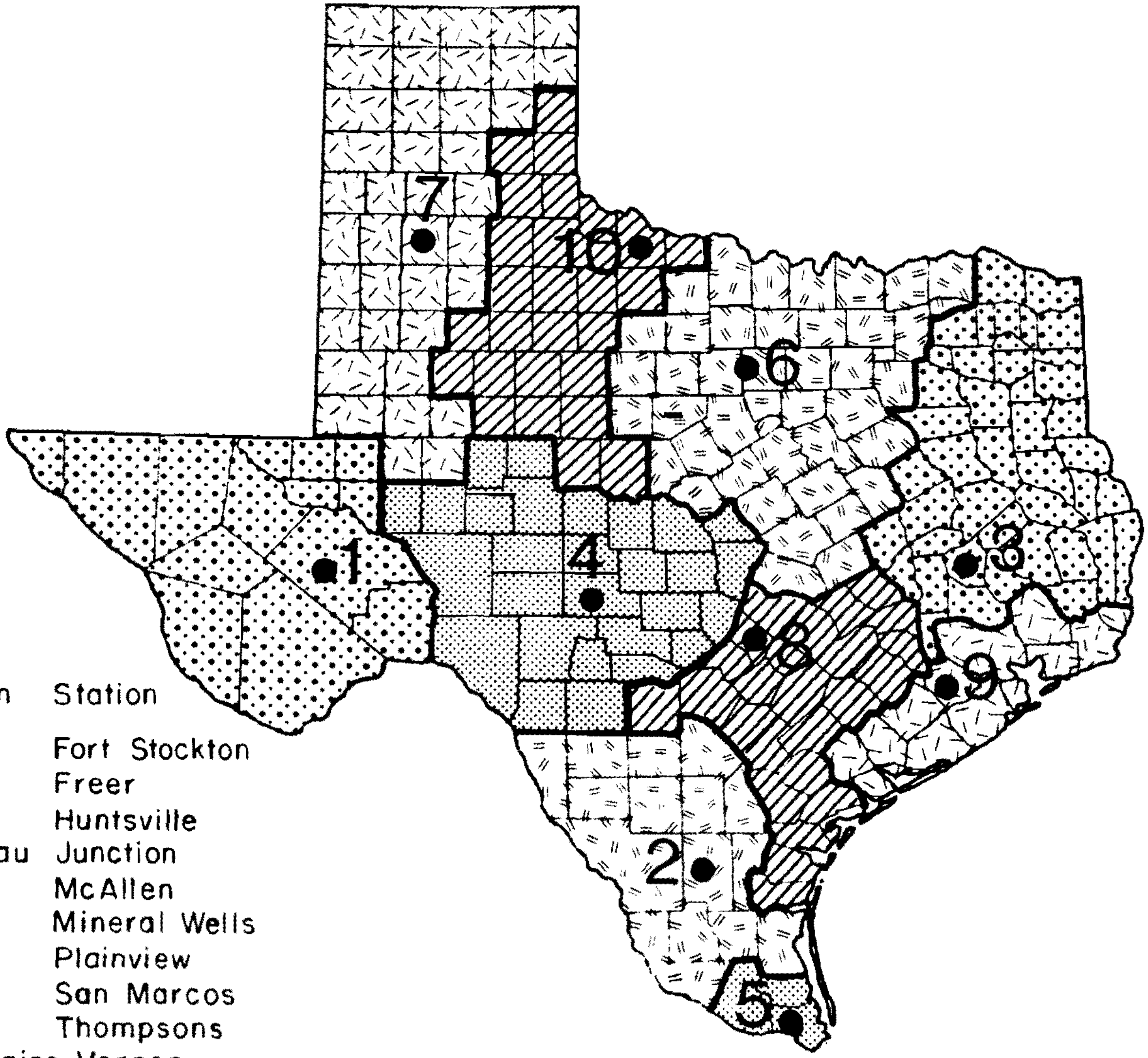
Tables B.1 to B.10 in Appendix B show the frequency distributions for the drop classes of the data for the climatological stations over a period of seven years, 1974 through 1980. Summaries of the complete data set on Texas temperature distributions are presented in Table 3.1.

In order to combine the original climatological regions, a statistical test that provided an appropriate criterion to compare the particular drop classes of the frequency distribution should be selected. A nonparametric test that requires no assumptions concerning the distribution from which the sample is drawn or any specific values of any parameters of that distribution was considered to be appropriate and the Kruskal-Wallis H Test was selected. This test permits testing the hypothesis that two or more independent samples are drawn from the same universe and is often referred to as a nonparametric test of analysis of variance. No assumptions need to be

TABLE 3.1. SUMMARY OF BELOW 50°F DAILY TEMPERATURE DROP DATA FOR CLIMATIC REGIONS IN TEXAS

Climatic Region	Representative Station	Range	Number of Days* 0 - 10	11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	61 - 70	>71
Trans Pecos	Fort Stockton	Average	68	67	45	6	1	0	0	0
		Maximum	83	81	56	10	2	0	0	0
		Minimum	55	57	36	1	0	0	0	0
Southern	Freer	Average	59	34	7	0	0	0	0	0
		Maximum	69	45	11	0	0	0	0	0
		Minimum	46	28	3	0	0	0	0	0
East Texas	Huntsville	Average	60	43	17	2	0	0	0	0
		Maximum	67	48	36	5	0	0	0	0
		Minimum	50	36	9	0	0	0	0	0
Edwards Plateau	Junction	Average	51	51	32	6	1	0	0	0
		Maximum	67	68	40	11	2	0	0	0
		Minimum	31	34	15	0	0	0	0	0
Lower Valley	McAllen	Average	49	17	2	0	0	0	0	0
		Maximum	61	20	6	0	0	0	0	0
		Minimum	35	14	0	0	0	0	0	0
North Central	Mineral Wells	Average	54	49	27	7	1	0	0	0
		Maximum	68	57	42	10	1	0	0	0
		Minimum	9	28	14	4	0	0	0	0
High Plains	Plainview	Average	51	64	49	18	3	0	0	0
		Maximum	66	79	54	31	6	1	0	0
		Minimum	32	40	42	8	1	0	0	0
South Central	San Marcos	Average	60	53	21	3	0	0	0	0
		Maximum	70	60	34	4	0	0	0	0
		Minimum	46	46	14	0	0	0	0	0
Upper Coast	Thompsons	Average	59	35	9	0	0	0	0	0
		Maximum	72	51	13	2	0	0	0	0
		Minimum	41	25	4	0	0	0	0	0
Low Rolling Plains	Vernon	Average	54	52	38	10	2	0	0	0
		Maximum	63	67	53	17	3	1	0	0
		Minimum	46	41	21	4	0	0	0	0

* Below 50°F temperature drop class/°F.



No.	Climatic Region	Station
1	Trans Pecos	Fort Stockton
2	Southern	Freer
3	East Texas	Huntsville
4	Edwards Plateau	Junction
5	Lower Valley	McAllen
6	North Central	Mineral Wells
7	High Plains	Plainview
8	South Central	San Marcos
9	Upper Coast	Thompsons
10	Low Rolling Plains	Vernon

Fig 3.1. Ten climatic regions of Texas (National Climatic Center).

made about the distribution of the populations from which the samples are drawn except that they are continuous.

To make the H test, samples are first arranged by columns; the letter "c" is used to represent the number of columns, which is also the number of samples. The notation n_j represents the number of observations in the j^{th} sample, so the total number of observations is

$$n_1 + n_2 + \ldots + n_j + \ldots + n_c = n \qquad (3.1)$$

Each of the n observations is represented by a rank. A rank value of 1 is assigned to the largest value (if ranked in descending order); a rank value of 2 goes to the second largest value; and so on. The smallest observation is given the rank value equal to that of n. The values can also be ranked in ascending order, and the final outcome of the test will be the same.

The statistic H is computed as follows:

$$H = \frac{12}{n\ (n + 1)} \sum_{j=1}^{c} \frac{R^2 j}{n_j} - 3\ (n + 1) \qquad (3.2)$$

where

n_j = the total number of observations in the j^{th} sample,

n = the total number of observations in all of the samples,

R_j = the sum of the ranks in the j^{th} sample.

The statistic H is chi-square distributed with (c - 1) degrees of freedom when each of the samples contains at least six observations. When any sample is less than six, special tables are needed to interpret H.

The frequency distributions of all climatological regions were compared with each other by computing the statistic H for the corresponding drop classes of the frequency distributions. Computed H values are presented in Table B.11 of Appendix B. The null hypothesis that the frequencies of the drop classes of two different climatological regions follow the same distribution can be accepted if the calculated H parameter is less than the chi-square 3.841 value obtained for 95 percent confidence level. Depending on the number of drop classes for which the null hypothesis is accepted, the conclusion that two climatological regions follow the same temperature behavior can be reached and both regions can be combined to form a composite zone.

After studying the data, Freer and Thompson were combined to conform a composite zone, as were Huntsville and San Marcos, and Junction, Mineral Wells and Vernon; McAllen, Fort Stockton, and Plainview appeared to follow independent temperature patterns.

The, six composite zones obtained were named as follows:

Zone	Combined Region	Station
A	Lower Valley	McAllen
B	Southern-Upper Coast	Freer-Thompsons
C	East Texas-South Central	Huntsville-San Marcos
D	Edwards Plateau-North Central-Low Rolling Plains	Junction-Mineral Wells Vernon
E	Trans Pecos	Fort Stockton
F	High Plains	Plainview

The map in Fig 3.2 shows the final configuration of all composite zones. As a general rule, the limits of the climatological regions were accepted, but the southern section of the South Central Region was separated from the rest of the region and included in Zone B because it seemed logical that all regions located close to the Gulf of Mexico coast have the same climatological behavior pattern.

INPUT VARIABLES DEPENDING ON TEMPERATURE CHARACTERISTICS

Once the composite zones are obtained, the next step consists of assigning adequate values to all those ARKRC-2 input variables whose values depend directly on the different temperature characteristics of each zone.

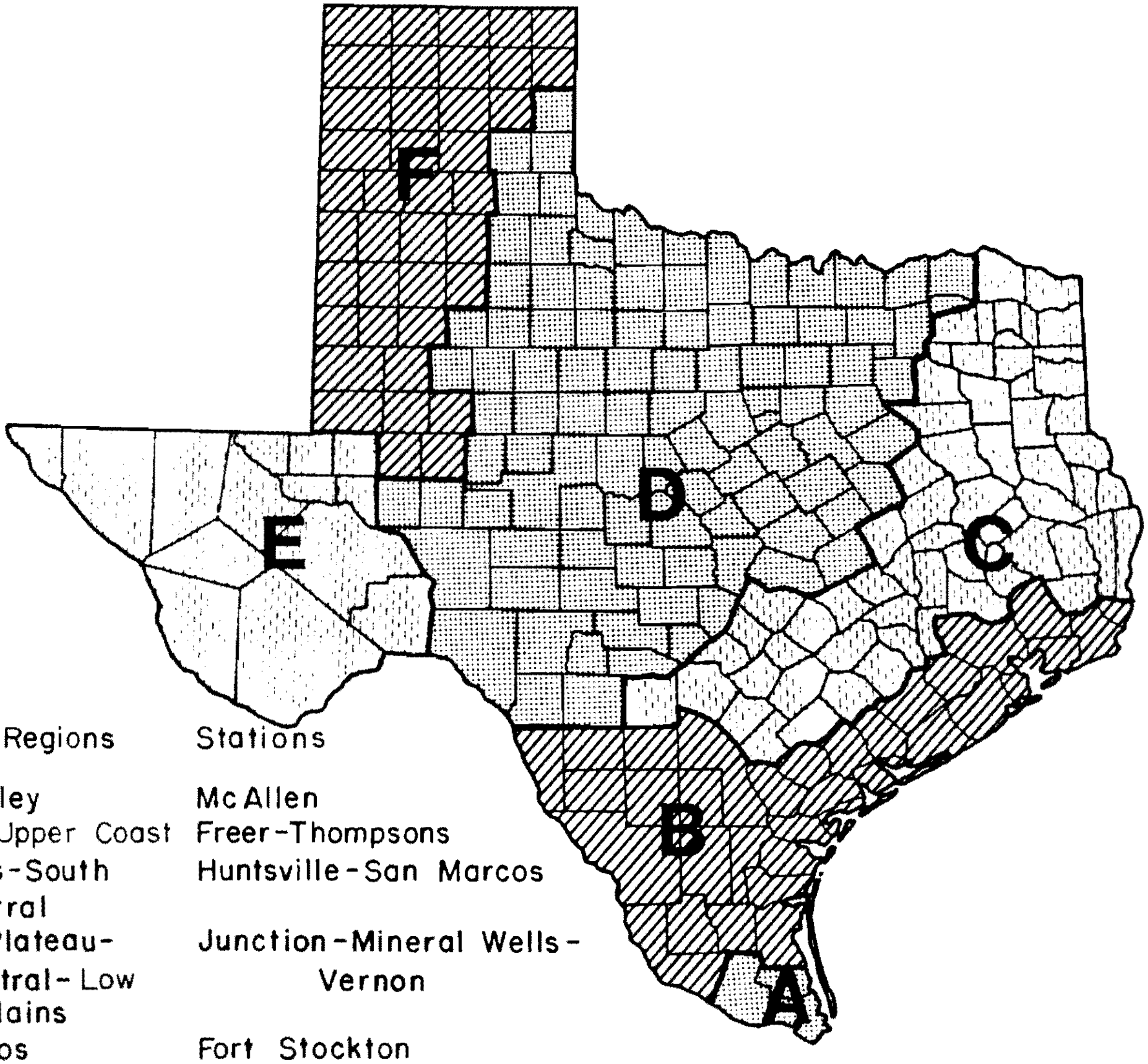
First, the yearly frequencies of minimum temperature must be determined for all climatic regions. This is accomplished in ARKRC-2 through a series of variables, DAY1 to DAY7, previously defined in Chapter 2. The values of these variables correspond to the average frequency distributions of below 50°F temperature drops, cited in Table 3.1.

The frequency distributions for the composite zones were determined by averaging the values of the climatic regions involved and are presented in Table 3.2.

A review of the temperature distributions for each composite zone shows that Zone A has the mildest climate (as far as the development of reflection cracking is concerned), while Zone F has the most severe. Thus, with the selection of Zones B, D, and F for developing the design equations and hand solutions, overlays in Zone A can be conservatively designed using the Zone B equation. Furthermore, overlays for Zones C and E can be designed by

TABLE 3.2. YEARLY FREQUENCY OF MINIMUM TEMPERATURE FOR COMPOSITE ZONES

		Ranges of Minimum Daily Temperature, °F						
Composite Zones	Climatic Regions	49-40 Day 1	39-30 Day 2	29-20 Day 3	19-10 Day 4	9-0 Day 5	-1--11 Day 6	-11--20 Day 7
A	Lower Valley	49	17	2	0	0	0	0
B	Southern - Upper Coast	59	35	8	0	0	0	0
C	East Texas - South Central	60	48	19	3	0	0	0
D	Edwards Plateau - North Central - Low Rolling Plains	53	51	32	8	1	0	0
E	Trans Pecos	68	67	45	6	1	0	0
F	High Plains	61	64	49	18	3	0	0



Zones	Combined Regions	Stations
A	Lower Valley	McAllen
B	Southern-Upper Coast	Freer-Thompsons
C	East Texas-South Central	Huntsville-San Marcos
D	Edwards Plateau-North Central-Low Rolling Plains	Junction-Mineral Wells-Vernon
E	Trans Pecos	Fort Stockton
F	High Plains	Plainview

Fig 3.2. Six composite zones.

interpolating between the results of designs for Zones B and D, and D and F, respectively.

Other input variables depending directly on the temperature characteristics of the composite zones to be analyzed are the overlay effective creep modulus, EOV, and the overlay dynamic modulus, EDV.

EOV was estimated using the Heukelom and Klomp nomographs in Figs 2.6, 2.7, and 2.8, assuming a loading time of 6 hours; a Ring and Ball softening point temperature TR & B of 51.8°C; a penetration index equal to -1; and a volume concentration of aggregate in the overlay mix, C_V , equal to 0.89. The design temperatures necessary in Fig 2.7 to determine asphalt bitumen stiffness modulus for all the climatic regions of the state were calculated averaging the temperatures of the drop classes in the frequency distributions of below 50°F drops. Then, the design temperatures for the selected composite zones were determined by averaging the values of the climatic regions involved. EDV for the composite zones was estimated following the same procedure as for EOV, but a loading time of one second was used. The calculated value for EOV and corresponding values for EDV for all composite zones are shown in Table 3.3.

SUMMARY OF VALUES FOR ARKRC-2 INPUT VARIABLES FOR GENERATING EQUATIONS

A series of selected values for all the input variables needed in the ARKRC-2 computer program and used in this analysis as the basis for the development of the deterministic equations are presented in Table 3.4.

It is important to point out that the applicability of the deterministic equations obtained here and the design aids derived from them is limited to the range of values cited in Table 3.4 selected as typical for the Texas conditions. Other conditions different than these invalidate the results and

TABLE 3.3. RECOMMENDED VALUES FOR OVERLAY EFFECTIVE CREEP MODULUS, EOV, AND OVERLAY DYNAMIC MODULUS, EDV, FOR COMPOSITE ZONES

Composite Zones	EOV (psi)	EDV (psi)
B	15000	300000
D	30000	600000
F	60000	1200000

TABLE 3.4. TYPICAL TEXAS VALUES OF ARKRC-2 INPUT VARIABLES FOR GENERATING THE REGRESSION EQUATIONS

Input Category	Factor	JCP/JRCP	CRCP
1. Problem Description			
2. Existing Concrete Pavement Characteristics	Pavement type	JCP/JRCP	CRCP
	Condition	Uncracked	Cracked
	Joint or crack spacing, ft	From 10 to 60*	From 3 to 9*
	Slab thickness, inches	10	8
	PCC creep modulus, psi	4.5×10^6	4.5×10^6
	PCC thermal coefficient in/in/°F	4.0×10^{-6}	4.0×10^{-6}
	PCC unit weight, pcf	145	145
	Movement at sliding, in	0.02	0.02
3. Existing Pavement Reinforcement Characteristics	Bar diameter, in		0.625
	Bar spacing, in		6.25
	Steel elastic modulus, psi		30×10^{-6}
	Steel thermal coefficient, in/in/°F		5.0×10^{-6}
	Steel concrete bond stress, psi		500
4. Existing Pavement Movement Characteristics	High temperature ("best fit" line), °F	80	80
	Joint or crack width at high temperature, in	0.04	0.04
	Low temperature ("best fit" line), °F	60	60
	Joint or crack width at low temperature, in	From 0.0436 to 0.1048**	From 0.0411 to 0.0497 **
	Minimum temperature observed, °F	0	0
5. Asphalt Concrete Overlay Characteristics	Overlay thickness, in	From 1 to 6	From 1 to 6*
	Overlay creep modulus, psi	From 15000 to 60000***	From 15000 to 60000***
	Overlay dynamic modulus, psi	From 300000 to 1200000***	From 300000 to 1200000***
	Overlay thermal coefficient, in/in/°F	14×10^{-6}	14×10^{-6}
	Overlay unit weight, pcf	140	140
	Overlay bond-slip stress, psi	250	250
	Bond breaker width, ft	From 0 to 1*	From 0 to 1*

(continued)

TABLE 3.4. (CONTINUED)

Input Category	Factor	JCP/JRCP	CRCP
6. Intermediate Layer Characteristics	Intermediate layer thickness, in	From 0 to 6*	From 0 to 6*
	Intermediate layer creep modulus, psi	5000	5000
	Intermediate layer dynamic modulus, psi	20000	20000
	Intermediate layer thermal coefficient, in/in/°F	20×10^{-6}	20×10^{-6}
	Intermediate layer unit weight, pcf	120	120
7. Design Traffic	Total number of 18-kip ESAL	10000000	10000000
8. Yearly Frequency of minimum temperatures	Number days in one year that temperature will descend down 50°F in ranges 0-10°F, 11-20°F; 21-30°F; 31-40°F; 41-50°F; 51-60°F; 61-70°F; and above 71°F	From Table 3.2****	From Table 3.2****

Notes:

*Variables considered as more significant in the model and whose values will be varied through the usual range for the Texas conditions as described in Table above.

**Value forced for the conditions established by the rest of the variables in this category to obtain the desired value of restraint coefficient β (beta) or BP in the analysis, according to relationship described in Chapter 2.

$$BP = \beta = 1 - \frac{WL-WH}{\alpha \ SPC \ (TH-TL)}$$

BP is one of the more significant variables in the model and a range of 0.1 to 0.7 was selected as adequate for Texas conditions.

***Values selected depending on the overlay location according to Table 3.3.

****Values selected depending on the overlay location from Tables 3.2.

a more detailed analysis based on actual runs of ARKRC-2 program must be made.

CHAPTER 4. DEVELOPMENT OF EQUATIONS

The basic methodology of the ARKRC-2 program requires two basic design parameters in the analysis: overlay life and maximum deflection factor. Due to the iterative procedure followed by the ARKRC-2 program to solve for the critical tensile strains in the overlay, it is not possible to derive an equation which can provide an exact solution for overlay life. For this reason, it is necessary to use linear regression analysis to obtain the best fit through a simulated set of observations generated as output from the ARKRC-2 computer program. The final regression equation will provide an approximate solution.

On the other hand, the equations for the overlay tensile strain are deterministic in nature. Therefore, the equations for the other design parameter, maximum deflection factor, can be easily converted into a design chart.

OVERLAY DESIGN LIFE EQUATION

The development of the equations to predict overlay life, based on the tensile strain criteria, occurred in several stages.

Mathematical Model

The selected mathematical model to represent the deterministic relationship between overlay life and a set of significant factors is a log transform of Y_T of the form

$$\begin{aligned} \text{In}\ (Y_T) = {} & a_o + a_1x_1 + a_2x_2 + \ldots. + a_nx_n \\ & + a_{11}x_1x_1 + a_{12}x_1x_2 + \ldots. + a_{1n}x_1x_n \\ & + a_{22}x_2x_2 + a_{23}x_2x_3 + \ldots. + a_{2n}x_2x_n \\ & + a_{33}x_3x_3 + a_{34}x_3x_4 + \ldots. + a_{3n}x_3x_n \\ & \quad \vdots \\ & + a_{nn}x_nx_n \end{aligned}$$

where the x's represent the significant factors (independent variables) and the a's represent the coefficients to each term in the model.

Significant Factors

Among all the factors that affect overlay life, five were considered the most significant and selected as independent variables for jointed concrete pavements as well as for continuously reinforced concrete pavements. These factors were selected by first eliminating those variables whose variation would not be significant given the traffic and environmental conditions prevailing in Texas; and then by determining among the remaining variables through experience and a brief sensitivity analysis, those factors having great influence on overlay life:

(1) joint or crack spacing (SPACE),

(2) restraint coefficient (BP),

(3) overlay thickness (THOV),

(4) intermediate layer thickness (TH2), and

(5) bond breaker width (BBW).

The values for the less significant factors used in developing the JCP/JRCP and CRCP equations were selected based on Table 3.8.

Levels of Significant Factors

In order to generate the necessary observations for the design parameter overlay life, it was decided to vary the five selected significant factors at three levels each while holding the rest of the variables constant. Values were selected to cover the appropriate inference space. The values chosen are listed in Tables 4.1 and 4.2 for JCP/JRCP and CRCP, respectively.

Factorial Experiment and Inference Space

Since five significant factors (or independent variables) were selected for the JCP/JRCP and CRCP equations, the choice of three variational levels results in a full factorial that would require 3^5 or 243 program runs to generate the observations. The full factorial was not considered prohibitive and was selected for the experiment design.

The observations required were generated by running the ARKRC-2 computer program for all treatment combinations.

A summary of the complete set of observations resulting from the experiment, showing values of the design parameter for each combination of values of the five input variables varied was developed.

Since highway pavements, usually, are not designed to last more than 30 years, an inference space of 0.5 to 30 years was selected for screening the observations. Therefore, all the observations that resulted in predicted overlay life, Y_T, outside the selected inference space were removed from the data. The following numbers of remaining observations were obtained for the equations.

TABLE 4.1. LEVELS OF SIGNIFICANT FACTORS FOR DEVELOPING JCP AND JRCP EQUATIONS

Factor	Levels		
	Low	Medium	High
Joint spacing, SPACE (ft)	10.	35.	60.
Restraint coefficient, BP	0.1	0.4	0.7
Overlay thickness, THOV (in)	1.0	3.5	6.0
Intermediate layer thickness, TH2 (in)	0.0	3.0	6.0
Bond breaker width, BBW (ft)	0.0	0.5	1.0

TABLE 4.2. LEVELS OF SIGNIFICANT FACTORS FOR DEVELOPING CRCP EQUATIONS

	Levels		
Factor	Low	Medium	High
Crack spacing, SPACE (ft)	3.	6.	9.
Restraint coefficient, BP	0.1	0.4	0.7
Overlay thickness, THOV (in.)	1.0	3.5	6.0
Intermediate layer thickness, TH2 (in.)	0.0	3.0	6.0
Bond breaker width, BBW (ft)	0.0	0.5	1.0

Description and Results of Regression Analysis

The final choice of regression equations was made using stepwise linear regression computer programs SPSS Multiple Regression (Ref 3) and STEP-01 (Ref 4) with logarithmic transformation of the independent variable to reflect the exponential nature of the relationship. Better fits were obtained using this transformation than using any other tried, with more variance being explained by fewer independent variables and less prediction error for the dependent variable.

Tables 4.3 and 4.4 present the final equations and their characteristics derived from the regression analysis. The equations are designed to predict the natural log of the overlay life in years. The BP (beta) term in the equation is calculated using the observed slab movement, ΔC , over a range in temperature, ΔT , for a given joint or crack spacing, SPACE:

$$BP = 1 - \left[\frac{\Delta C/\Delta T}{6 \times 10^{-5} \times \text{SPACE}} \right]$$

A descriptive analysis of predicting accuracy of the regression equations is accomplished in Chapter 5.

Development of Design Chart

Due to the large number of terms involved in the final equations, it is not possible from a practical standpoint to develop nomographs for the six regression equations presented before. Thus, a series of design charts for specific values of bond breaker width selected to cover the range of

TABLE 4.3. REGRESSION EQUATIONS FOR JCP/JRCP

Dependent Variable	Term	Regression Coefficients		
		Zone B	Zone D	Zone F
Ln YT	Intercept	-2.6518288	-3.558694	-4.2469051
	SPACE	-0.15068453	-0.14551861	-0.1274655
	BP		1.4841551	1.3934734
	THOV	1.0628898	1.1512555	1.1967011
	BBW	10.839022	7.5309911	6.5697628
	TH2	1.2560671	1.6109489	1.8542028
	SPACE^2	0.0012069795	0.0010009874	0.00081692389
	SPACE•THOV	0.0020575505	0.0037453337	0.0040482578
	SPACE•BBW	-0.045756019	-0.025025247	-0.019591045
	SPACE•TH2		0.0022492858	0.0026843367
	BP^2	3.906002	3.178171	2.648167
	BP•BBW	3.0753712	1.1599796	0.90104467
	BP•THOV		-0.18072486	-0.06910158
	BP•TH2	0.16567187		
	THOV^2	-0.083157911	-0.090956836	-0.093896821
	THOV•BBW	-0.44108087	-0.33870111	-0.34185849
	THOV•TH2	0.343447097	0.0214088	
	BBW^2	-3.7610864	-2.2642428	-2.0119935
	TH2^2	-0.1053074	-0.15693917	-0.18729504
R^2		0.935	0.9418	0.9614
Standard Error		0.3369	0.3183	0.2585

TABLE 4.4. REGRESSION EQUATIONS FOR CRCP

Dependent Variable	Term	Regression Coefficients Zone B	Zone D	Zone F
Ln YT	Intercept	-1.0944111	-0.07198865	-0.91919414
	SPACE	-.60871905	-0.66388592	-0.58880267
	BP	1.2585862		0.94392586
	THOV	1.178346	0.70092127	0.7584288
	BBW		9.5869787	7.8300849
	TH2	1.127672	1.040688	1.3347342
	SPACE^2	0.026084694	0.025891317	0.019020192
	SPACE•BP		0.18644098	0.12908939
	SPACE•THOV			0.010380231
	SPACE•BBW	1.2650961	-0.19797695	-0.11949454
	SPACE•TH2		0.0098708534	0.019891676
	BP^2	2.2405340	2.0610882	1.4820345
	BP•THOV	0.10935394	0.10491195	
	BP•TH2	0.10951431		-0.10628485
	BP•BBW		1.6435695	0.97321618
	THOV^2	-0.093027621	-0.043266204	-0.0516222
	THOV•BBW	-0.91399002	-0.42160225	-0.44296164
	THOV•TH2	0.05661395	0.069249790	0.013831238
	BBW^2		-2.6720834	-2.2693593
	BBW•TH2	-0.95836688	0.29313124	
	TH2^2	-0.74335245	-0.09044584	-0.1315603
R^2		0.9945	0.9712	0.9726
Standard Error		0.1085	0.2233	0.2144

practical values that this variable may take were developed and are presented in Appendix D.

The design charts derived are affected by the type of safety factor whose development is outlined in Chapter 5.

OVERLAY SHEAR STRAIN EQUATIONS

As described in Chapter 2, ARKRC-2 uses a model that determines the maximum shear strain, γ_{OV} , to which the overlay can be subjected to resist N_T repetitions of the 18-kip equivalent single axle load producing that maximum shear strain. The fatigue relationship that ARKRC-2 uses is deterministic and can be expressed as follows:

$$\gamma_{OV} = 0.7587 \cdot EDV^{-0.3022} \cdot DTN18^{-0.02703}$$

where

EDV = overlay dynamic modulus, psi,
DTN18 = design 18-kip equivalent single axle load applications.

The maximum allowable deflection factor, F_w, corresponding to that maximum shear strain, γ_{OV} , can be obtained through another deterministic expression:

$$F_w = 7.123 \times 10^{-3} \cdot \gamma_{OV} \cdot (EDV \cdot THOV + 0.963 \cdot ED2 \cdot TH2)$$

where

THOV = overlay thickness, inches,

ED2 = intermediate layer dynamic modulus, psi, and

TH2 = intermediate layer thickness, inches.

Both equations assume that Poisson's ratio for the overlay material is 0.30 and for the intermediate layer is 0.35.

Development of Design Charts

From the above two equations the design chart shown in Fig 6.15 was developed. The term in the second equation involving the intermediate layer characteristics resulted insignificant for the standard Arkansas mix open-graded base course properties and was eliminated from the design chart.

From the chart, the user should be able to estimate the maximum allowable deflection factor (F_w) to use for detecting those joints with poor load transfer that can cause premature reflection cracking.

CHAPTER 5. ACCURACY ANALYSIS

ACCURACY OF PREDICTION

The objective of this chapter is to analyze the accuracy of the regression equations and design charts as predictors of ARKRC-2 output and ensure that predictions are within design tolerances.

The statistical characteristics derived from the regression analysis that directly indicate the goodness of fit are summarized in Table 5.1. All the equations have relatively high coefficients of determination ($R^2 > 0.93$) and small standard error for residuals (less than 0.34), thus permitting assume good accuracy of prediction.

The residuals or the errors involved in the prediction of the natural log of overlay life can be considered independent and normally distributed about the line of regression. By selecting a series of confidence levels (90, 80, and 70) a brief analysis can be performed on the first regression equation that involves the higher standard error for residuals, to interpret the statistics and get a more realistic feeling of the accuracy of prediction:

Standard error for residuals $= \sigma_E = 0.3369$

$$\left.\begin{aligned} Z_{90} &= 1.64 \\ Z_{80} &= 1.28 \\ Z_{70} &= 1.04 \end{aligned}\right\} \text{two-tail values}$$

The limiting value of error in the prediction of the natural log of the overlay life in years for the confidence intervals assumed above are

TABLE 5.1. SUMMARY STATISTICS FROM REGRESSION ANALYSIS

Statistical Characteristics	Summary Statistics					
	JCP/JRCP-B	JCP/JRCP-D	JCP/JRCP-F	CRCP-B	CPCP-D	CRCP-F
Mean of overlay life (Y_T) computed from ARKRC-2 (Years).	7.715	8.677	8.624	7.705	10.677	9.812
Standard deviation of overlay life (σ_{YT}) computed from ARKRC-2 (Years).	7.652	8.375	8.262	7.251	9.183	8.720
Mean of predicted overlay life ($\hat{Y}_T$) from regression equations (Years).	7.495	8.470	8.617	7.793	10.783	9.874
Standard deviation of predicted overlay life ($\sigma_{\hat{Y}T}$) from regression equations (Years).	7.390	8.390	8.716	7.674	10.033	9.314
Degrees of freedom	64	81	96	23	47	71
R^2	0.935	0.9418	0.9614	0.9945	0.9712	0.9726
Standard error for residuals (σE)	0.3369	0.3183	0.2585	0.1085	0.2233	0.2144

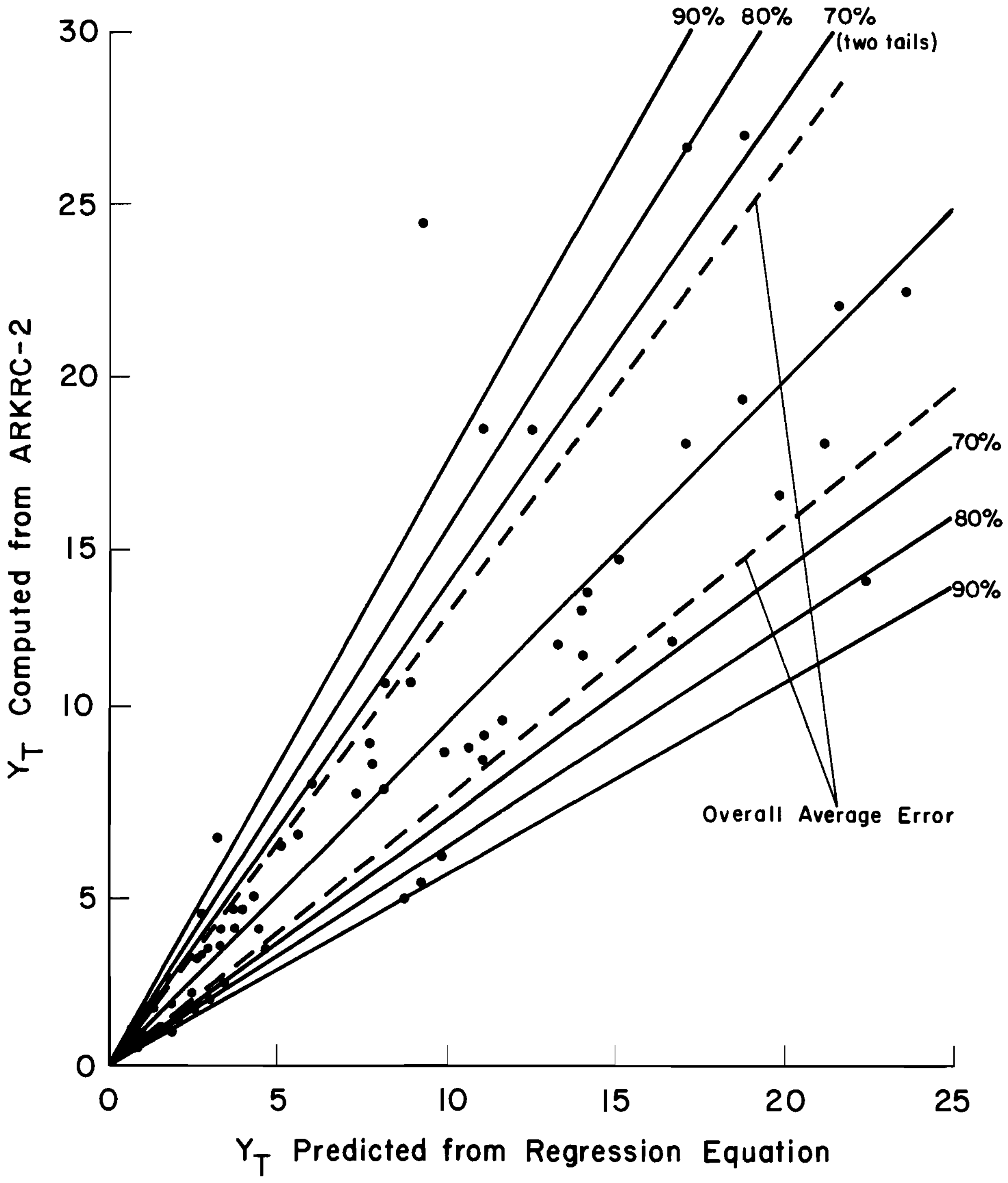


Fig 5.1. Ranges of prediction for different confidence levels for the JCP/JRCP-B regression equation.

$$E = \mu \pm Z_\alpha \sigma_E$$

$$E = 0 \pm Z_\alpha (0.3369)$$

where the error in terms of the natural log of overlay life in years can be expressed, by definition, as

$$\text{Ln } \hat{Y}_T - \text{Ln } Y_T = \pm E$$

where

$\hat{Y}_T$ = predicted value of overlay life, in years, and

Y_T = assumed real value of overlay life from ARKRC-2, in years.

Therefore

$$\text{Ln } \hat{Y}_T - \text{Ln } Y_T = \text{Ln } (\hat{Y}_T/Y_T) = \pm E = \pm Z_\alpha (0.3369)$$

$$\text{Ln } (\hat{Y}_T/Y_T) = \pm Z_\alpha (0.3369)$$

$$\hat{Y}_T/Y_T = e^{\pm Z_\alpha (0.3369)}$$

which for different confidence levels, α , results in the following values:

α, %	Z_α	$e^{+ Z_\alpha (0.3369)}$	$e^{- Z_\alpha (0.3369)}$
90	1.64	1.7376	0.5755
80	1.28	1.5392	0.6497
70	1.04	1.4196	0.7044

This means that for 90 percent of the predictions, the predicted value will fall between the range limited by $1.74Y_T$ and $0.58Y_T$; 80 percent of the predictions will fall between $1.54Y_T$ and $0.65Y_T$; and 70 percent of the predictions will fall between $1.42Y_T$ and $0.71Y_T$, which implies a maximum error of less than 42 percent.

Therefore, selecting a real value obtained from ARKRC-2 in the mean of the inference space fixed for the regression equations or a value of overlay life equal to 15 years, the regression equation will provide a predicted value that for 90 percent confidence level will fall between 26.10 years and 8.70 years. For an 80 percent confidence level the predicted value will fall between 23.1 year and 9.75 years and for a 70 percent confidence level the predicted value will fall between 21.3 years and 10.5 years.

Following the same analysis for the rest of the equations gives the values in Table 5.2.

Also, under the same assumption, that the residuals or errors are independent and normally distributed about the line of regression, the overall average percent error can be computed. This statistic is presented in Table 5.3 for all regression equations.

In other words, although all equations have relatively high coefficients of determination, their accuracy of prediction is somewhat less than may be apparent. Basically, the maximum error is about 50 percent for the least accurate JCP/JRCP-B equation for an 80 percent confidence level, which means that if ARKRC-2 predicts an overlay life of 15 years, by using the appropriate regression equation, the predicted value will be off by no more than 7 years (80 percent of the time). The JCP/JRCP-D and JCP/JRCP-F equations have approximately the same level of accuracy as the JCP/JRCP-B

TABLE 5.2. ACCURACY RANGES OF PREDICTION FOR REGRESSION EQUATION

Statistical Characteristics		Summary Statistics					
		JCP/JRCP-B	JCP/JRCP-D	JCP/JRCP-F	CRCP-B	CRCP-D	CRCP-F
Standard error for residuals (σ_E)		0.3369	0.3183	0.2585	0.1085	0.2233	0.2144
Confidence Interval	Accuracy Ranges of Prediction						
α = 90	$e^{+ Z\alpha (\sigma_E)}$	1.74	1.69	1.53	1.19	1.44	1.42
	$e^{- Z\alpha (\sigma_E)}$	0.58	0.59	0.65	0.84	0.69	0.70
α = 80	$e^{+ Z\alpha (\sigma_E)}$	1.54	1.50	1.39	1.15	1.33	1.32
	$e^{- Z\alpha (\sigma_E)}$	0.65	0.67	0.72	0.87	0.75	0.76
α = 70	$e^{+ Z\alpha (\sigma_E)}$	1.42	1.39	1.31	0.12	1.26	1.25
	$e^{- Z\alpha (\sigma_E)}$	0.70	0.72	0.76	0.89	0.79	0.80
Assuming a real value as obtained from ARKRC-2 in the mean of the inference space (Years).		15	15	15	15	15	15
α = 90	Superior limit (Years)	26.06	25.28	22.92	17.92	21.63	21.32
	Inferior limit (Years)	8.63	8.90	9.82	12.56	10.40	10.55
α = 80	Superior limit (Years)	23.09	22.59	20.88	17.24	19.96	19.74
	Inferior limit (Years)	9.75	9.98	10.77	13.05	11.27	11.40
α = 70	Superior limit (Years)	21.29	20.69	19.63	16.79	10.92	18.75
	Inferior limit (Years)	10.57	10.77	11.46	13.40	11.89	12.00

TABLE 5.3. OVERALL AVERAGE PERCENT ERROR FOR REGRESSION EQUATIONS

Equation	σ_E	Average Percent Error
JCP/JRCP-B	0.3360	31
JCP/JRCP-D	0.3183	29
JCP/JRCP-F	0.2585	23
CRCP-B	0.1085	9
CRCP-D	0.2233	20
CRCP-F	0.2144	19

equation, whereas the most accurate CRCP-B equation will be off by no more than 2 years. Finally, the CRCP-D and CRCP-F equations will result in maximum errors of 4 years (for an 80 percent confidence level).

On the other hand, based on Table 5.3, it can be seen that the entire universe of predictions will be off on the average by 31 percent for the JCP/JRCP-B regression equation which is the least accurate, whereas for the most accurate CRCP-B equation predictions will have an average error of 9 percent.

Figure 5.1 shows a series of Y_T (Y_T computed from ARKRC-2) versus ($\hat{Y}_T$ predicted as obtained from corresponding regression equation) points plotted for the JCP/JRCP-B regression equation. The line of equality is drawn and also the lines corresponding to a 90 percent confidence level (5 percent each tail), 80, 70, and the overall average error. Plots for the rest of the equations are included in Appendix C and can be analyzed as graphical evidence of the predicting accuracy of the regression equations.

DEVELOPMENT OF SAFETY FACTORS

Based on the statistical principles used to analyze the accuracy of the regression equations, a form of safety factor may be developed for each equation. Thus, the design values of overlay life obtained from the modified regression equations will be conservative the selected percentage of the time.

The fundamental assumption that residuals or prediction errors are independent and normally distributed about the line of regression will be set up here again, but now the one-tail Z values corresponding to 90, 80, and 70 percent confidence levels will be utilized.

Therefore,

$$\left.\begin{array}{lcl} Z_{90} \text{ percent} & = & 1.28 \\ Z_{80} \text{ percent} & = & 0.84 \\ Z_{70} \text{ percent} & = & 0.52 \end{array}\right\} \quad \text{one-tail values}$$

And,

$$\text{Ln } \hat{Y}_T - \text{Yn } Y_T = + E = + Z_\alpha \sigma_E$$

$$\text{Ln } (\hat{Y}_T / Y_T) = +Z_\alpha \sigma_E$$

$$Y_T / \hat{Y}_T = e^{-Z_\alpha \sigma_E}$$

where $\hat{Y}_T$, Y_T , and σ_E are as defined before.

Then, $Y_T / \hat{Y}_T$ values were calculated from this relationship for the confidence levels selected and for all regression equations. The values are shown in Table 5.4.

As can be seen in Table 5.4, safety factors for a 90 percent confidence level seem to be too rigorous, whereas the less severe factors corresponding to 80 and 70 look quite appropriate. Selecting the factors for an 80 percent confidence level, the maximum reduction is about 25 percent for the least accurate JCP/JRCP-B regression equation. Thus, the predicted values $\hat{Y}_T$ obtained from the regression equations and reduced by the corresponding safety factors ($\hat{Y}_T$*) will be conservative 80 percent of the time ($\hat{Y}_T^* < Y_T$).

Figure 5.2 presents a plot of a series of Y_T values computed from ARKRC-2 (Y_T) versus their corresponding $\hat{Y}_T$ values (Y_T predicted) (zero error in the prediction) and also the line representing an 80 percent confidence level, i.e., with a slope equal to 0.75. As predicted, only 20 percent of the plotted points in this graph fall below this line.

TABLE 5.4. $Y_T/\hat{Y}_T$ VALUES FOR REGRESSION EQUATIONS

Regression Equation	σ_E	$Y_T/\hat{Y}_T = e^{-Z_\alpha \sigma_E}$		
		σ = 90 %	σ = 80 %	σ = 70 %
JCP/JRCP-B	0.3369	0.65	0.75	0.84
JCP/JRCP-D	0.3183	0.67	0.77	0.85
JCP/JRCP-F	0.2585	0.72	0.80	0.87
CRCP-B	0.1085	0.87	0.91	0.95
CRCP-D	0.2233	0.75	0.83	0.89
CRCP-F	0.2144	0.76	0.84	0.90

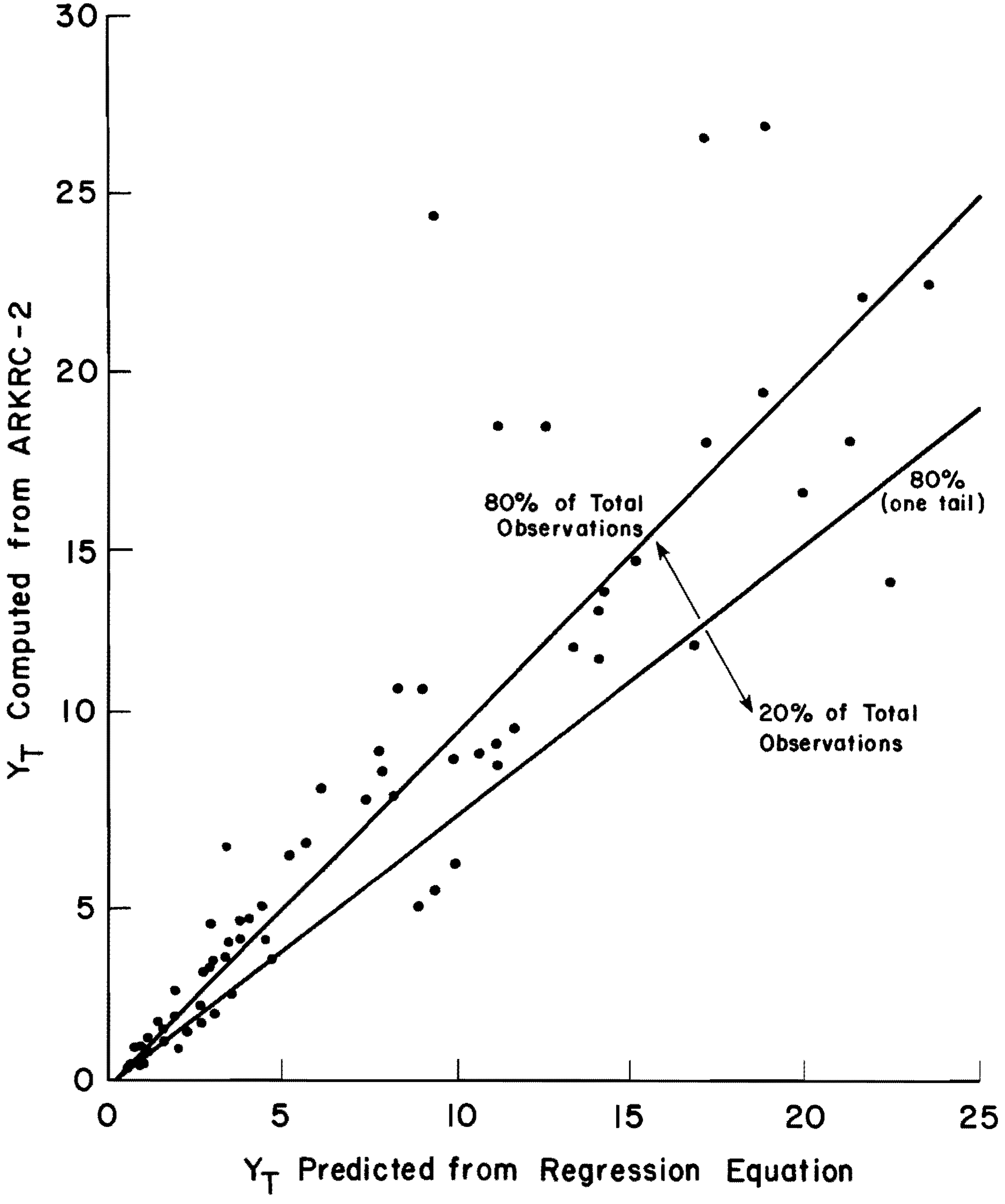


Fig 5.2. Effect of safety factor on predicted values for the JCP/JRCP-B regression equation.

CHARTS COMPARED TO REGRESSION EQUATIONS

In this section, values for the design parameter (overlay life) obtained from the charts for some of the combinations of the independent variables are compared with values from the regression equations.

A set of test data consisting of 25 different combinations of the independent variables was prepared from each design chart, resulting in a total of 225 observations. Values for the design parameter (overlay life) corresponding to each of the 225 combinations were then computed from the corresponding regression equations. The statistics derived from comparing the design parameter obtained from the charts ($\hat{Y}_{T1}$) with the corresponding values from the regression equations ($\hat{Y}_{T2}$) are summarized in Table 5.5.

As shown in Table 5.5, the percent error involved in the predictions on the average ranges from 10 to 23. The loss of accuracy due to the use of the charts instead of the regression equations can be said to be irrelevant when the variation and uncertainty of the input used are considered.

Putting together all the errors involved in the prediction from the JCP/JRCP-B (BBW = 1) design chart, when ARKRC-2 predicted 15 years in overlay life, the design chart on the average would be predicting, on the non-conservative side:

$$\hat{Y}_T = (15)\ (1.3)\ (0.75)\ (1.20) = 17.6 \text{ years}$$

TABLE 5.5. COMPARISON OF RESULTS OF THE DESIGN PARAMETER VALUE (OVERLAY LIFE) AS OBTAINED FROM CHARTS AND REGRESSION EQUATIONS

Design Chart		Degrees of Freedom (DF)	$\sqrt{\frac{\Sigma\left(\frac{\hat{Y}_{T1}}{\hat{Y}_{T2}} - 1\right)^2}{DF}}$	Average Percent Error
JCP/JRCP-B	BBW = 0	22	0.18	15
	BBW = 1	20	0.23	20
JCP/JRCP-D	BBW = 0	19	0.16	14
	BBW = 1	16	0.24	21
JCP/JRCP-F	BBW = 0	21	0.17	15
	BBW = 1	17	0.12	10
CRCP-B	BBW = 0	22	0.14	12
CRCP-D	BBW = 0	20	0.16	14
CRCP-F	BBW = 0	18	0.26	23

where

1.3 = predicting error associated with regression equation,

0.75 = safety factor, and

1.20 = predicting error associated with design chart.

or a total 18 percent error.

SUMMARY

The predicting accuracy of the regression equations, the development of appropriate safety factors and a brief evaluation of the error involved in the design charts are discussed in this chapter. In general, the regression equations are adequate predictors of the ARKRC-2 computer model. The least accurate regression equation will be off on the average by 31 percent whereas for the most accurate the average error is about 9 percent. Appropriate safety factors were developed based on an 80 percent confidence level. The error introduced in the design parameter overlay life when obtained directly from the design charts instead of the regression equations can be assumed to be irrelevant when considering the uncertainty of the design inputs.

CHAPTER 6. DESIGN PROCEDURE

This chapter is intended to provide a design procedure with three possible levels of detail. The first two levels are computer based, whereas the third consists of a hand solution. In selecting one of the three possible levels, a compromise must be sought between available resources and the level of accuracy desired.

FIRST LEVEL - PRECISE CHARACTERIZATION

This level is accomplished by generating the values for all input variables as described extensively in Ref 1 and running the ARKRC-2 program. This option would provide the most detailed and precise design solution.

SECOND LEVEL - INTERMEDIATE CHARACTERIZATION

The effort of the second level is reduced by running ARKRC-2 based on a series of recommended values for Texas environmental conditions. The designer is required to follow the steps outlined below:

(1) Generate Design Inputs

  (a) Physical Pavement Characteristics. Such as pavement type, joint or crack spacing, slab thickness, and reinforcement characteristics (if CRCP).

  (b) Thermal Characteristics of Cracks or Joints. Obtain the thermally related horizontal movement of cracks or joints from field surveys by the following procedure. A series of metal reference points must be installed on both sides of several cracks or joints, and measure the distance between these points over a range of air temperatures. It is recommended that these measurements be obtained for five different temperatures per day for a minimum of two consecutive days. The metal reference points may consist of brass bolts; placement is illustrated in Fig 6.1. The designer determines the number and locations for representative measurement. Table 6.1 provides a sample form for collection of the horizontal movement data from a single crack or joint. The grid at the bottom of the table is provided to allow the user to plot the data after they have been recorded. For each crack or joint, draw the "best-fit" straight line through the data. The user then selects a data set for use in analyzing the potential for reflection cracking in the design section. The high temperature joint or crack width and the low temperature joint or crack width are determined.

(c) Overlay Characteristic. Define the proposed overlay thickness along with the overlay creep and dynamic moduli depending on the climatological conditions of the design section location. Recommended values for these parameters for all climatological regions are presented in Table 6.2.

The climatic regions that Texas is divided into by the National Climatic Center are shown in Fig 6.2.

(d) Intermediate Layer Thickness and Bond Breaker Width.

(e) Yearly Frequency of Minimum Temperatures. The corresponding yearly frequency of minimum temperatures must be selected based on Table 6.3, depending on the climatological region.

(f) Remaining Variables. The rest of the ARKRC-2 input variables must be defined according to Table 6.4.

(2) Run ARKRC-2 Program

Different design alternatives can be generated by running the ARKRC-2 program varying overlay thickness, THOV, intermediate layer thickness, TH-2, and bond breaker width, BBW, alternatively. The use of an open graded intermediate layer in combination with a bond breaker strip is very effective in minimizing reflection cracking. Bond breaker strips should never be wider than one foot since they might cause severe "pop-outs" of unbounded sections.

The basic results obtained from the ARKRC-2 output are number of years to 50 percent reflection cracking, Y_T , and maximum allowable deflection factor, F_w .

(3) Design for Different Levels of Reflection Cracking

If the user is interested in estimating when different levels of reflection cracking will be reached (based on tensile strain criteria), the following procedure may be applied:

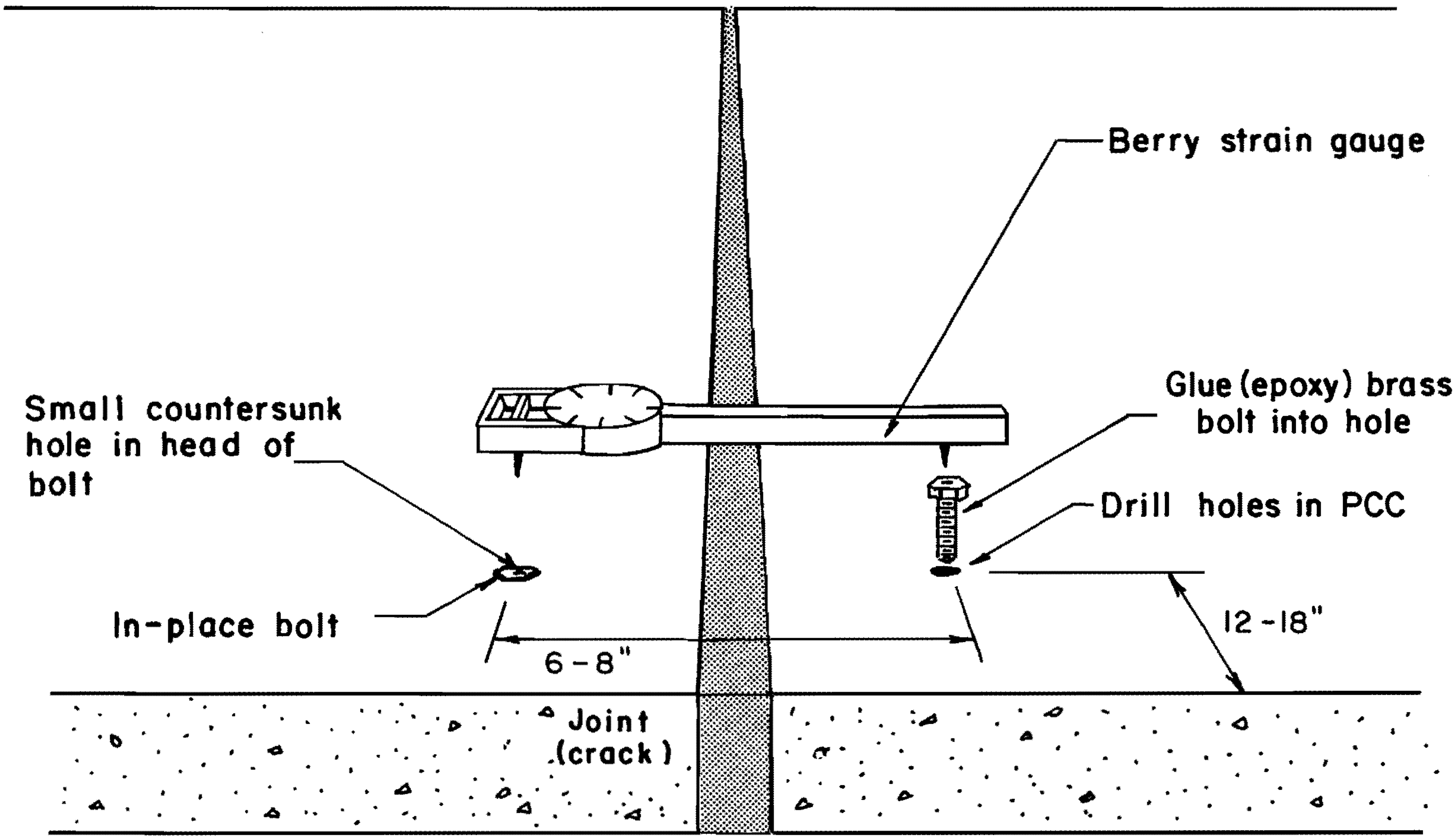
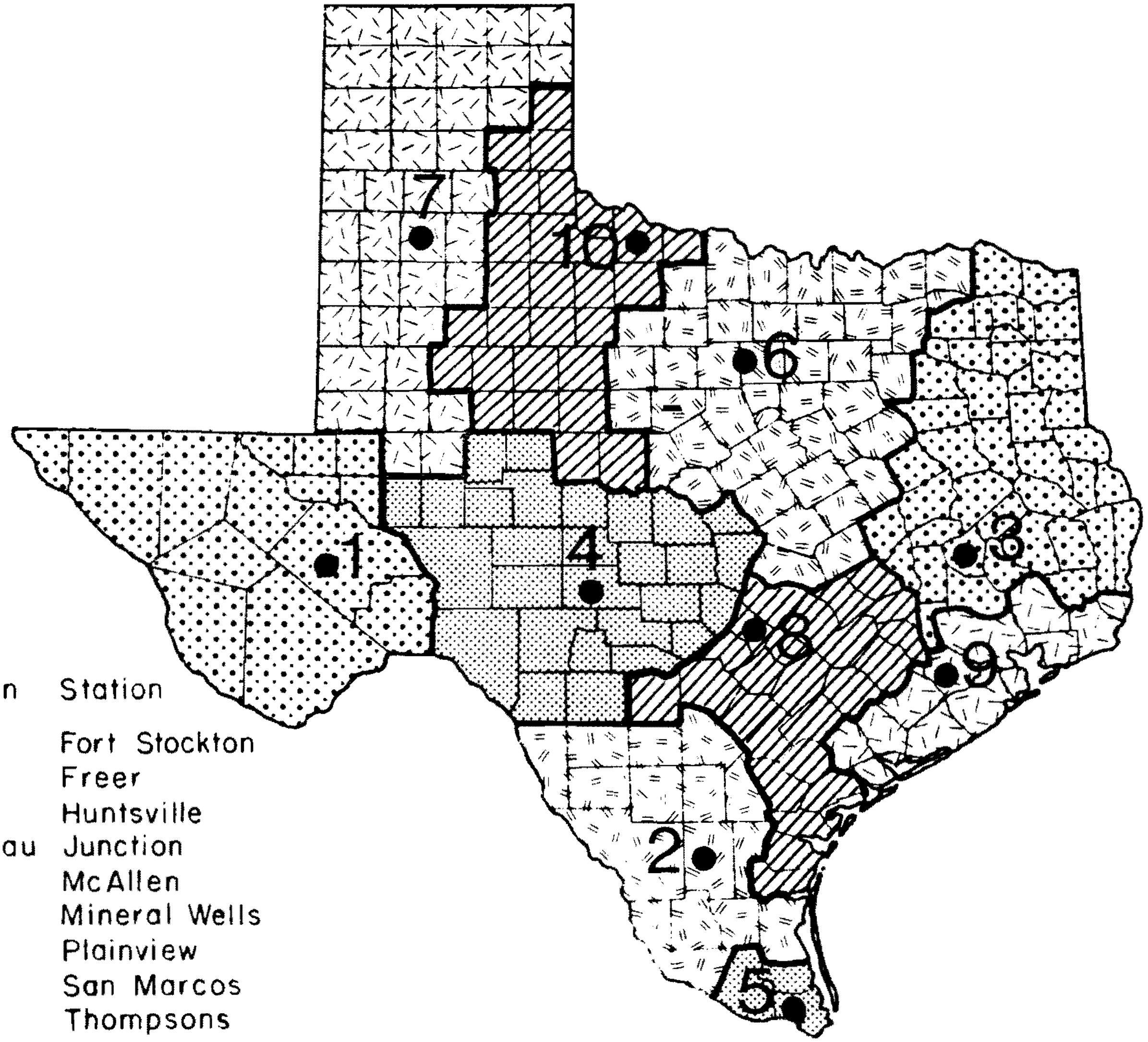


Fig 6.1. Placement of brass bolts for measurement of horizontal slab movement (after Ref 1).



No.	Climatic Region	Station
1	Trans Pecos	Fort Stockton
2	Southern	Freer
3	East Texas	Huntsville
4	Edwards Plateau	Junction
5	Lower Valley	McAllen
6	North Central	Mineral Wells
7	High Plains	Plainview
8	South Central	San Marcos
9	Upper Coast	Thompsons
10	Low Rolling Plains	Vernon

Fig 6.2. Ten climatic regions of Texas (National Climatic Center).

TABLE 6.1. SAMPLE FORM FOR COLLECTING HORIZONTAL MOVEMENT DATA (AFTER REFERENCE 1)

REFLECTION CRACKING ANALYSIS DATA
HORIZONTAL SLAB MOVEMENTS

Project: ____________________
Location: ____________________
Joint/crack No. ____________________ Recorder ____________
Slab Lengths: Upstream side ____________ Downstream side ____________

Measurement Number	Date	Time of Day	Pavement Temperature °F	Joint/Crack Width (inches)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				

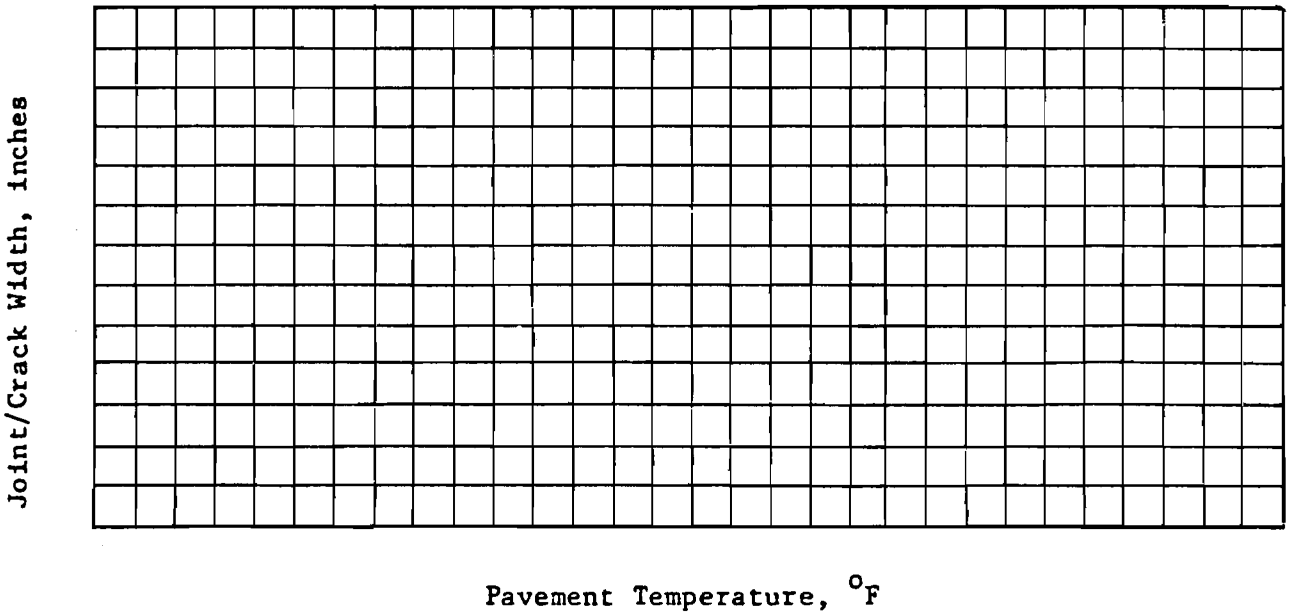


TABLE 6.2. RECOMMENDED VALUES FOR OVERLAY EFFECTIVE CREEP MODULUS, EOV, AND OVERLAY DYNAMIC MODULUS, EDV, FOR ALL CLIMATIC REGIONS

Climatic Region	EOV (psi)	EDV (psi)
Trans Pecos	28,000	560,000
Southern	17,000	340,000
East Texas	20,000	400,000
Edwards Plateau	28,000	560,000
Lower Valley	16,000	320,000
North Central	25,000	500,000
High Plains	35,000	700,000
South Central	22,000	440,000
Upper Coast	17,000	340,000
Low Rolling Plains	32,000	640,000

TABLE 6.3. YEARLY FREQUENCY OF MINIMUM TEMPERATURE FOR ALL CLIMATIC REGIONS

	Ranges of Minimum Daily Temperature, °F						
Climatic Region	49-40 DAY 1	39-30 DAY 2	29-20 DAY 3	19-10 DAY 4	9-0 DAY 5	-1--11 DAY 6	-1--20 DAY 7
Trans Pecos	68	67	45	6	1	0	0
Southern	59	34	7	0	0	0	0
East Texas	60	43	17	2	0	0	0
Edwards Plateau	51	51	32	6	1	0	0
Lower Valley	49	17	2	0	0	0	0
North Central	54	49	27	7	1	0	0
High Plains	51	64	49	18	3	0	0
South Central	60	53	21	3	0	0	0
Upper Coast	59	35	9	0	0	0	0
Low Rolling Plains	54	52	38	10	2	0	0

TABLE 6.4. TYPICAL VALUES FOR ARKRC-2 INPUT VARIABLES FOR CONDITIONS IN TEXAS

Input Category	Factor	Typical Values	
Problem Description			
Existing Concrete Pavement Characteristics	Pavement type	JCP/JRCP	CRCP
	Condition	Uncracked	Cracked
	PCC creep modulus, psi	4.5×10^6	4.5×10^6
	PCC thermal coefficient, in./in./°F	4.0×10^{-6}	4.0×10^{-6}
	PCC unit weight, pcf	145	145
	Movement of sliding, in.	0.02	0.02
Existing Pavement Reinforcement Characteristics	Steel elastic modulus, psi		30×10^6
	Steel thermal coefficient, in./in./°F		5.0×10^{-6}
	Steel-concrete bond stress, psi		500
Existing Pavement Movement Characteristics	Minimum temperature observed, °F	0	0
Asphalt Concrete Overlay Characteristics	Overlay thermal coefficient, in./in./°F	14×10^{-6}	14×10^{-6}
	Overlay unit weight, pcf	140	140
	Overlay bond-slip stress, psi	250	250
Intermediate Layer Characteristics	Intermediate layer creep modulus, psi	5000	5000
	Intermediate layer dynamic modulus, psi	20000	20000
	Intermediate layer thermal coefficient, in./in./°F	20×10^{-6}	20×10^{-6}
	Intermediate layer unit weight, pcf	120	120
Design Traffic	Total number of 18-kip ESAL	10^7	10^7
Early Frequency of Minimum Temperatures			

(a) Select the level of reflection cracking considered as a limit.

(b) Use Table 6.5 to determine the E-value corresponding to the selected reflection cracking level.

(c) Solve for the number of years, Y, corresponding to the desired level of reflection cracking, using the following formula:

$$Y = 1.585^{Z} \cdot Y_T$$

where

Y_T = number of years before 50 percent reflection cracking is reached (as determined from step 2).

It should be pointed out that the accuracy of this prediction is decreased for very high or very low levels of reflection cracking.

(4) Check Load Transfer

From the program output a maximum value for the deflection factor will be obtained and those cracks or joints whose deflection factors exceed this maximum limit, due to poor load transfer, will have to be subjected to rehabilitation prior to overlay placement to avoid premature reflection cracking.

To obtain the deflection factors for the cracks or joints, it is necessary to obtain deflection measurements at each crack or joint by using the Dynaflect. Figure 6.3 shows the recommended positioning of the Dynaflect and its geophones within the lane with respect to the joint or crack. The deflection measurements are taken in the outside wheelpath of the outside lane. The load wheels and geophone no. 1 are located on the upstream side of the joint. Designating the deflection from geophones 1 and 2 as W_l (loaded side) and W_u (unloaded side), respectively, the deflection factor for the joint or crack can be computed using the following equation:

$$F_w = \frac{W_l - W_u}{W_l + W_u}$$

It is recommended that the deflections be obtained during a period representative of the base support conditions after overlay. For the case of jointed concrete pavements (JCP or JRCP), it is

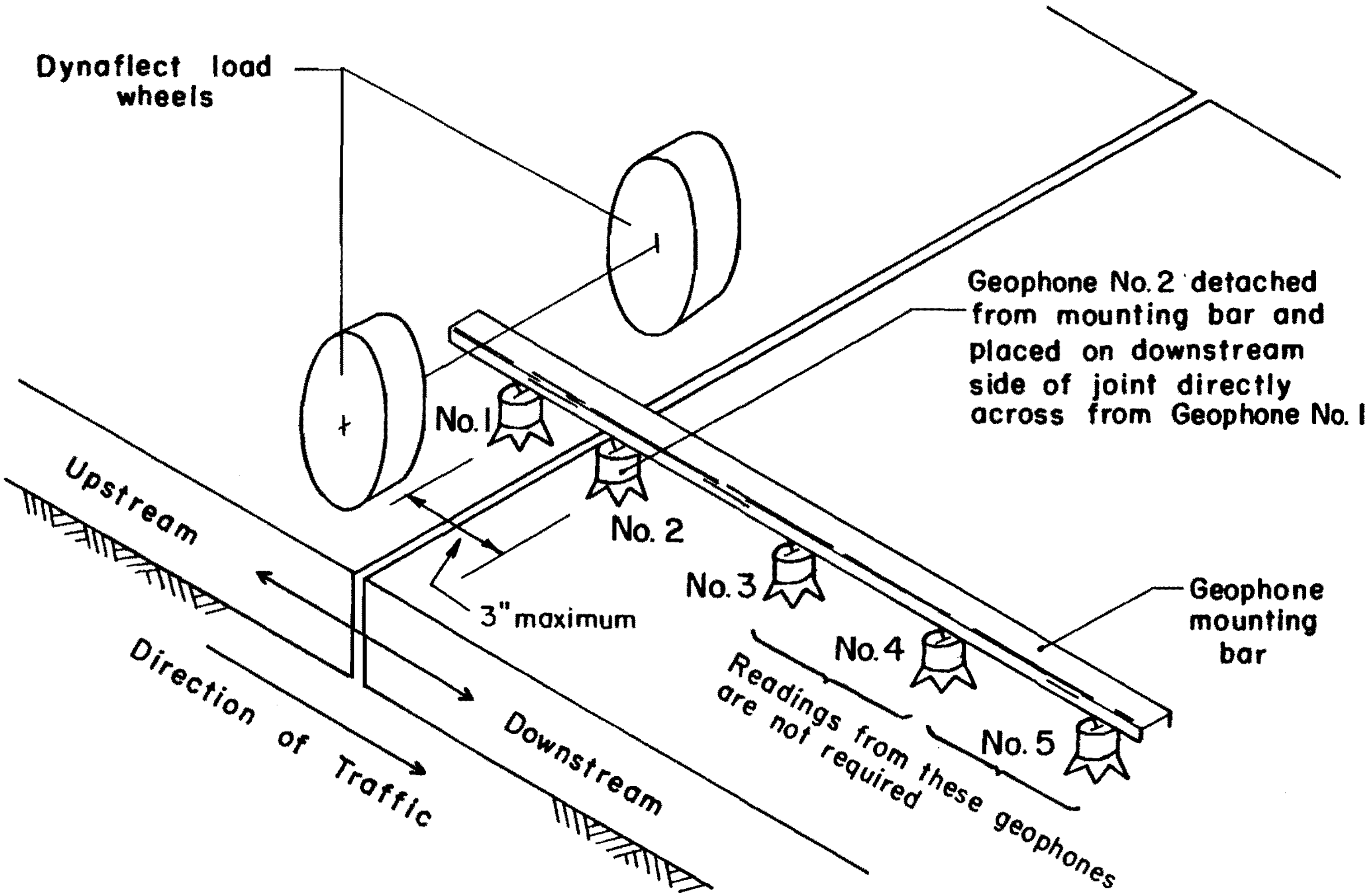


Fig 6.3. Required positioning of Dynaflect load wheels and geophones for load transfer deflection measurements (after Ref 1).

TABLE 6.5. Z-VALUES CORRESPONDING TO DIFFERENT LEVELS OF REFLECTION CRACKING (AFTER REF 1)

Percent Reflection Cracking	Z-Values
1	-2.330
5	-1.645
10	-1.282
15	-1.037
20	-0.841
25	-0.674
30	-0.524
35	-0.385
40	-0.253
45	-0.126
50	0.000
55	0.126
60	0.253
65	0.385
70	0.524
75	0.674
80	0.841
85	1.037
90	1.282
95	1.645
99	2.330

desirable to obtain measurements at every construction joint. For the case of continuously reinforced concrete pavements (CRCP), the deflection measurements should be obtained for a series of 3 to 5 cracks at approximate 200-foot intervals.

After the deflection factors have been computed for the design section it is useful to prepare a longitudinal profile plot of F_w versus distance along the roadway as shown in Fig 6.4, to indicate those joints requiring undersealing.

(5) Select Best Design Alternative

The final design must be one for which the selected overlay thickness along with specific values for intermediate layer thickness and bond breaker strip width will result in reasonable overlay life and will also provide an economical solution. In the cost determination, care must be taken to include the costs associated with undersealing of those cracks or joints requiring it.

THIRD LEVEL - HAND SOLUTION

This level consists of a hand solution based on a series of design charts, presented in Figs 6.6 to 6.14, to predict overlay life and the design chart, presented in Fig 6.15, to determine maximum deflection factor.

Before illustrating the application, the design chart's most limiting constraints are discussed:

(1) Figure 6.5 provides a map of Texas showing the six composite climatic zones. The charts presented herein were developed only for Zones B, D, and F. Recognizing that Zone A has the mildest climate, then overlays in Zone A can be conservatively designed using the Zone B design chart. Furthermore, overlays in Zones C and E can be designed by interpolating between the results of designs for Zones B and D and D and F, respectively.

(2) The applicability of the design charts is limited to the range of values selected as typical in deriving the deterministic equations for the prevailing conditions in Texas. Since the model used in ARKRC-2 is not very sensitive to the Portland Cement Concrete Properties, there was no use in deriving different charts for different types of concretes; therefore, the values selected for creep modulus (4.5×10^6 psi) and thermal coefficient (4×10^{-6}) were based on the average properties of the Texas concrete pavements.

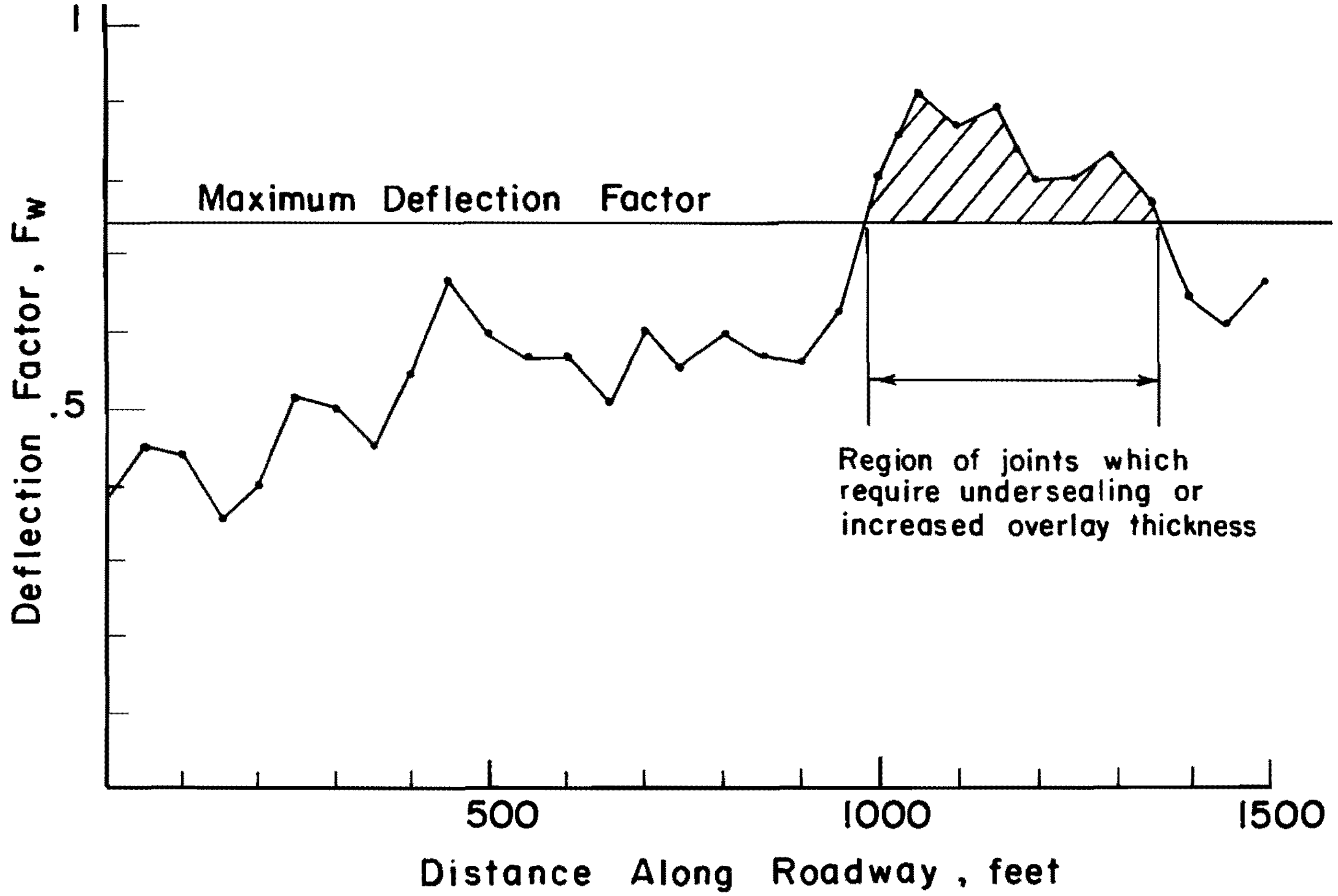
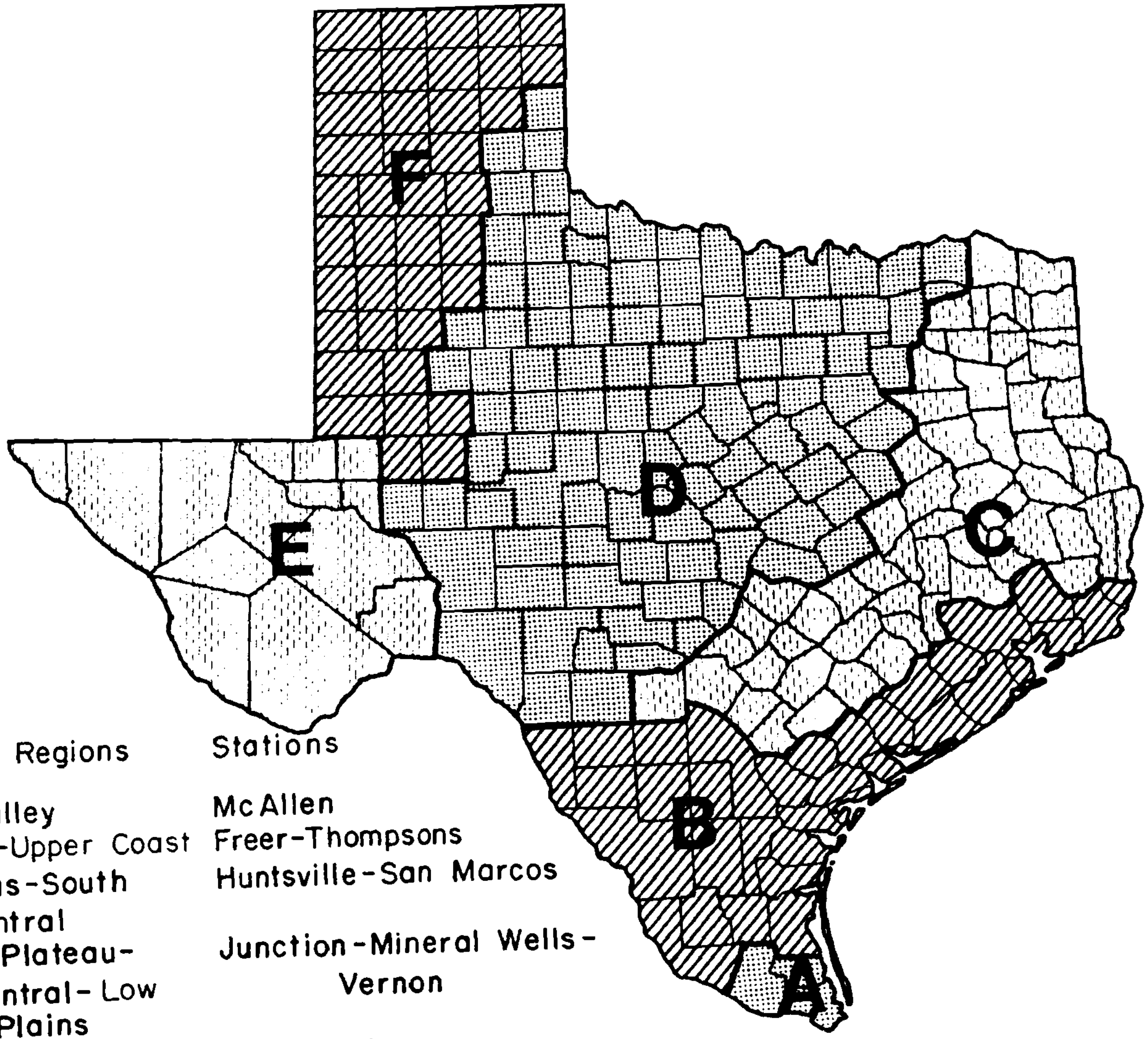


Fig 6.4. Graph of field deflection factors for 50-foot JCP illustrating application of ARKRC-2 maximum deflection factor in detecting joints which will cause premature reflection cracking in the overlay design considered (after Ref 1).



Zones	Combined Regions	Stations
A	Lower Valley	McAllen
B	Southern-Upper Coast	Freer-Thompsons
C	East Texas-South Central	Huntsville-San Marcos
D	Edwards Plateau-North Central-Low Rolling Plains	Junction-Mineral Wells-Vernon
E	Trans Pecos	Fort Stockton
F	High Plains	Plainview

Fig 6.5. Six composite zones.

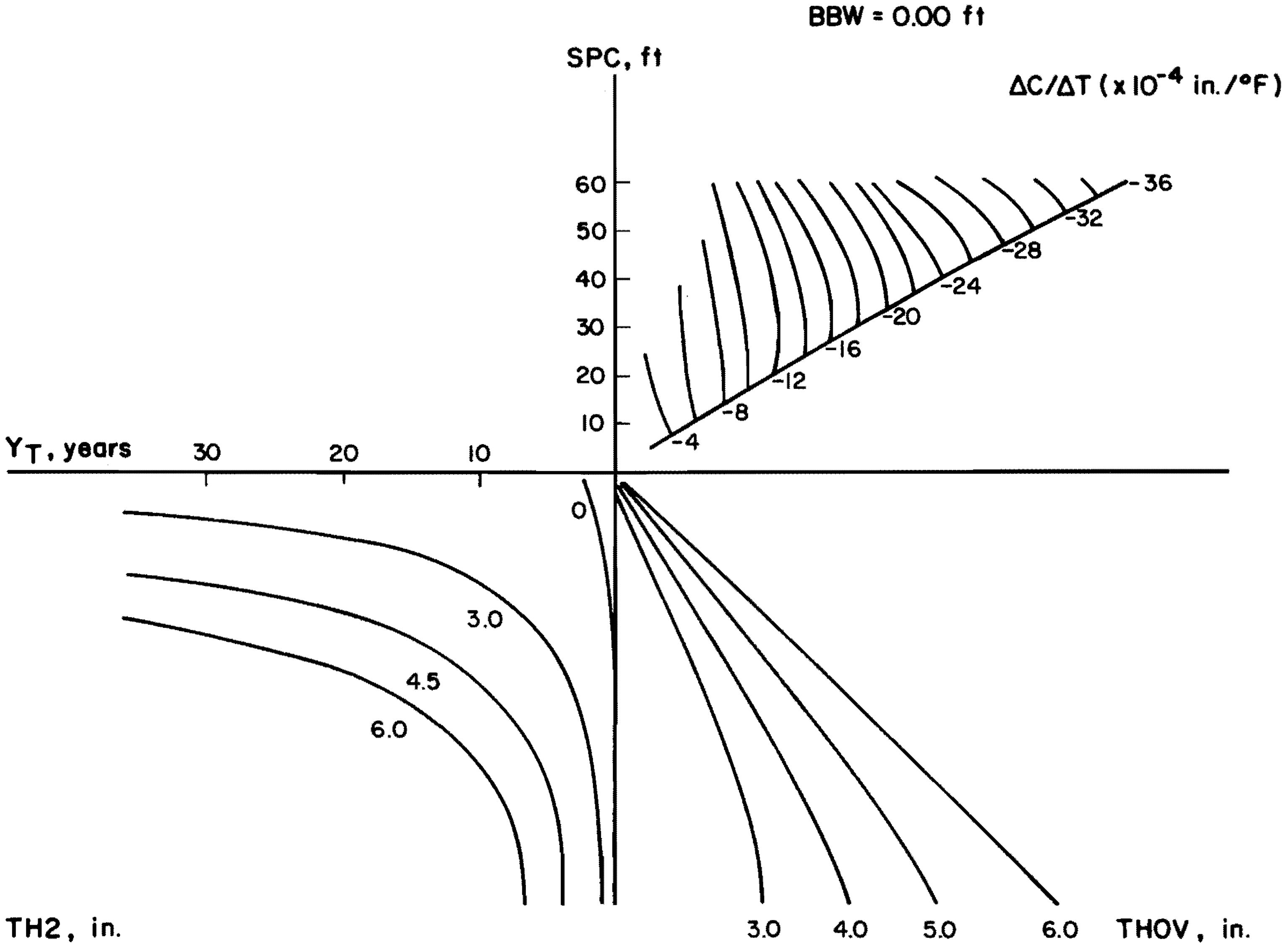


Fig 6.6. JCP/JRCP-B (BBW= 0 ft.) design chart.

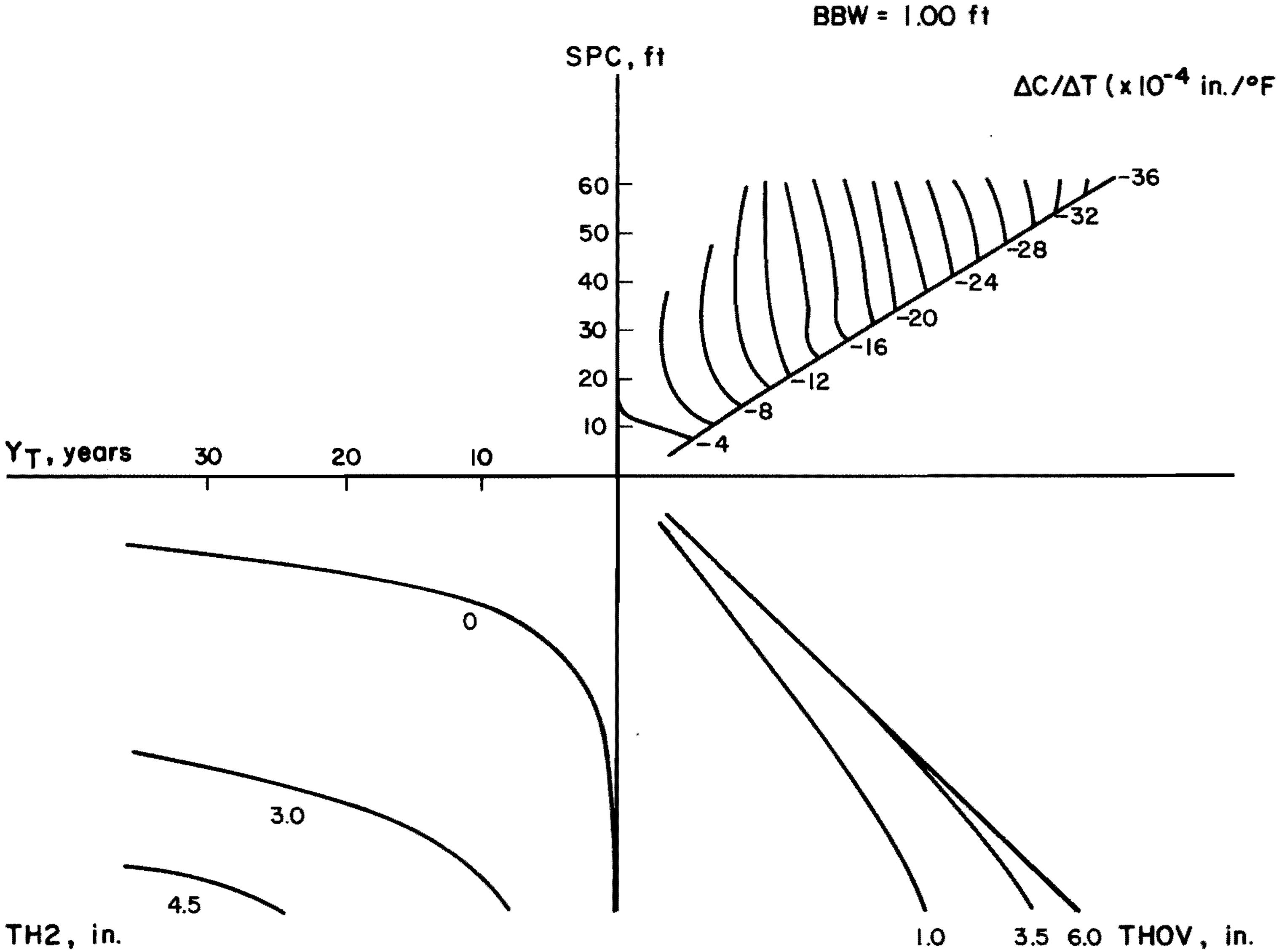


Fig 6.7. JCP/JRCP-B (BBW=1 ft.) design chart.

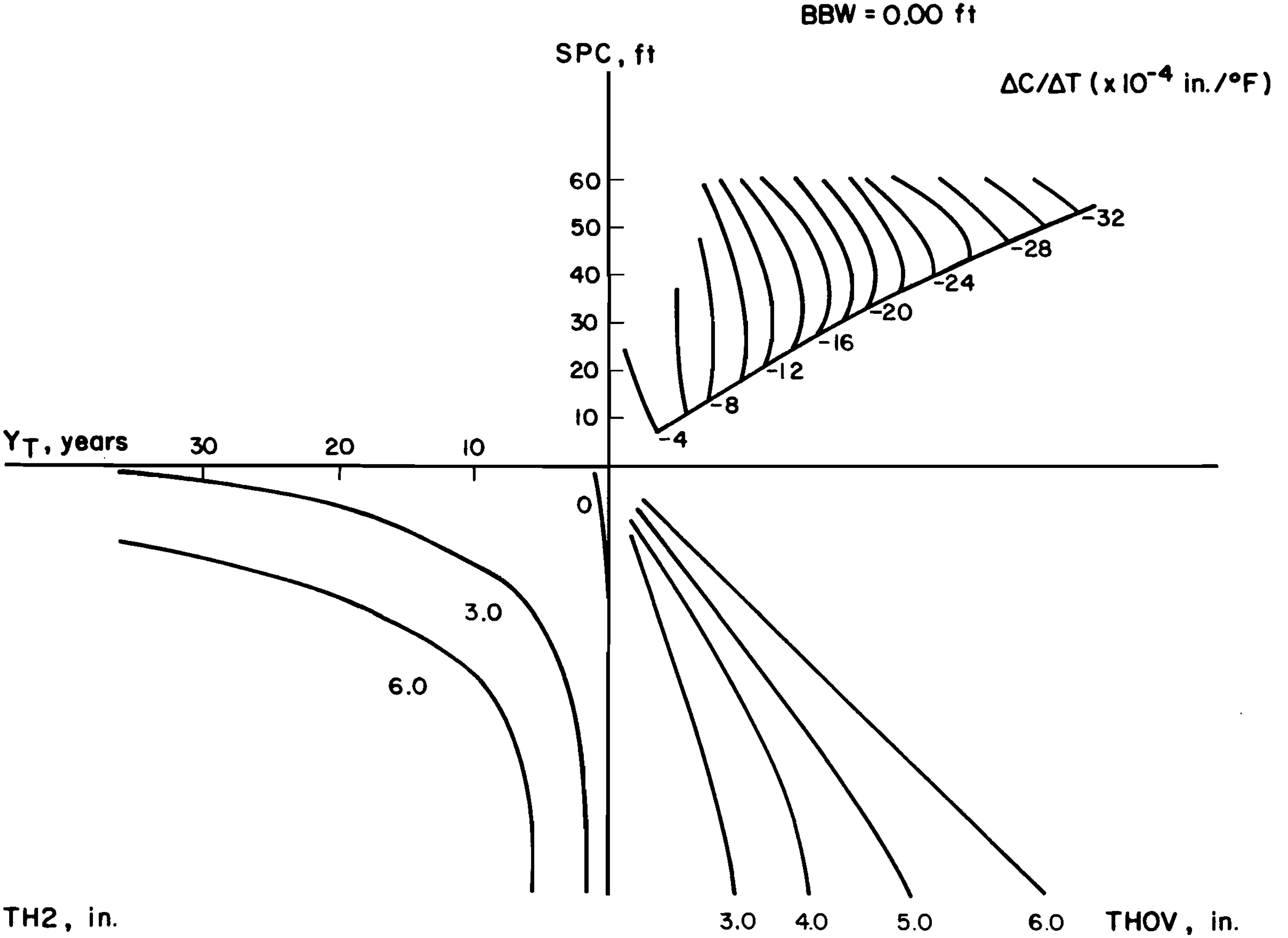


Fig 6.8. JCP/JRCP-D (BBW=0 ft) design chart.

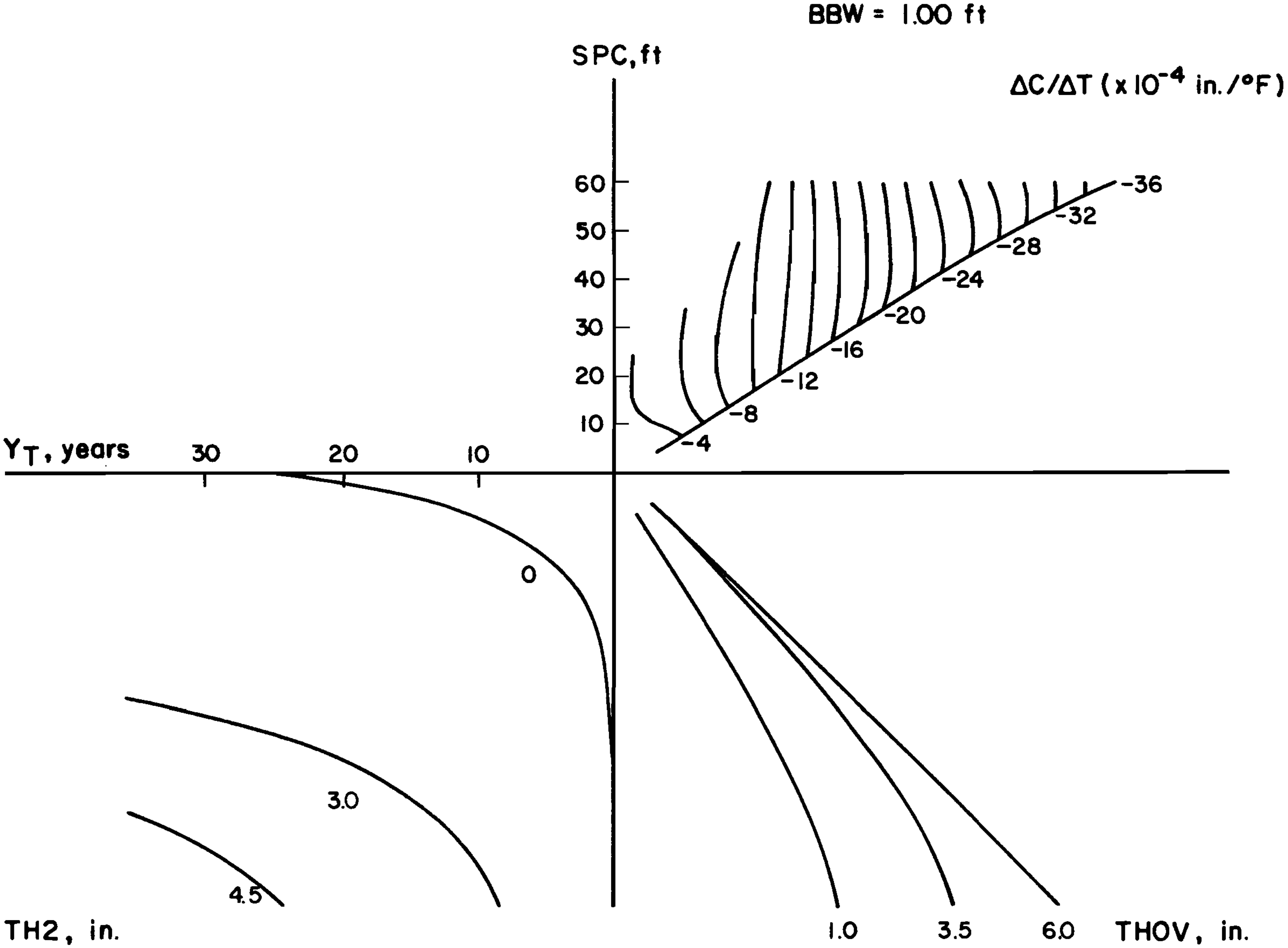


Fig 6.9. JCP/JRCP-D (BBW=1 ft) design chart.

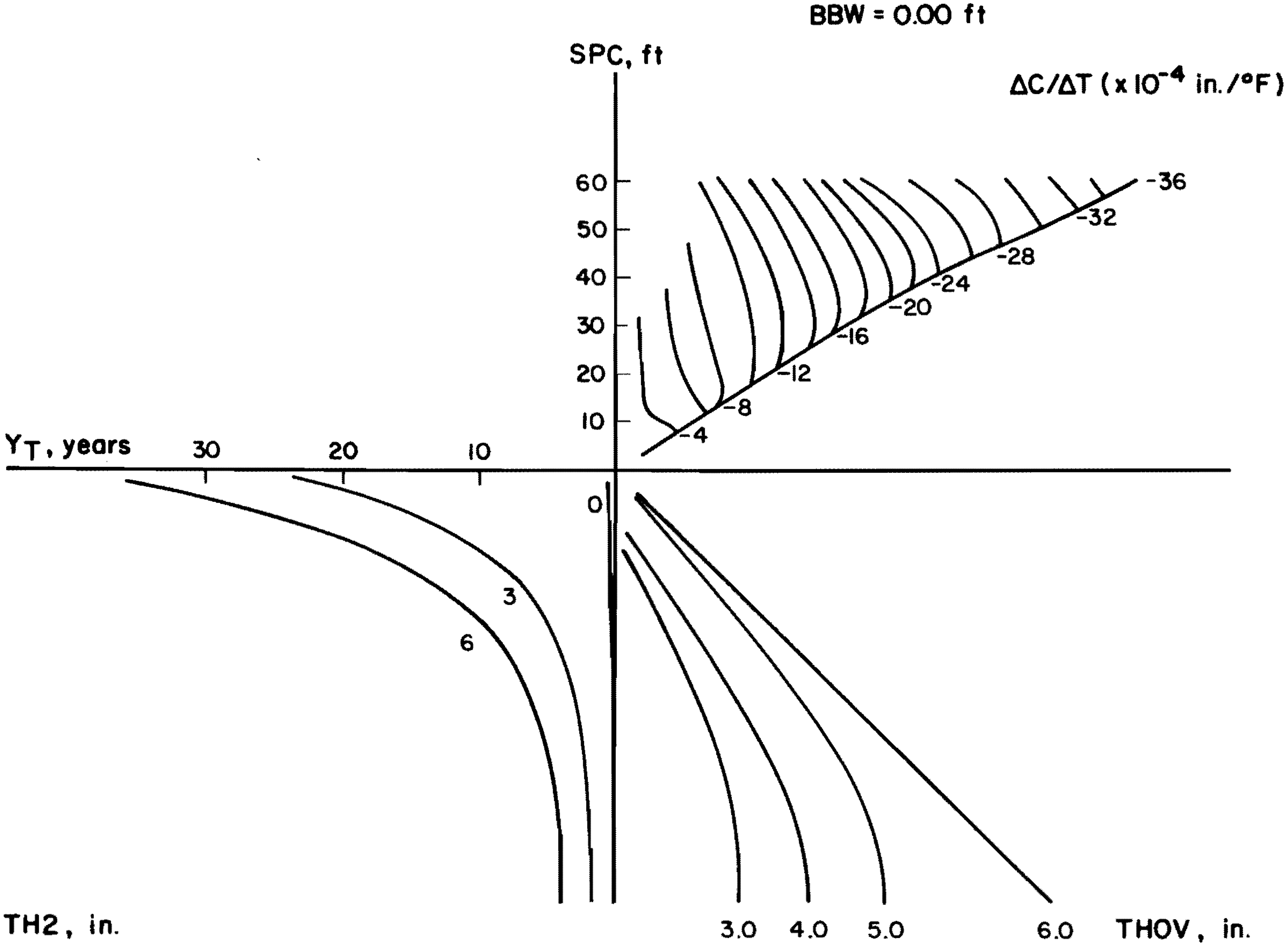


Fig 6.10. JCP/JRCP-F (BBW= 0 ft) design chart.

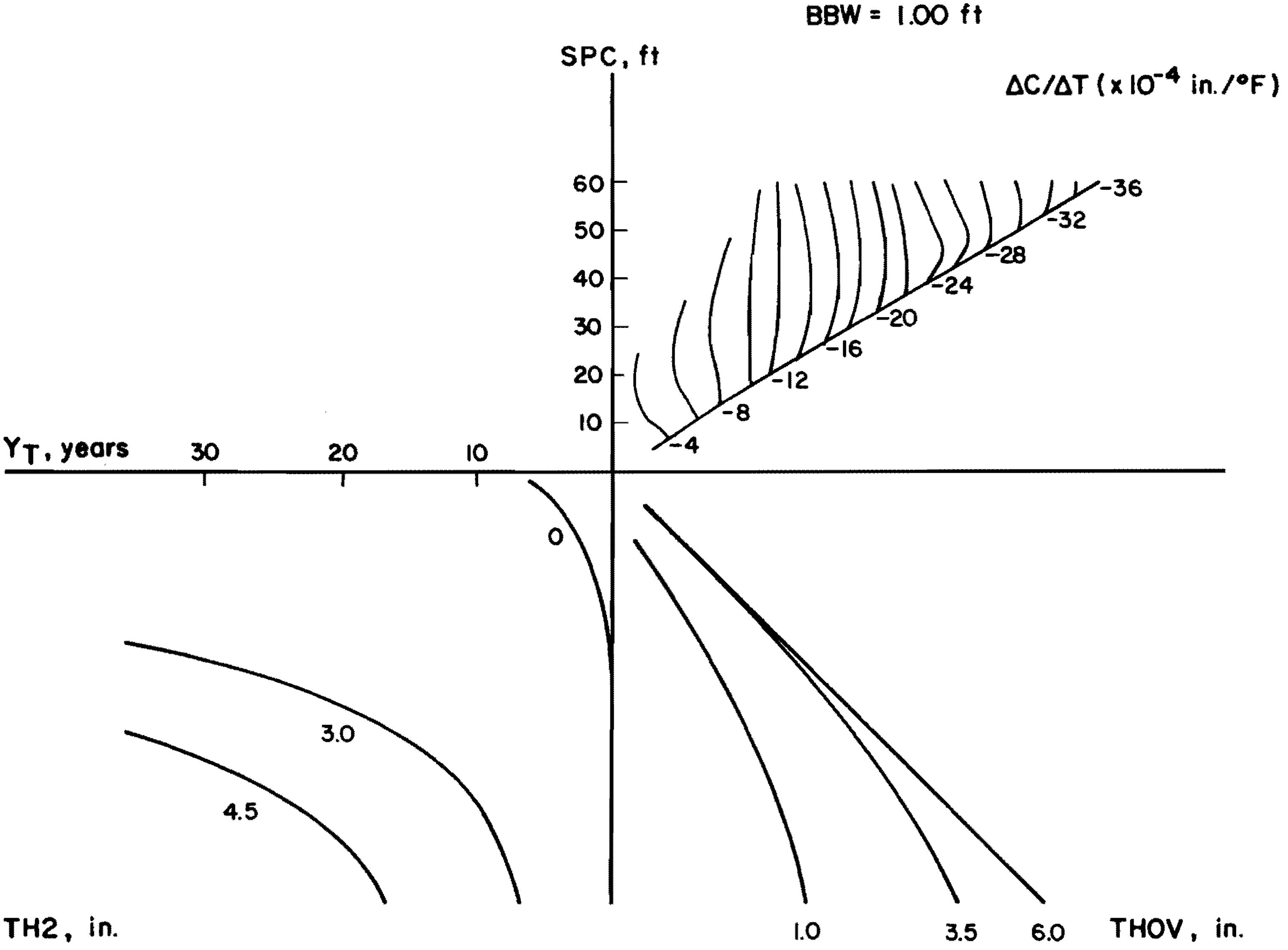


Fig 6.11. JCP/JRCP-F (BBW=1 ft) design chart.

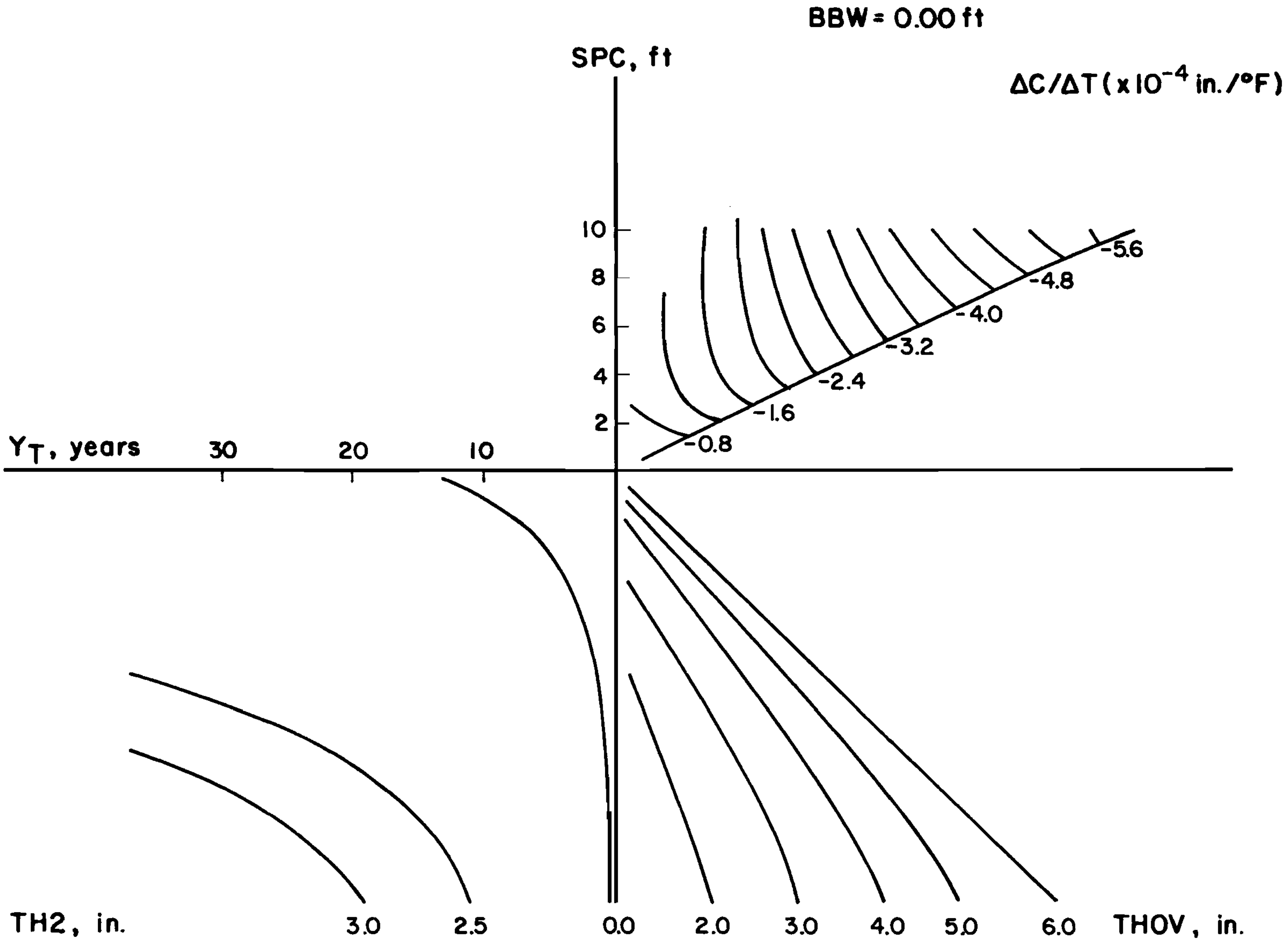


Fig 6.12. CRCP-B (BBW=0 ft) design chart.

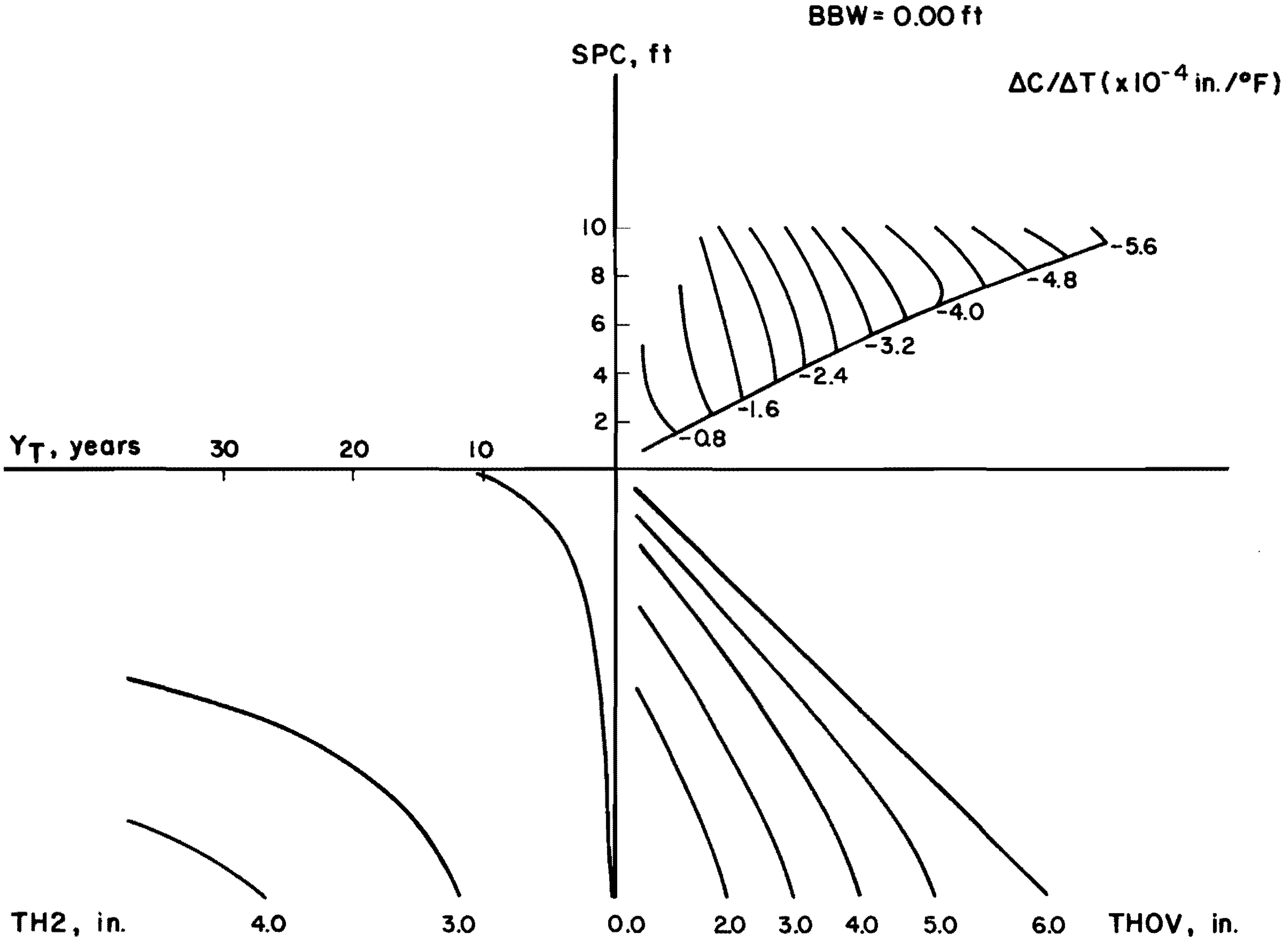


Fig 6.13. CRCP-D (BBW=0 ft) design chart.

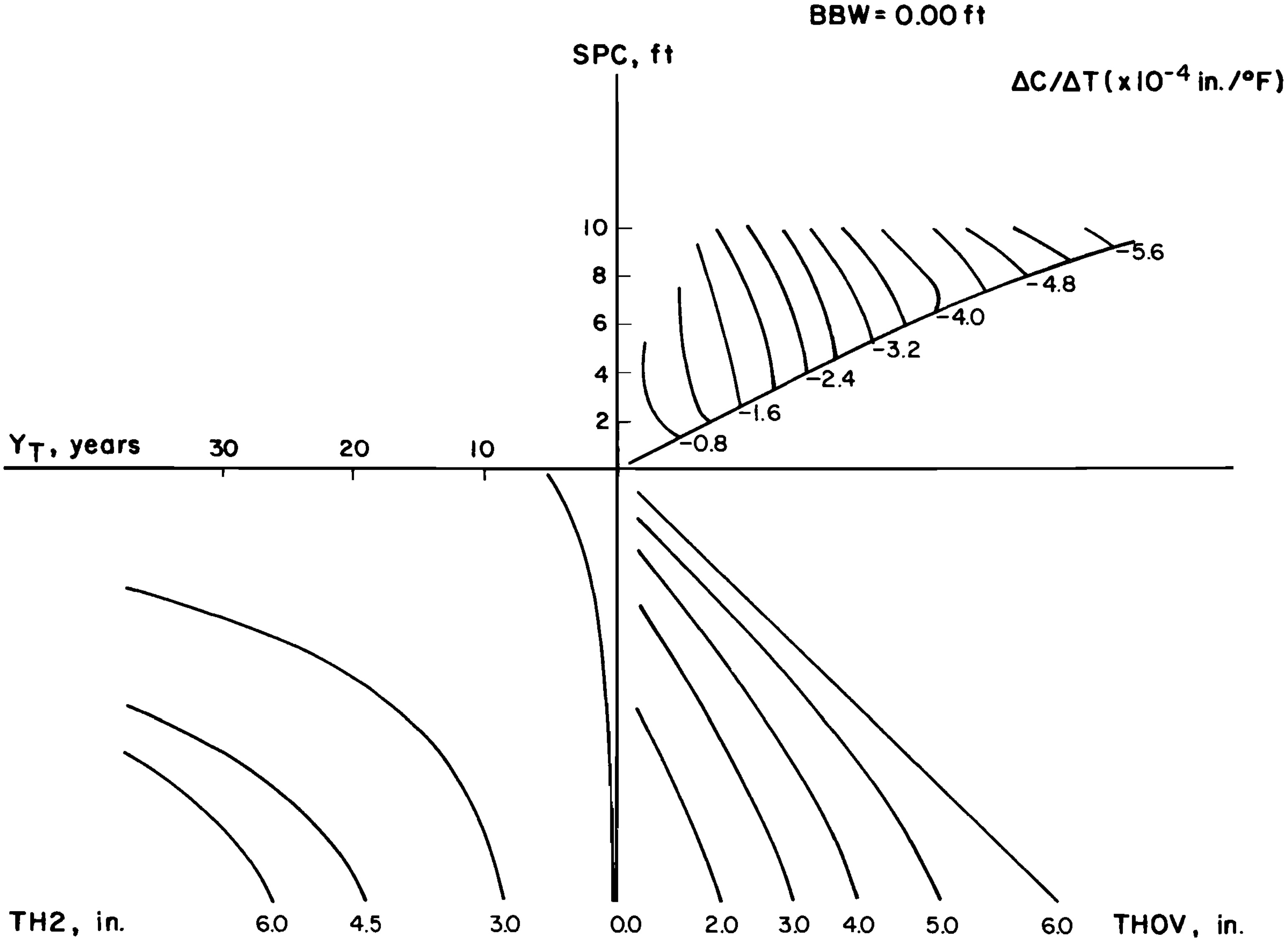


Fig 6.14. CRCP-F (BBW=0 ft) design chart.

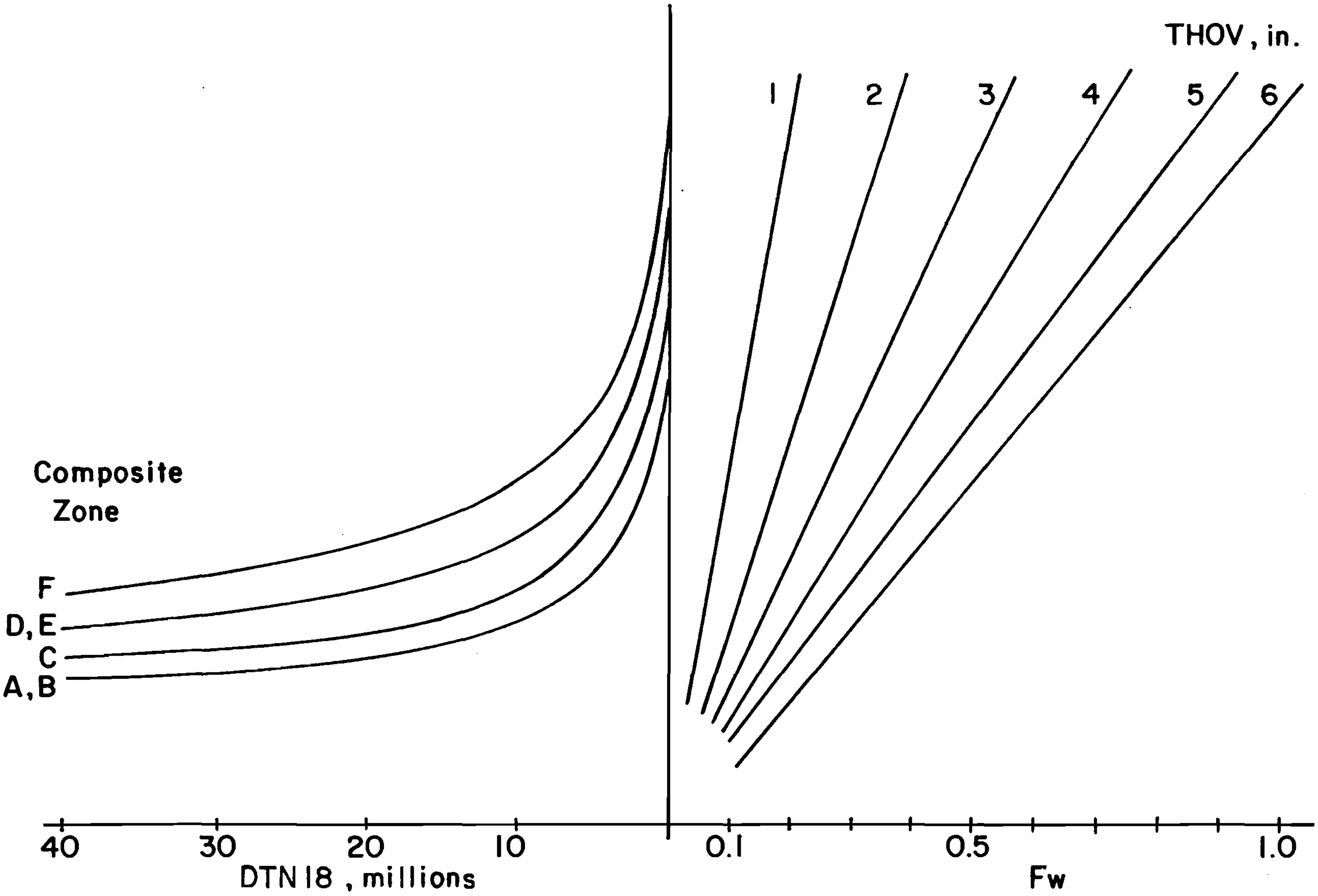


Fig 6.15. Design chart for estimating allowable deflection factor, F_w.

(3) The JCP/JRCP design charts are derived for a typical 10-inch thick jointed pavement, whereas the CRCP charts were developed for the standard CRCP cross-section used in Texas (8-inch slab with No. 5 bars at 6.25-inch centers).

(4) For cases where an intermediate layer is used, the design charts are only applicable to those which have the properties and characteristics of the standard Arkansas mix open-graded base course. For denser mixes, the results provided by the design charts will be conservative.

The design charts shown in Figs 6.6 to 6.15 to predict overlay life and maximum allowable deflection factor may be used in two possible ways:

(1) to determine the overlay substituting life and check how well it is performing in terms of reflection cracking (assuming adequate load transfer in cracks or joints of original PCC pavement) and

(2) to determine the most economical design alternative from the reflection cracking standpoint.

CHECKING OVERLAY SUBSISTING LIFE

The step-by-step procedure for determining overlay subsisting life is:

(1) Determine the location of the section from Fig 6.5.

(2) Obtain the following data from the condition survey on the original PCC section before overlay placement.

   (a) Determine the number of cracks or joints in the specific section and obtain the average crack or joint spacing.

   (b) Define the characteristics of the thermally related horizontal movement of cracks or joints in the original pavement following the procedure described for the intermediate characterization level (second) when generating design inputs (step 1b). The slope $\Delta C/\Delta T$ must be defined for the "best-fit" line through the horizontal movement versus temperature data points plotted in Table 6.1 form. $\Delta C/\Delta T$ will always be negative and representative of the crack or joint potential to develop reflection cracking.

(3) Select the design chart to be used from Figs 6.6 to 6.14, depending on the location of the specific section (from step 1), type of rigid pavement (either JCP, JRCP, or CRCP), and bond breaker width, if provided (only JCP/JRCP).

(4) Enter the design chart with the following inputs:

  (a) crack or joint spacing (from step 2a),

  (b) slope $\Delta C/\Delta T$ (from step 2b),

  (c) overlay and intermediate layer thicknesses from actual condition of the rehabilitated section.

  Read on the horizontal scale the number of service years for 50 percent reflection cracking (Y_T).

(5) Extrapolate to any other level of reflection cracking, if failure criterion is different than 50, and determine the number of years, Y, to reach that level, following the procedure outlined for the intermediate characterization level (step 3).

(6) Determine the overlay subsisting life by subtracting the number of years, Y, to failure criterion (as obtained in step 5) from the period the overlay has been in service.

(7) To check if the overlaid section is behaving according to the theoretical model in ARKRC-2 after the specific in-service period, the steps below must be followed:

  (a) Determine the number of reflected cracks from the condition survey on the section after the specific in-service period.

  (b) Compute the actual percent reflection cracking, dividing the number of reflected cracks (from step 7a) by the number of cracks or joints in the original PCC before overlay placement (from step 2a).

  (c) Obtain for the actual percent reflection cracking (from 7b) the number of years Y_a to reach that reflection cracking level (as described in step 5). Y_a must be equal to the in-service period between overlay construction and the time of the condition survey (referred in step 7a).

Example:

Design inputs:

Real 500-foot-long overlaid section in Harrison County (Zone C).
Number of cracks in original CRCP before overlay = 125
Average crack spacing = JPC = 4.0 ft

$\Delta C/\Delta T = -1.2 \times 10^{-4}$ in./°F
Overlay thickness = THOV = 4.0 in.
Intermediate layer thickness = TH2 = 0.0 in.
Failure will be reached when 70 percent reflection cracking appears on overlay.

Overlay subsisting life will be checked after a two-year in-service period.

Interpolating between design charts CRCP-B (Fig 6.16) and CRCP-D (Fig 6.17):

Y_T (for 50 percent reflection cracking) = 3 years

Number of years Y to failure criterion:

From Table 6.5, $Z_{70} = 0.524$

$Y = (1.585)^{0.524}(3) = 3.82$ years

Overlay subsisting life:

SL = 3.82 - 2 = 1.82 years (1 year and 10 months)

From the condition survey on the overlaid section after the two-year in-service period:

Number of reflected cracks = 26
Percent reflection cracking = 26/125 = 20.8 percent
From Table 6.5, $Z_{20} = -0.841$

$Y = (1.585)^{-0.841}(3) = 2.04$ years $\doteq$ 2 years

Therefore, the overlay section is behaving according to the ARKRC-2 model and failure criterion will be reached after 1 year and 10 months from time of survey.

A series of overlaid CRCP sections in Texas, located in climatological zones not included when the ARKRC-2 program was calibrated, were checked following the procedure outlined above. The predictions of the number of years, Y_a, to the levels of reflection cracking presented in the 1982 condition survey, resulted conservative by 10 to 20 percent when compared to the actual overlay life to time of survey (1982).

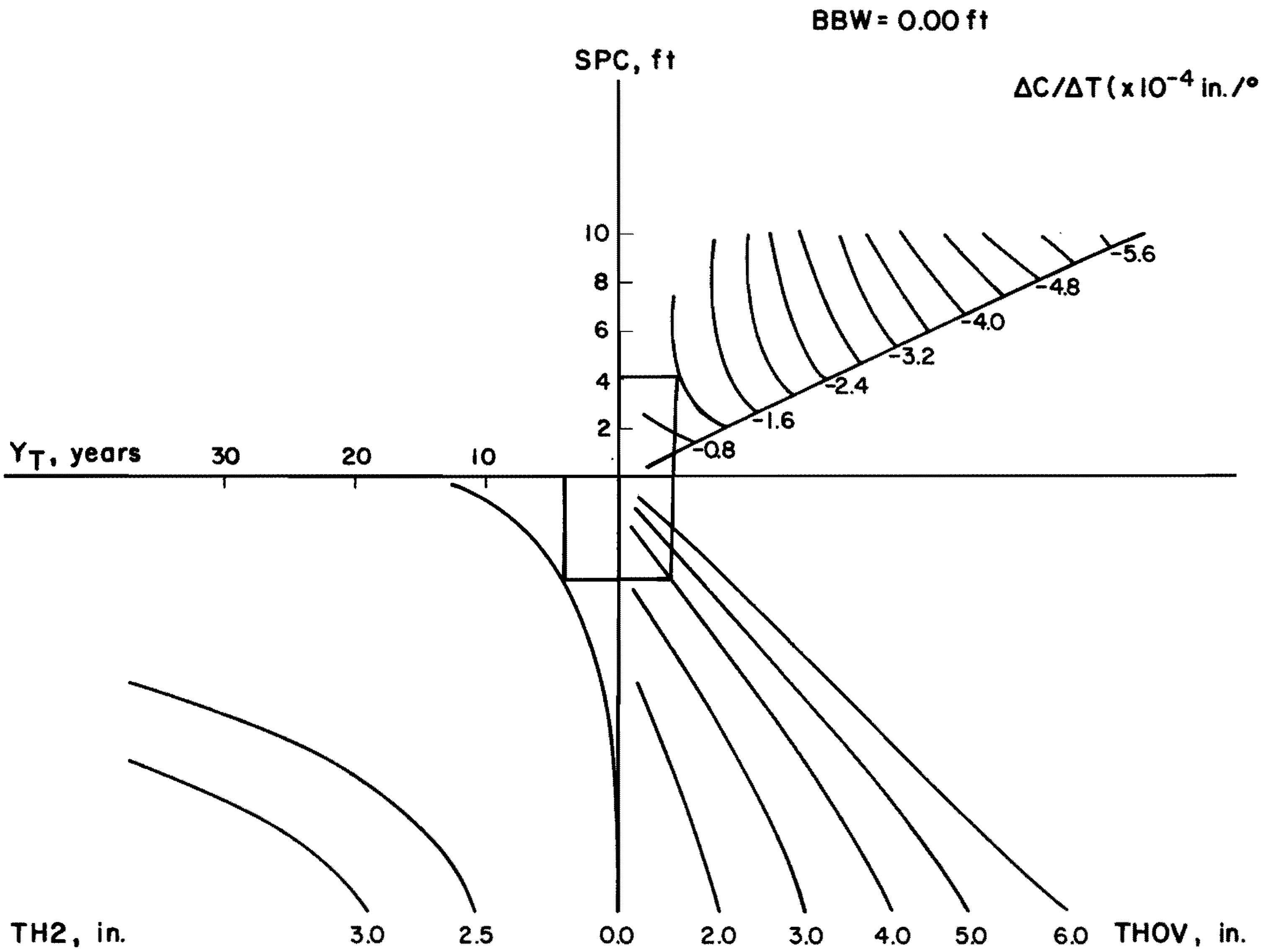


Fig 6.16. CRCP-B (BBW = 0 ft) design chart.

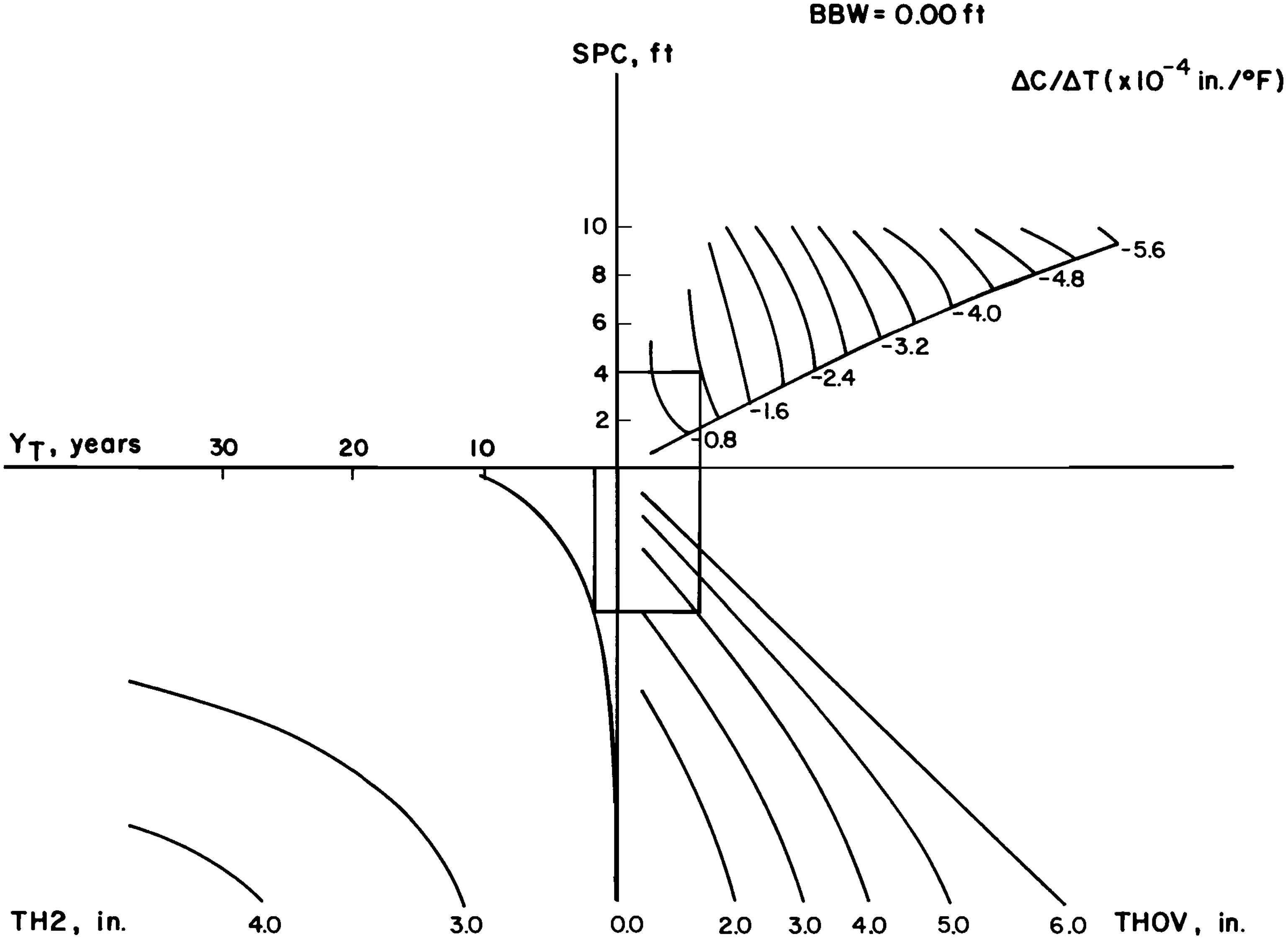


Fig 6.17. CRCP-D (BBW = 0 ft) design chart.

SELECTING DESIGN ALTERNATIVE

The procedure to be followed to generate a suitable design alternative is:

(1) Same as step 1 of the procedure to check overlay subsisting life.

(2) Same as step 2 of the procedure to check overlay subsisting life.

(3) Same as step 3 of the procedure to check overlay subsisting life.

(4) Define the design period Y (years) to reach a specific reflection cracking level (failure criterion). If the failure criterion is different than 50, the number of years Y_T to 50 percent reflection cracking must be determined following the procedure outline for the intermediate characterization level (step 3).

(5) Enter the design charts for BBW = 0 ft and BBW = 1 ft with the following inputs:

   (a) crack or joint spacing (from step 2a).

   (b) slope $\Delta C/\Delta T$ (from step 2b)

   (c) number of years Y_T to 50 percent reflection cracking (from step 4)

   Define the combinations of overlay and intermediate layer thicknesses, THOV and TH2, meeting the requirements of the design inputs above.

(6) For all design alternatives generated in step 5, determine those cracks or joints requiring undersealing along the design section or any other rehabilitation technique to increase load transfer, following the procedure below:

   (a) forecast the total number of 18-kip ESAL, DTN18, expected during the design period Y.

   (b) Enter the design chart in Fig 6.15 for estimating the maximum allowable deflection factor with DTN18 (from 6a); the zone where the design section is located (from step 1); and the overlay thickness, THOV, corresponding to each design alternative (from step 5).

   (c) Draw the values of the maximum deflection factor, for all design alternatives, on a longitudinal profile plot of deflection factor F_W versus distance along the roadway, as shown in Fig 6.4. The profile plot may be obtained as described for the intermediate characterization level (step 4).

(7) Determine the cost associated with each design alternative generated in step 5 (combinations of bond breaker width, overlay thickness and intermediate layer thickness) and select the most feasible solution. The costs associated with rehabilitating those cracks or joints with poor load transfer for each design alternative, must be included in the cost analysis.

Example:

Design inputs:

A 1500-foot-long JCP section located in Duval County (Zone B).
Joint spacing = SPC = 50.0 ft

$\Delta C / \Delta T = -12 \times 10^{-4}$ in./°F
Failure criterion: 70 percent reflection cracking after Y = 25 years of in-service period
Design 18-kip ESAL applications = DTN18 = 20×10^{6}

Number of years Y_T to 50 percent reflection cracking:

From Table 6.5, $Z_{70} = 0.524$

$Y_T = 25/(1.585)^{0.524} = 19.64$ years

From design charts, the following design alternatives are obtained:

From JCP/JRCP - B (BBW = 0 ft, Fig 6.18):

Alternative 1: THOV = 6.0 in. TH2 = 4.5 in.
Alternative 2: THOV = 5.0 in. TH2 = 5.0 in.
Alternative 3: THOV = 4.5 in. TH2 = 6.0 in.

From JCP/JRCP - B (BBW = 1 ft, Fig 6.19):

Alternative 4: THOV = 6.0 in. TH2 = 1.0 in.
Alternative 5: THOV = 3.5 in. TH2 = 1.0 in.
Alternative 6: THOV = 1.0 in. TH2 = 1.5 in.

Alternatives 4, 5 and 6 are rejected since the open graded intermediate layer can not be less than 2.5 or 3 inches since some of the aggregate particles are as large as 2.5 inches.

Maximum allowable deflection factors from Fig 6.20 for design alternatives:

Alternative 1: F_w max = 0.26
Alternative 2: F_w max = 0.20
Alternative 3: F_w max = 0.17

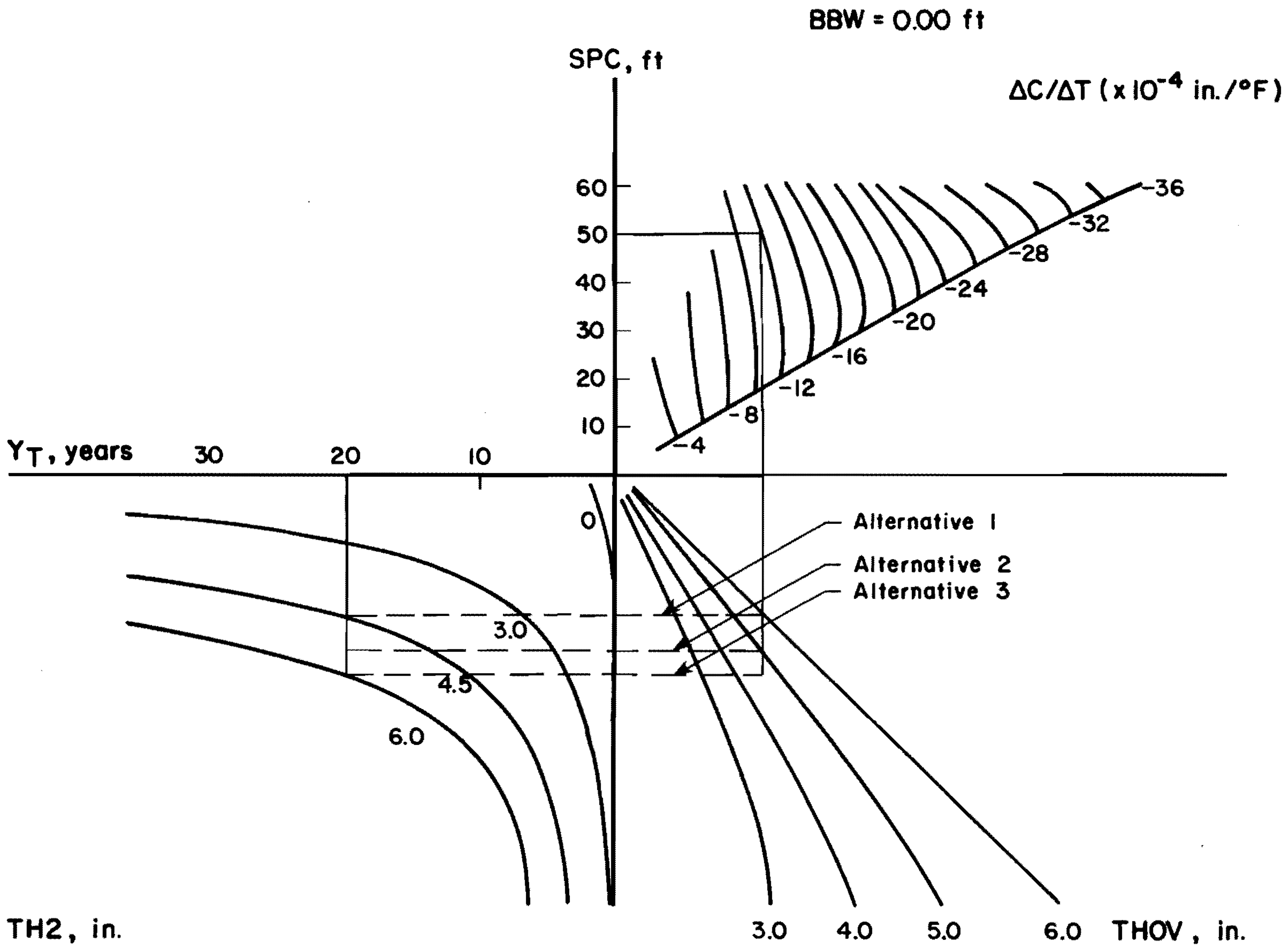


Fig 6.18. JCP/JRCP-B (BBW = 0 ft) design chart.

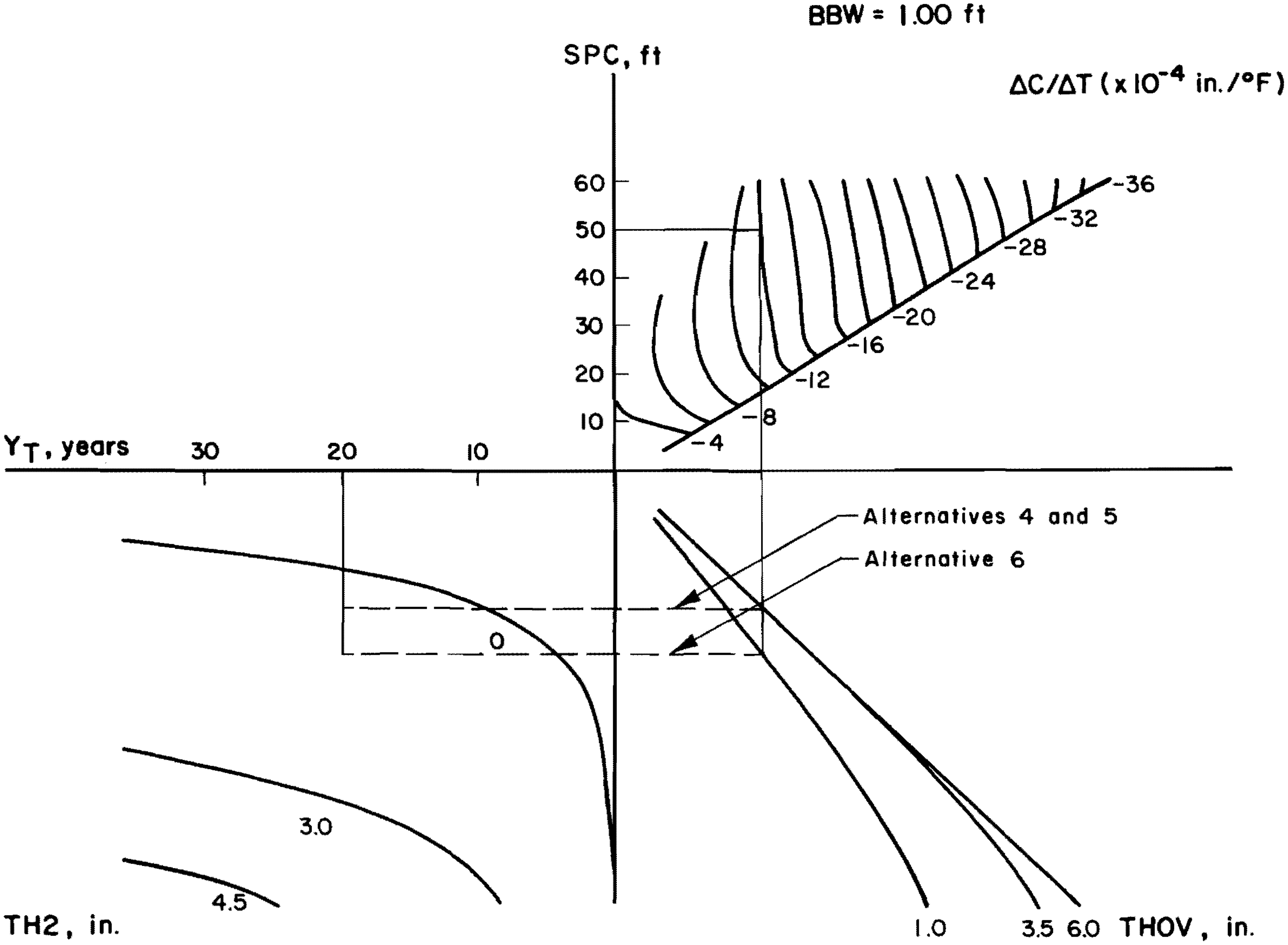


Fig 6.19. JCP/JRCP-B (BBW = 1 ft) design chart.

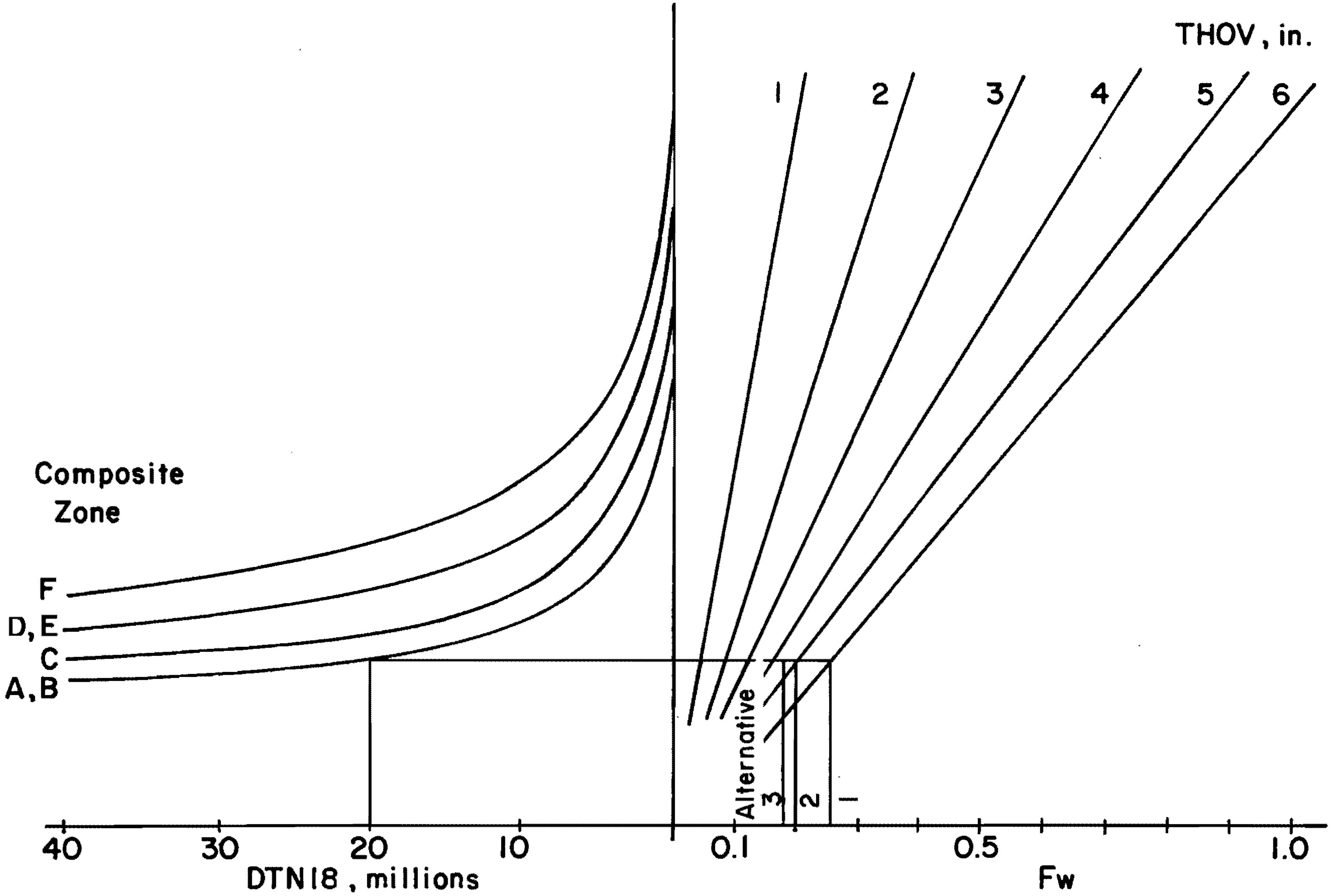


Fig 6.20. Design chart for estimating allowable deflection factor, F_w .

The longitudinal profile of deflection factors F_w versus distance along the roadway showing those joints requiring undersealing in the design section for all alternatives is shown in Fig 6.21.

Assuming the costs of material and placement operations are $150/yd^3 for the open graded intermediate layer, $200/yd^3 for the HMAC overlay and $150 for undersealing one joint, the costs associated with each alternative are presented in Table 6.6. Alternative 2 should be selected based on the results obtained.

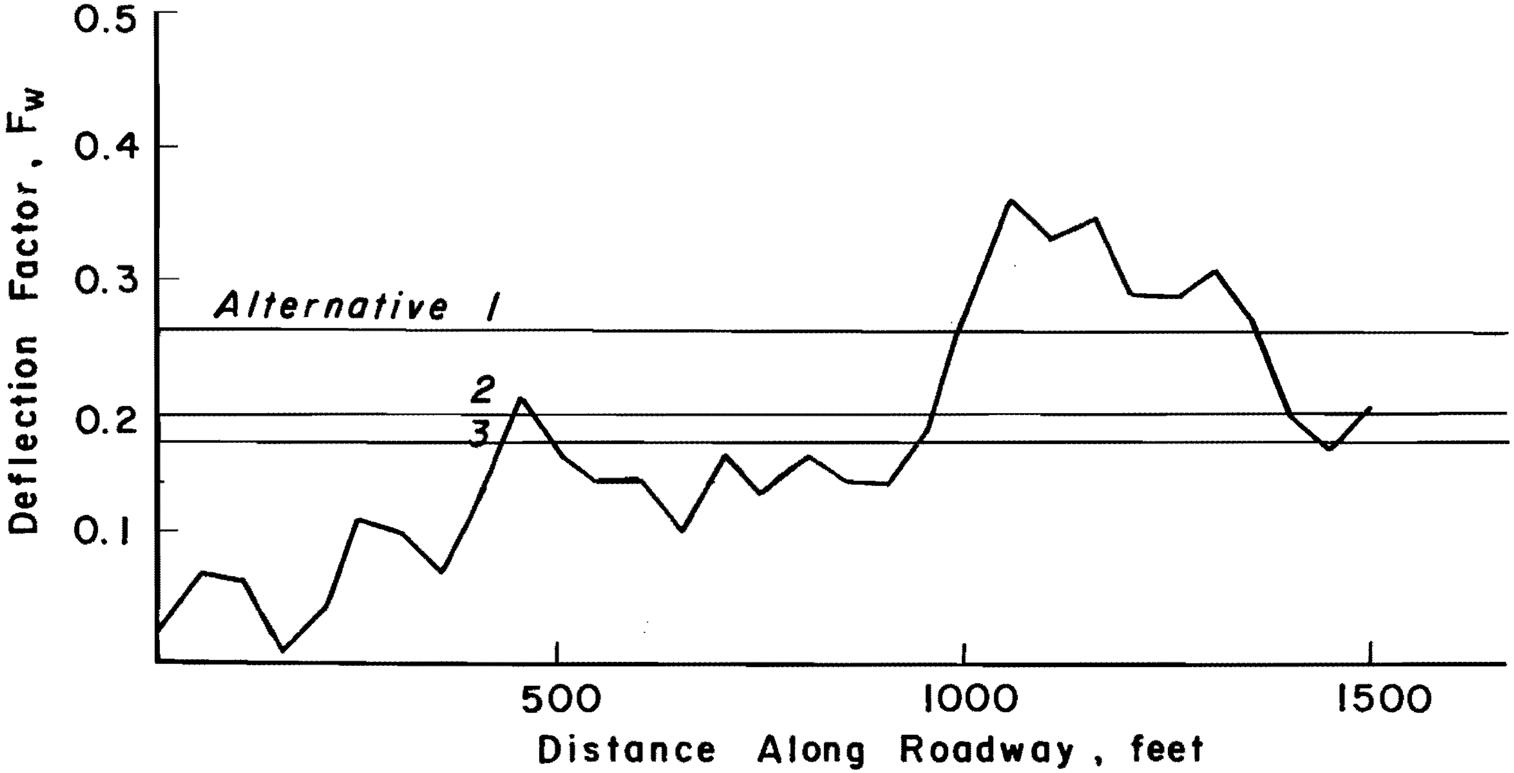


Fig 6.21. Joint requiring undersealing in the design section for all design alternatives.

TABLE 6.6. COMPARISON OF COSTS FOR ALTERNATIVES

	Unit Costs			Amount				
Alternative	Intermediate Layer ($/CY)	Overlay ($/CY)	Undersealing ($/Joint)	TH2 (in.)	THOV (in.)	No. of Joints to Underseal	Cost of Layers* ($)	Cost of Undersealing ($)
1	150	200	150	4.5	6.0	8	104,040	1,200
2	150	200	150	5.0	5.0	11	97,200	1,650
3	150	200	150	6.0	4.5	12	99,900	1,800

Alternative	Total Cost ($)
1	105,240
2	98,850
3	101,700

* for 1,500-foot-long section, 12 feet wide

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions and recommendations developed in this study.

CONCLUSIONS

(1) The design procedure presented here is based on the theoretical analysis of the mechanisms leading to the appearance of reflection cracking complimented with a series of field measurements that directly characterize the pavement potential for developing this distress type.

(2) The design of a specific overlay project can be made in any of three possible ways, according to the level of accuracy and detail desired in the results. The first level is computer based with very precise input data characterizing the conditions of the problem. The second level is also computer based, but the selection of the input data is made from a series of recommended values for the conditions prevailing in Texas. The third level is a hand solution based on a simplified set of equations and design charts developed for typical conditions of Texas pavements.

(3) The predicting capabilities of the design charts developed in this study were checked versus the performance of various Texas overlaid sections. These sections were located in climatological zones not included when the ARKRC-2 program was calibrated. The predictions of overlay life compared very well with the actual performance of the surveyed sections, thus permitting verification of the accuracy of the design charts and especially of the ARKRC-2 model.

(4) In Texas, the common practice has been to use thicker overlays to minimize reflection cracking although the implementation of such a technique may not be sufficient for pavements exhibiting a large potential for reflection cracking. For these cases, the design procedure permits combining of two or three techniques to achieve the desired overlay performance.

RECOMMENDATIONS

(1) The level of detail required in the design analysis must be an optimum compromise between economy and the desired accuracy of results.

(2) Direct use in the design of the regression equations will eliminate the error associated with reading from the design charts. The regression equations can be easily used with a small programmable desk calculator.

(3) It may be desirable to extend the capacity of ARKRC-2 by including a wider range of techniques to minimize reflection cracking. The effectiveness of these techniques could be evaluated from a theoretical standpoint.

(4) For any overlay project constructed using the new design procedure, it is recommended that a program of periodic surveys be conducted in order to monitor the performance of these projects and to provide feedback on the adequacy of the procedure as well as a basis for re-calculation. The fatigue equations may be adjusted to obtain a better calibration to actual performance.

REFERENCES

1. "Arkansas Reflection Cracking Analysis and Overlay Design Procedure," The University of Arkansas, Arkansas State Highway and Transportation Department, Austin Research Engineers, Inc., Report No. NA3/1, February 1982.

2. "Overlay Design and Reflection Cracking Analysis for Rigid Pavement, Volume 1 - Development of New Design Criteria," Austin Research Engineers, Inc., Report RHWA-RD-77-66, August 1977.

3. Nie, N. H., et al, Statistical Packages for the Social Sciences, Second Edition, McGraw-Hill, New York, NY, 1975.

4. "Minimizing Reflection Cracking of Pavement Overlays," NCHRP Special Report 92, Transportation Research Board, Washington, D. C., 1982.

5. Von Voorhis, M. G., How to Make Alignment Charts, McGraw-Hill, New York, NY, 1937.

6. Levens, A. J., Nomography, Second Edition, John Wiley and Sons, New York, NY, 1959.

7. National Climatic Center, Federal Building, Asheville, North Carolina, 28801.

8. Chang, Hong-Jun, Robert L. Lytton, and Samuel H. Carpenter, "Prediction of Thermal Reflection Cracking in West Texas," Research Report 18-3, Texas Transportation Institute, Texas A & M University, March 1976.

9. Schnitter, O., W. R. Hudson, and B. F. McCullough, "A Rigid Pavement Overlay Design Procedure for Texas SDHPT," Research Report 177-13, Center for Transportation Research, The University of Texas at Austin, May 1978.

10. "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Volume 2 - Design Procedure," Report No. FHWA-RD-77-76, Austin Research Engineers, Inc., August 1977.

11. Darter, Michael I., W. R. Hudson, "Probabilistic Design Concepts Applied to Flexible Pavement System Design," Research Report 123-18, Texas State Department of Highways and Public Transportation, Texas A & M University, Center for Highway Research, The University of Texas at Austin, May 1973.

12. Anagnos, James N. and Thomas W. Kennedy, "Practical Method of Conducting the Indirect Tensile Test," Research Report No. 98-10, Center for Highway Research, The University of Texas at Austin, August 1972.

13. Neville, A. M., *Properties of Concrete*, Reprinted 1975, Pitman Publishing Ltd., London.

14. Jones, Jr., Truman R. and T. J. Hirsch, "The Physical Properties of Concrete at Early Ages," Texas Transportation Institute, Texas A & M University, College Station, Texas, August 1961.

APPENDIX A

TEXAS REFLECTION CRACKING ANALYSIS AND OVERLAY DESIGN PROGRAM

GUIDE FOR DATA INPUT

APPENDIX A. TEXAS REFLECTION CRACKING ANALYSIS AND OVERLAY DESIGN PROGRAM GUIDE FOR DATA INPUT

This appendix provides the necessary input data instruction for operating the ARKRC-2 program. The user should refer to the Design Procedure (Chapter 6) for criteria on the selection of appropriate data.

Two data input forms have been provided. The long form is presented first and is the required form for the first problem of every run. A short form is provided to allow the user to change overlay design characteristics (on successive problems) for a given design section without having to repeatedly input the data that remain constant. Figure A.1 provides an illustration of both the long ad short data forms.

It should be noted that "real" variables can be placed anywhere in the available field but must be punched with a decimal point. Integer numbers, on the other hand, should be right justified in their field and punched without the decimal point. Alphanumeric variables allow the use of any combination of numbers and/or letters in an available field.

Input Data Long Form

Card No. 1: Problem Description

IPROB = Problem number, integer, Col. 1-4, right justify.
PRODES = Problem description, alphanumeric, Col. 5-80.

Card No. 2: Existing Concrete Pavement

PVTYPE = Pavement type, alphanumeric, Col. 1-4.
" JCP" - plain jointed concrete pavement.
"JRCP" - jointed reinforced concrete pavement.
"CRCP" - continuously reinforced concrete pavement.
UC = Pavement condition, alphanumeric, Col. 5.
"U" - uncracked.
"C" - cracked.

SPACE = Joint (or crack) spacing (feet), real, Col. 11-20.
THC = Concrete slab thickness (inches), real, Col. 21-30.
EC = Creep modulus of concrete (psi), real, Col. 31-40.
ALFC = Concrete thermal coefficient (in./in./°F), real, Col. 41-50.
DENSC = Concrete density or unit weight (pcf), real, Col. 51-60.
DS = Concrete slab movement at sliding (inches), real, Col. 61-70.

Card No. 3: Existing Pavement Reinforcement

BARD = Longitudinal bar diameter (inches), real, Col. 11-20.
BARS = Longitudinal bar spacing (inches), real, Col. 21-30.
ES = Steel elastic modulus (psi), real, Col. 31-40.
ALFS = Steel thermal coefficient (in./in./°F), real, Col. 41-50.
SMU = Steel to concrete bonding stress (psi), real, Col. 51-60.

Card No. 4: Existing Pavement Movement Characteristion

TH = High temperature (°F), real, Col. 11-20.
WH = Joint (crack) width at high temperature (inches), real, Col. 21-30.
TL = Low temperature (°F), real, Col. 31-40.
WL = Joint (crack) width at low temperature (inches), real, Col. 41-50.
TI = Minimum temperature observed (°F), real, Col. 51-60.

Card No. 5: Asphalt Concrete Overlay Characteristics

THOV = Overlay thickness (inches), real, Col. 11-20.
EOV = Overlay creep modulus (psi), real, Col. 21-30.
EDV = Overlay dynamic modulus (psi), real, Col. 31-40.
ALFV = Overlay thermal coefficient (in./in./°F), real, Col. 41-50.
DENSOV = Overlay density or unit weight (pcf), real, Col. 51-60.
OVBS = Overlay to concrete surface bond-slip stress (psi), real, Col. 61-70.

BBW = Bond breaker width (feet), real, Col. 71-80.

Card No. 6: Intermediate Layer Characteristics

TH2 = Intermediate layer thickness (inches), real, Col. 11-20.
E2 = Intermediate layer creep modulus (psi), real, Col. 21-30.
ED2 = Intermediate layer dynamic modulus (psi), real, Col. 31-40.

ALF2 = Intermediate layer thermal coefficient (in./in./°F), real, Col. 41-50.
DENS2 = Intermediate layer density or unit weight (pcf), real, Col. 51-60.

Card No. 7: Design Traffic

DTN18 = Design 18-kip single axle wheel loads, real, Col. 11-20.

Card No. 8: Yearly Frequency of Minimum Temperatures

DAY 1 = Average number of days during the year in which the minimum temperature is between 40 and 49°F, real, Col. 11-20.

DAY 2 = Average number of days during the year in which the minimum temperature is between 30 and 39°F, real, col. 21-30.

DAY 3 = Average number of days during the year in which the minimum temperature is betwleen 20 and 29°F, real, Col. 31-40.

DAY 4 = Average number of days during the year in which the minimum temperature is between 10 and 19°F, real, Col. 41-50.

DAY 5 = Average number of days during the year in which the minimum temperature is between 0 and 9°F, real, Col. 51-60.

DAY 6 = Average number of days during the year in which the minimum temperature is between -10 and -1°F, real, Col. 61-70.

DAY 7 = Average number of days during the year in which the minimum temperature is between -20 and -11°F, real, Col. 71-80.

Card No. 9: Instruction Card

APS = Instruction code for next problem, alphanumeric, Col. 1-4.
= "ALL" - Use input data long form for next problem.
= "PART" - Use input data short form for next problem.
= "STOP" - No more problems, stop execution.

Input Data Short Form

In cases where only the design variables are being changed, it is not necessary for the user to input all the data for each problem (it is still required for the first problem of each run). This short two-card form may be used to change any one or combination of design variables while keeping the rest of the data from the preceding problem constant.

Card No. 1: Short Form for Design Variables

IPROB = Problem number, integer, Col. 6-10, right justify.
EOV = Overlay creep modulus (psi), real, Col. 11-20.
THOV = Overlay thickness (inches), real, Col. 21-30.
TH2 = Intermediate layer thickness (inches), real, Col. 31-40.
BBW = Bond breaker width (feet), real, Col. 41-50.
DTN18 = Design 18-kip single axle wheel loads, real, Col. 51-60.

Card No. 2: Instruction Card

Same as Card No. 9 in long form.

Input Data Long Form (required for first problem of every run):

CARD NUMBER / COLUMN NUMBER	1 5	10	20	30	40	50	60	70	80
1.	IPROB	PRODES (PROBLEM DESCRIPTION)							
2.	PVTYPE	☒	SPACE	THC	EC	ALFC	DENSC	DS	
3.	REINF		BARD	BARS	ES	ALFS	SMU		
4.	MOVMT CHAR		TH	WH	TL	WL	T1		
5.	OVERLAY		THOV	EOV	EOV	ALFV	DENSOV	OVBS	BBW
6.	INTR LAYER		TH2	E2	ED2	ALF2	DENS2		
7.	TRAFFIC		DTN18						
8	FREQ DAYS		DAY_1	DAY_2	DAY_3	DAY_4	DAY_5	DAY_6	DAY_7
9.	APS								

Input Data Short Form

1.	SHORT	IPROB	EOV	THOV	TH2	BBW	DTN18
2.	APS						

Fig A.1. Summary input guide for Arkansas Reflection Cracking Analysis and Design Program, ARKRC-2

```
ARKRC - ARKANSAS REFLECTION CRACKING ANALYSIS AND OVERLAY
        DESIGN PROGRAM - VERSION 2.0 - NOVEMBER 1981

PROBLEM   1 DESCRIPTION                                     PAGE 1
ARKRC2 EXAMPLE PROBLEM, 26-FT JCP ON I-30 NEAR BENTON ARKANSAS

                            *******************
                            * INPUT VARIABLES *
                            *******************

    EXISTING CONCRETE PAVEMENT
          TYPE                                                    JCP
          CONDITION                                         UNCRACKED
          JOINT SPACING, FT                                     26.00
          SLAB THICKNESS, IN.                                   10.00
          CONCRETE CREEP MODULUS, PSI                        3400000.
          CONCRETE THERMAL COEFFICIENT, IN/IN/F             .00000750
          UNIT WEIGHT OF CONCRETE, PCF                          145.0
          MOVEMENT AT SLIDING, IN                               .0200

    EXISTING PAVEMENT REINFORCEMENT
          BAR DIAMETER, IN.                                     0.000
          BAR SPACING, IN.                                      0.000
          ELASTIC MODULUS OF STEEL, PSI                     30000000.
          THERMAL COEFFICIENT OF STEEL, IN/IN/F            0.00000000
          MAXIMUM BOND STRESS, PSI                                 0.

    EXISTING PAVEMENT MOVEMENT CHARACTERIZATION
          HIGH TEMPERATURE, DEGREES F                            84.0
          JOINT/CRACK WIDTH AT HIGH TEMPERATURE, IN.         .0650000
          LOW TEMPERATURE, DEGREES F                             34.0
          JOINT/CRACK WIDTH AT LOW TEMPERATURE, IN.          .1700000
          MINIMUM TEMPERATURE OBSERVED, DEGREES F                 0.0

    ASPHALT CONCRETE OVERLAY CHARACTERISTICS
          THICKNESS (BINDER + SURFACE), IN.                      3.00
          CREEP MODULUS, PSI                                   29000.
          DYNAMIC MODULUS, PSI                                614000.
          THERMAL COEFFICIENT, IN/IN/F                      .00001400
          UNIT WEIGHT, PCF                                      140.0
          MAXIMUM BOND STRESS, PSI                               250.
          BOND BREAKER WIDTH, FT.                                0.00

    INTERMEDIATE LAYER CHARACTERISTICS
          THICKNESS, IN.                                         4.00
          CREEP MODULUS, PSI                                    5000.
          DYNAMIC MODULUS, PSI                                 20000.
          THERMAL COEFFICIENT, IN/IN/F                      .00002000
          UNIT WEIGHT, PCF                                      120.0

    DESIGN TRAFFIC (18-KIP ESAL)                            10000000.
```

Figure A.2. Example print-out of ARKRC-2 program for first problem of overlay design for 26-foot JCP in Arkansas.

```
ARKRC - ARKANSAS REFLECTION CRACKING ANALYSIS AND OVERLAY
        DESIGN PROGRAM - VERSION 2.0 - NOVEMBER 1981

PROBLEM   1 DESCRIPTION                                         PAGE 2
ARKRC2 EXAMPLE PROBLEM, 26-FT JCP ON I-30 NEAR BENTON ARKANSAS

    YEARLY FREQUENCY OF CRITICAL MINIMUM TEMPERATURES

                  MINIMUM       NO. OF
         TEMP.  TEMPERATURE    DAYS PER
         CLASS  RANGE (DEG F)    YEAR
         -----  -------------  --------
           1      +49 TO +40      57.
           2      +39 TO +30      61.
           3      +29 TO +20      36.
           4      +19 TO +10      11.
           5      + 9 TO   0       2.
           6      - 1 TO -10       0.
           7      -11 TO -20       0.


                           ****************
                           * ARKRC OUTPUT *
                           ****************


    BETA VALUES
         BEFORE OVERLAY                                          .10256
         AFTER OVERLAY (UNBONDED REGION)                         .17089
         AFTER OVERLAY (BONDED REGION)                           .20439

    DESIGN SHEAR STRAIN CRITERIA
         MAXIMUM OVERLAY SHEAR STRAIN                           .000173
         MAXIMUM DEFLECTION FACTOR                                 .237

    FATIGUE LIFE (TENSILE STRAIN CRITERIA)

                NO. OF       OVERLAY       ALLOWABLE
         TEMP.  DAYS PER  TENSILE STRAIN   FATIGUE      YEARLY
         CLASS    YEAR       (IN/IN)        CYCLES      DAMAGE
         -----  --------  --------------  ---------     ------
           1       57.       .0003878      34681.        .0016
           2       61.       .0011635        595.        .1025
           3       36.       .0019391         90.        .4003
           4       11.       .0027147         26.        .4248
           5        2.       .0034904         10.        .1957

                                                        ------
                           TOTAL YEARLY DAMAGE          1.1249

         NO. OF YEARS BEFORE FAILURE CRITERIA IS REACHED        .9
```

Figure A.3. (continued) Example print-out of ARKRC-2 program for first problem of overlay design for 26-foot JCP in Arkansas.

APPENDIX B

YEARLY FREQUENCY DISTRIBUTIONS

H TEST COMPUTED VALUES

TABLE B.1. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR FORT STOCKTON STATION (NATURAL CLIMATIC CENTER)

Year	Class*							
	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	83	68	40	6	0	0	0	0
1974	61	57	43	5	0	0	0	0
1975	74	81	43	1	0	0	0	0
1976	72	72	43	10	1	0	0	0
1977	55	73	36	6	1	0	0	0
1978	57	62	46	5	0	0	0	0
1979	67	57	56	8	2	0	0	0
1980	72	64	49	5	0	0	0	0
Total	541	534	356	46	4	0	0	0
Average	68	67	45	6	1	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.2. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR FREER STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	61	30	11	0	0	0	0	0
1974	68	35	8	0	0	0	0	0
1975	52	30	4	0	0	0	0	0
1976	69	28	10	0	0	0	0	0
1977	61	34	4	0	0	0	0	0
1978	46	38	6	0	0	0	0	0
1979	65	45	11	0	0	0	0	0
1980	53	28	3	0	0	0	0	0
Total	475	268	57	0	0	0	0	0
Average	59	34	7	0	0	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.3. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR HUNTSVILLE STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	66	38	15	2	0	0	0	0
1974	58	41	15	0	0	0	0	0
1975	56	48	9	1	0	0	0	0
1976	67	45	11	4	0	0	0	0
1977	67	36	14	4	0	0	0	0
1978	50	40	36	2	0	0	0	0
1979	52	47	22	5	0	0	0	0
1980	67	46	11	1	0	0	0	0
Total	483	341	133	19	0	0	0	0
Average	60	43	17	2	0	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.4. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR JUNCTION STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	67	51	35	5	2	0	0	0
1974	49	48	36	8	1	0	0	0
1975	57	60	37	8	0	0	0	0
1976	60	56	39	11	1	0	0	0
1977	45	68	40	4	0	0	0	0
1978	31	40	23	7	0	0	0	0
1979	53	48	29	8	1	0	0	0
1980	45	34	15	0	0	0	0	0
Total	407	405	254	51	5	0	0	0
Average	51	51	32	6	1	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.5. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR MCALLEN STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	40	17	6	0	0	0	0	0
1974	51	14	0	0	0	0	0	0
1975	44	18	2	0	0	0	0	0
1976	61	17	2	0	0	0	0	0
1977	57	15	2	0	0	0	0	0
1978	35	17	2	0	0	0	0	0
1979	54	17	2	0	0	0	0	0
1980	48	20	0	0	0	0	0	0
Total	390	135	16	0	0	0	0	0
Average	49	17	2	0	0	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.6. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR MINERAL WELLS STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	64	55	23	6	1	0	0	0
1974	9	28	14	6	0	0	0	0
1975	68	56	27	4	0	0	0	0
1976	62	54	29	8	1	0	0	0
1977	61	39	25	10	1	0	0	0
1978	45	51	42	9	0	0	0	0
1979	55	51	31	10	0	0	0	0
1980	67	57	26	5	1	0	0	0
Total	431	391	217	58	4	0	0	0
Average	54	49	27	7	1	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.7. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR PLAINVIEW STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	32	68	50	10	5	0	0	0
1974	60	60	58	10	3	0	0	0
1975	56	40	57	8	1	0	0	0
1976	66	66	43	15	2	0	0	0
1977	45	76	42	19	3	0	0	0
1978	54	50	47	31	6	0	0	0
1979	42	75	49	24	2	1	0	0
1980	55	79	45	18	2	0	0	0
Total	410	514	391	141	24	1	0	0
Average	51	64	49	18	3	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.8. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR SAN MARCOS STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	66	53	15	3	0	0	0	0
1974	46	51	16	0	0	0	0	0
1975	57	50	25	2	0	0	0	0
1976	69	57	17	4	0	0	0	0
1977	57	56	15	3	0	0	0	0
1978	59	47	34	3	0	0	0	0
1979	53	46	32	4	0	0	0	0
1980	70	60	14	1	0	0	0	0
Total	477	420	168	20	0	0	0	0
Average	60	53	21	3	0	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.9. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR THOMPSONS STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	59	29	12	0	0	0	0	0
1974	57	25	3	0	0	0	0	0
1975	62	32	6	0	0	0	0	0
1976	72	39	10	0	0	0	0	0
1977	68	34	10	1	0	0	0	0
1978	41	51	13	0	0	0	0	0
1979	58	32	11	2	0	0	0	0
1980	51	40	4	0	0	0	0	0
Total	468	282	69	3	0	0	0	0
Average	59	35	9	0	0	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.10. YEARLY FREQUENCY DISTRIBUTION OF BELOW 50°F DAILY TEMPERATURE DROPS FOR VERNON STATION (NATIONAL CLIMATIC CENTER)

	Class*							
Year	1-10 (°F)	11-20 (°F)	21-30 (°F)	31-40 (°F)	41-50 (°F)	51-60 (°F)	61-70 (°F)	>71
1973	59	43	21	4	3	0	0	0
1974	46	47	32	10	1	0	0	0
1975	48	58	39	5	0	0	0	0
1976	63	64	48	8	2	0	0	0
1977	52	42	27	11	2	1	0	0
1978	51	41	53	17	2	0	0	0
1979	58	54	41	17	2	0	0	0
1980	56	67	40	11	1	0	0	0
Total	433	416	301	83	13	1	0	0
Average	54	52	38	10	2	0	0	0

* Classes represent ranges of differences between 50 degrees fahrenheit and the daily minimum temperature.

Note: Some years have missing days.

TABLE B.11. COMPUTED H VALUES TO COMPARE DROP CLASSES OF CLIMATOLOGICAL REGIONS

Stations Compared		Drop Classes					Result of H Test
		1-10	11-20	21-30	31-40	41-50	
Stockton -	Freer	3.19	11.29	11.24	11.29	*	
	Huntsville	3.19	11.29	11.29	8.04	*	
	Junction	7.46	7.46	9.28	0.00	1.10	
	McAllen	9.28	11.29	11.29	11.29	*	
	Mineral Wells	3.19	11.29	9.93	0.28	1.59	
	Palinview	7.46	0.00	1.59	9.28	7.46	
	San Marcos	3.19	9.93	11.29	7.46	*	
	Thompsons	2.82	11.29	11.29	10.60	*	
	Vernon	6.35	5.83	2.48	2.48	2.16	
Freer -	Huntsville	0.00	6.89	6.89	6.35	*	
	Junction	3.19	8.04	11.29	6.35	*	
	McAllen	4.86	11.29	9.28	11.29	*	
	Mineral Wells	0.18	5.83	11.29	11.29	*	
	Palinview	2.16	10.60	11.29	11.29	*	
	San Marcos	0.00	11.29	11.29	6.35	*	
	Thompsons	0.00	0.18	0.18	2.82	*	**
	Vernon	2.48	9.28	11.29	11.29	*	
Huntsville -	Junction	3.57	2.82	6.35	4.41	*	
	McAllen	5.33	11.29	11.29	11.29	*	
	Mineral Wells	0.27	3.57	4.86	8.64	*	
	Plainview	3.57	7.46	11.29	11.29	*	
	San Marcos	0.00	3.04	1.59	0.00	*	**
	Thompsons	0.00	4.41	5.83	8.65	*	
	Vernon	3.18	3.19	8.65	8.65	6.35	
Junction -	McAllen	0.27	11.29	11.29	11.29	*	
	Mineral Wells	1.10	0.00	1.59	0.00	2.82	**
	Plainview	0.00	3.19	11.29	8.04	6.89	
	San Marcos	2.16	0.00	5.34	6.89	*	
	Thompsons	1.86	7.46	11.29	9.93	*	
	Vernon	0.40	0.00	1.33	1.59	1.59	**
McAllen -	Mineral Wells	2.82	11.29	11.29	11.29	*	
	Plainview	0.28	11.29	11.29	11.29	*	
	San Marcos	3.98	11.29	11.29	6.35	*	
	Thompsons	3.57	11.29	9.28	2.82	*	
	Vernon	1.33	11.29	11.29	11.29	6.35	
Mineral Wells -	Plainview	1.86	4.41	10.60	7.45	8.65	
	San Marcos	0.00	0.00	1.59	11.29	*	
	Thompsons	0.00	5.83	11.29	11.29	*	
	Vernon	1.10	0.18	3.19	1.33	2.82	**
Plainview -	San Marcos	2.48	3.98	11.29	11.29	*	
	Thompsons	1.86	9.92	11.29	11.29	*	
	Vernon	0.17	3.19	5.34	3.98	6.35	
San Marcos -	Thompsons	0.00	9.28	11.29	9.28	*	
	Vernon	2.16	0.00	6.89	9.92	6.35	
Thompsons -	Vernon	1.59	8.65	11.29	11.29	6.35	

For H < X 95 percent = 3.84, null hypothesis must be accepted (95 percent confidence level).

* H values have no significance for these cases.

** Null hypothesis accepted for all drop classes of frequency.

APPENDIX C

PLOTS OF COMPUTED OVERLAY LIFE FROM ARKRC-2 VERSUS PREDICTED OVERLAY LIFE FROM REGRESSION EQUATIONS

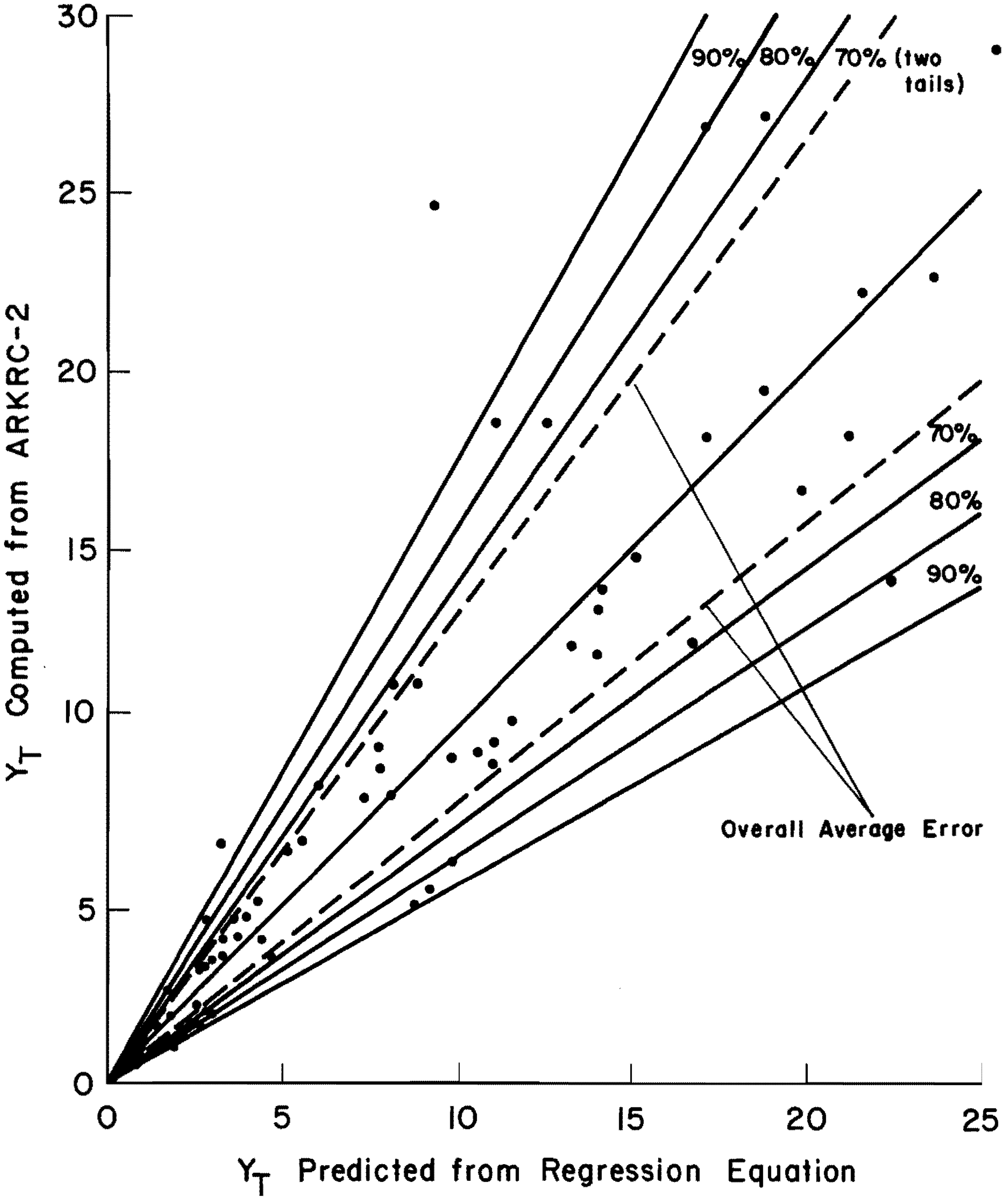


Fig C.1. Ranges of prediction for different confidence levels for the JCP/JRCP-B regression equation.

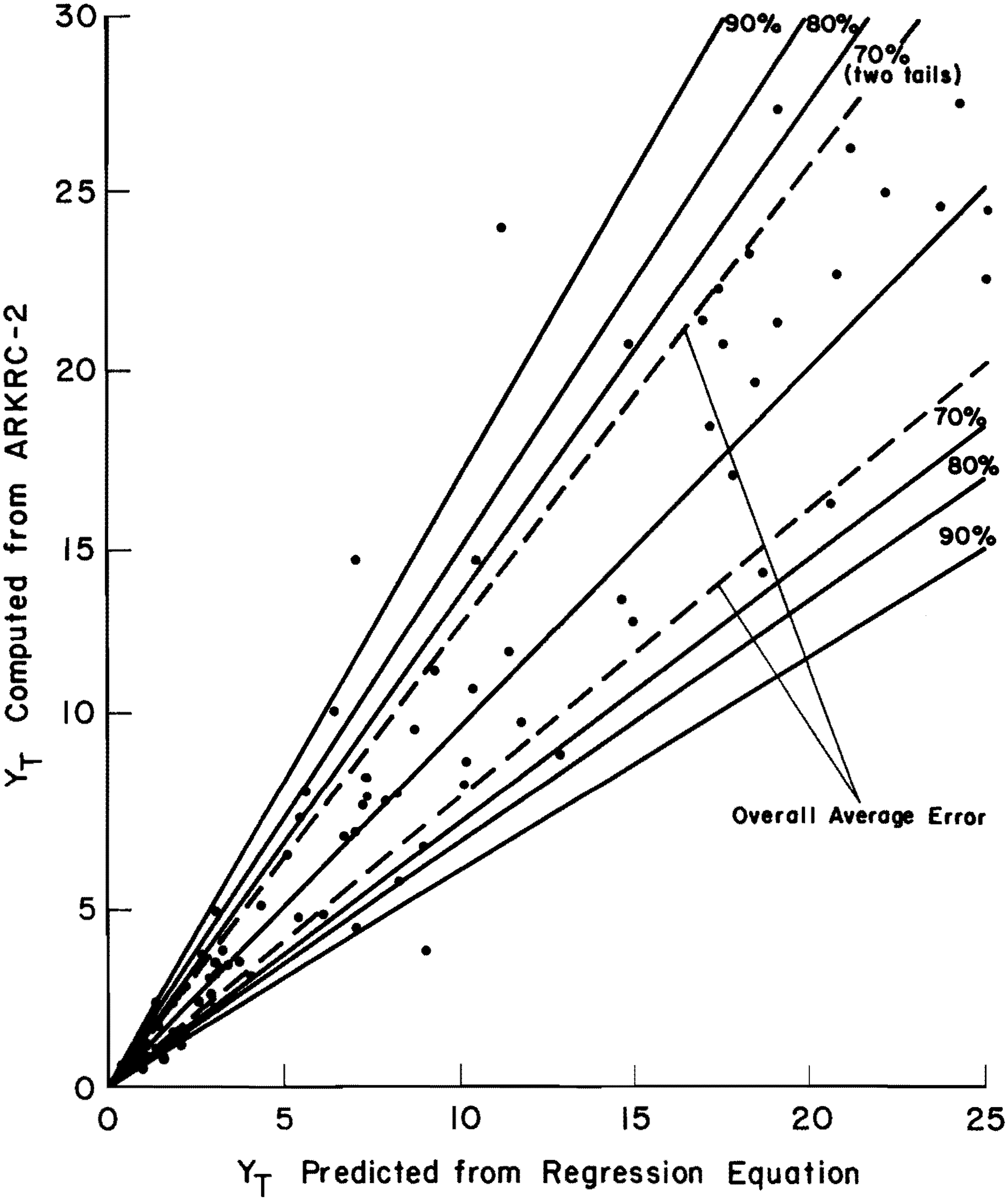


Fig C.2. Ranges of prediction for different confidence levels for the JCP/JRCP-D regression equation.

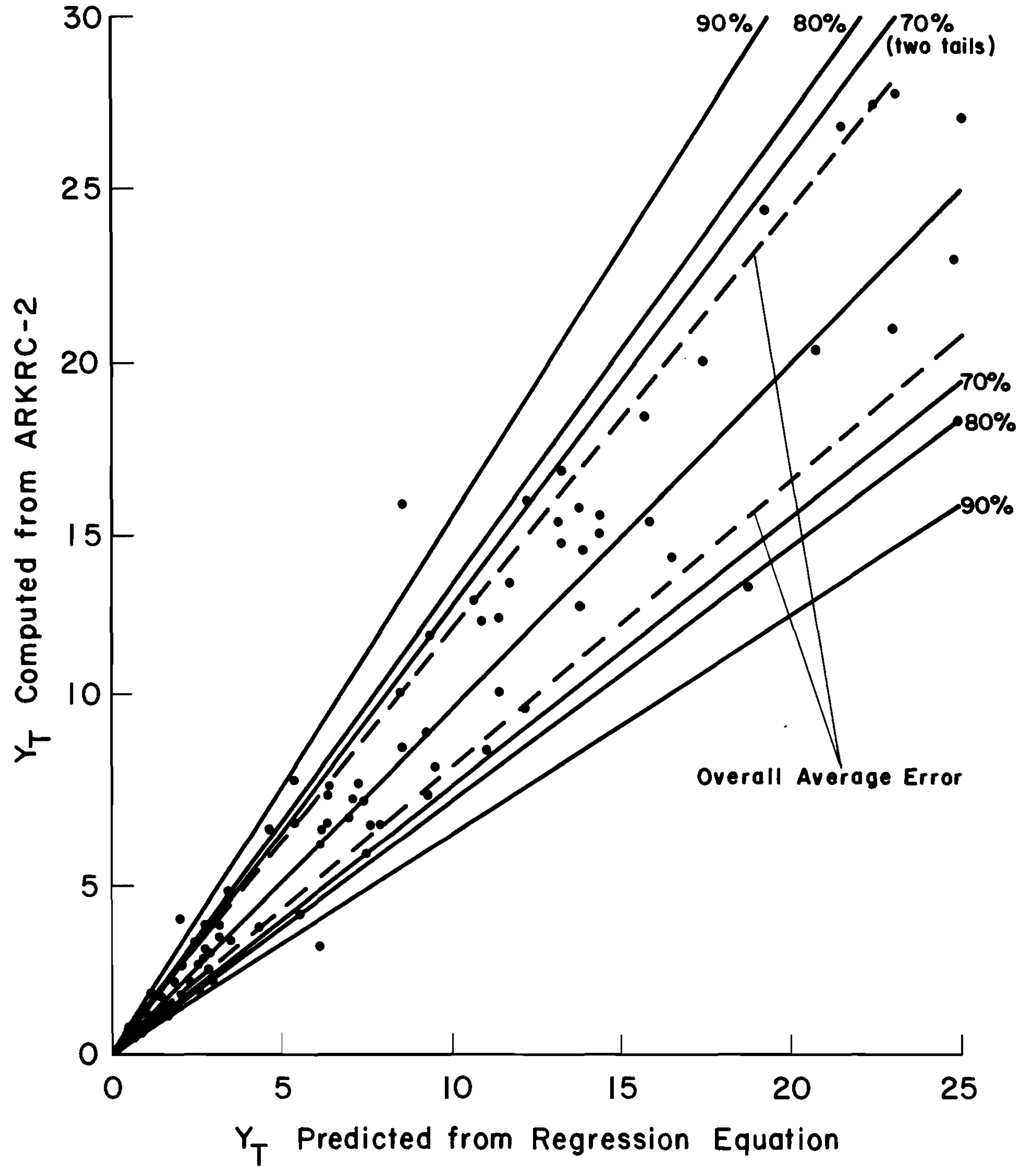


Fig C.3. Ranges of prediction for different confidence levels for the JCP/JRCP-F regression equation.

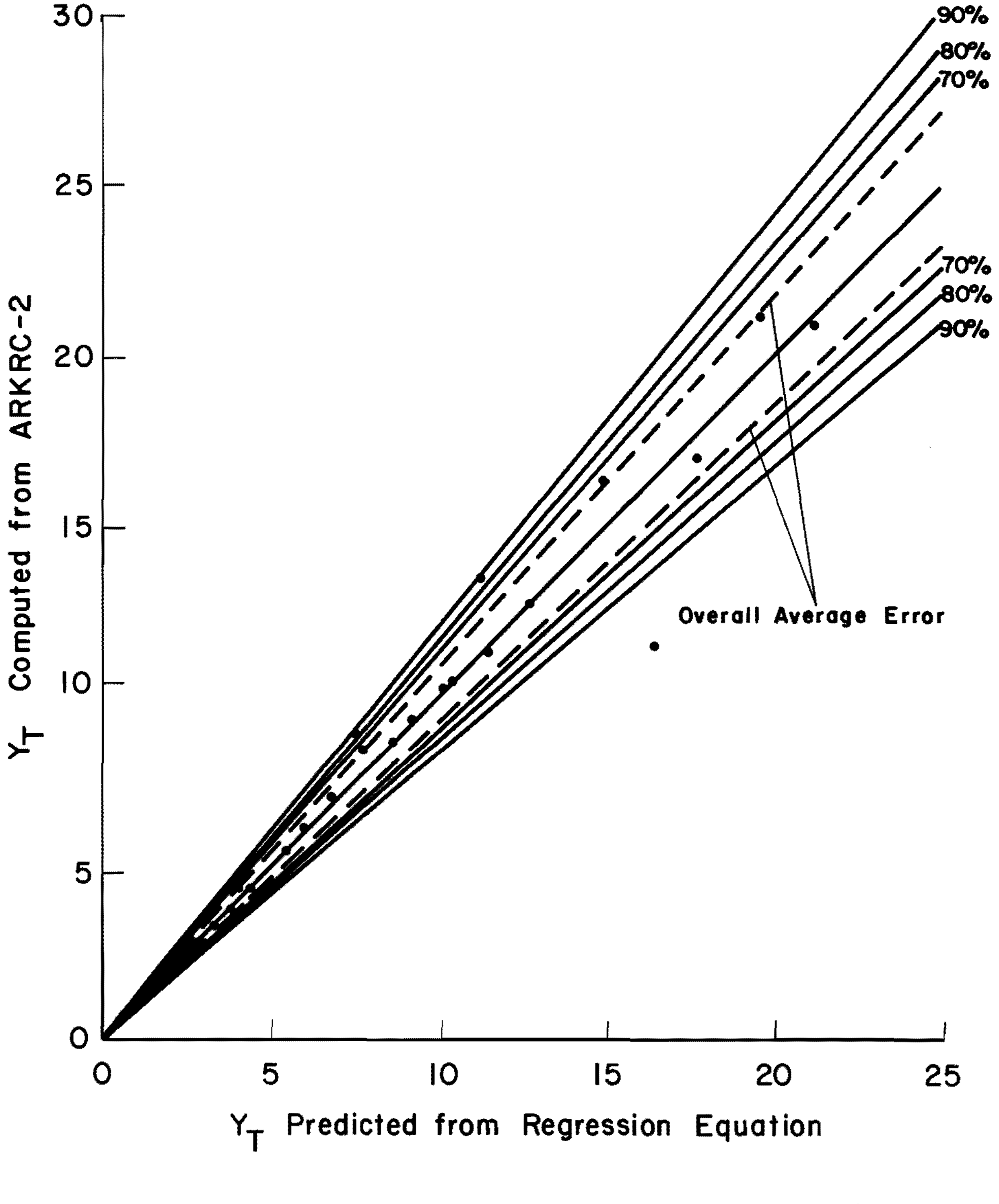


Fig C.4. Ranges of prediction for different confidence levels for the CRCP-B regression equation.

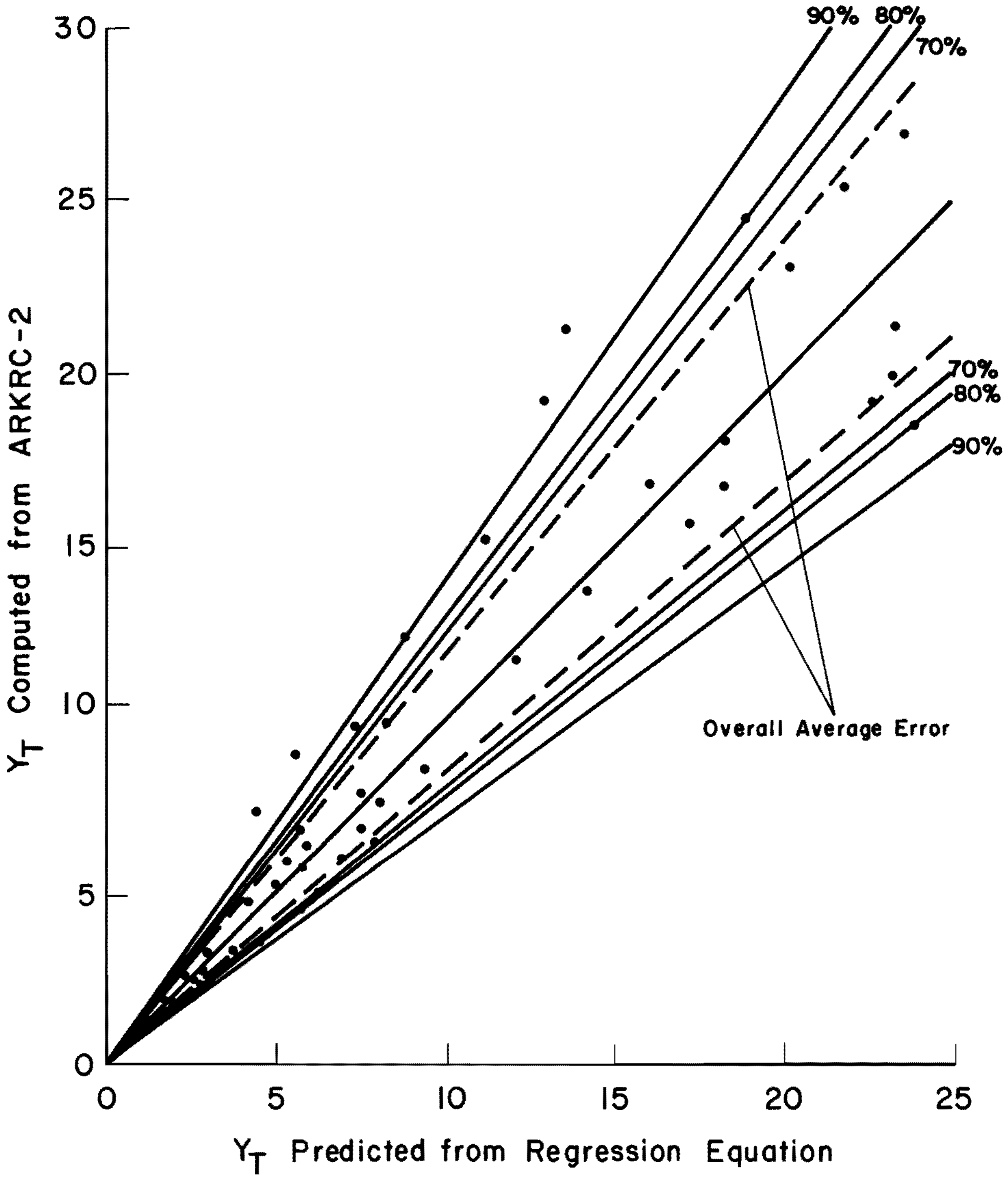


Fig C.5. Ranges of prediction for different confidence levels for the CRCP-D regression equation.

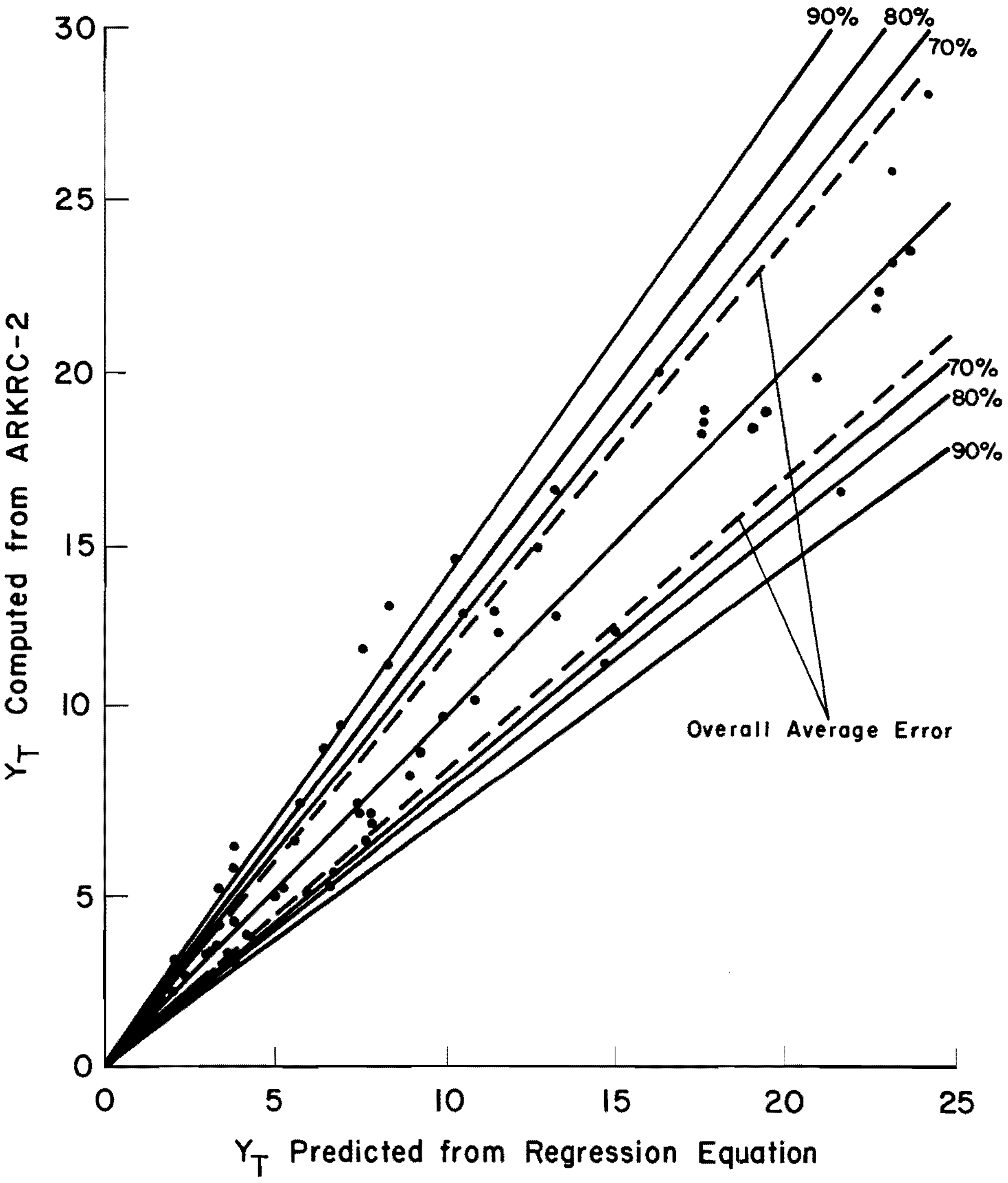


Fig C.6. Ranges of prediction for different confidence levels for the CRCP-F regression equation.