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FLEXIBLE PAVEMENT OVERLAY DESIGN PROCEDURES

Vol. 2. User Manual
August 1981
Final Report

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Federal Highway Administration

Offices of Research & Development
Structures and Applied Mechanics Division
Washington, D.C. 20590

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FOREWORD

This two-volume report, FHWA/RD-81/032 and 81/033, presents the results of research conducted by Resource International, Inc. for the Federal Highway Administration (FHWA), Office of Research, under contract DOT-FH-11-9315. This work was a part of FCP Project 6D, "Structural Rehabilitation of Pavement Systems." The study was initiated to evaluate the overlay procedure developed under contract DOT-FH-11-8544 by Austin Research Engineers, Inc., published in reports FHWA-RD-75-75 and FHWA-RD-75-76. This procedure, along with several others, was compared and a slightly revised version has been recommended for implementation. Volume 1 discusses the evaluation and modification of the flexible overlay design procedure, and Volume 2 is a user manual for the revised procedure.

The overlay method presented is a combination and modification of several existing methods and incorporates the latest state-of-the-art concepts in pavement evaluation and overlay determination. The overlay thickness is determined based on a fatigue distress function developed from the AASHO Road Test data. The existing pavement is evaluated using nondestructive dynamic deflection measurements and a visual survey which includes general observations regarding drainage, the existence of rutting and the presence and type of cracking.

Copies of this two-volume report are being given widespread distribution by FHWA Bulletin. Additional copies may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

NOTICE

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16. Abstract This report is a user's manual for the design of flexible overlays of flexible pavements. Detailed instructions are given on obtaining the necessary input data and entering this data into the completely computerized design package. The design procedure is based on fatigue cracking criterion and nondestructive evaluation of the existing pavement. Input is required from the following areas: 1) dynamic deflection testing, 2) limited condition surveys, 3) projected future traffic in terms of equivalent 18 Kip (80kN) axle loads, and 4) material characterization. The condition of the existing pavement is determined from dynamic deflection measurements using 3-4 layer elastic layer theory to characterize the existing pavement. The condition survey is limited to determination of the presence or absence of class 2 and 3 cracking, and the extent of this cracking, when present. Materials characterization requires the determination of layer thicknesses, estimation of layer Poisson's ratios, estimation of the stress dependency relationship of base and subgrade moduli, and estimation of the asphalt modulus-temperature relationship. Guidelines are presented for the solution of these parameters when laboratory testing is not available. In contrast with most other design methods, pavement evaluation and overlay thickness determination are done at each location where dynamic deflection measurements were made. This allows the pavement engineer to consider alternate repair strategies, such as improvements in drainage, recycling or reconstruction, in areas requiring thick overlays, and may consequently result in more economical solutions.

This report is Volume 2 of a two-part series. The first is: Flexible Pavement Overlay Design Procedures - Evaluation and Modification of the Design Method, Volume 1 (FHWA-RD-81/032)

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PREFACE

This research report outlines design procedures for asphaltic concrete overlay on flexible pavements. The analytical techniques and design procedures recommended in this document are based on sound, fundamental principles of the mechanics of paving materials and elastic layered systems.

The framework for these proposed overlay design procedures was initially developed by Austin Research Engineers, under contract with the Federal Highway Administration, Office of Research, Contract No. DOT-FH-11-8544. The FHWA-ARE design procedures were presented in two separate volumes: Report No. FHWA-RD-75-75 and FHWA-RD-75-76.

The evaluation of this new FHWA-ARE overlay design was contracted to Resource International Inc., under the financial support of the Office of Research, Federal Highway Administration, Contract No. DOT-FH-11-9315.

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CHAPTER 1
INTRODUCTION

This user manual is Volume 2 of a two-part report prepared for the Federal Highway Administration Office of Research on the development and design of a "standard" method for flexible pavement overlay design and is part of FHWA FCP Project 5D, Structural Rehabilitation of Flexible Pavements. The procedure developed herein is based in part on "Asphaltic Concrete Overlays of Flexible Pavements (FHWA-RD-75-75) (1) as well as a review of numerous other overlay schemes in use throughout the world and combines the most desirable features of these schemes into one easy-to-use, state-of-the-art system.

1.1 OBJECTIVE

This user manual outlines a procedure for the design of asphaltic concrete overlays on existing asphaltic concrete pavement surfaces. It is intended as a guide to the user on the type and form of information required as input to the procedure and contains all elements necessary for the user to prepare designs for flexible pavement overlays. This manual does not cover in detail the theory or the reasons and logic underlying the procedure. Technical documentation is presented in Volume 1 (2) which describes in depth the research developments upon which this design procedure is based.

1.2 SCOPE OF PROCEDURE

An existing pavement may require overlay for various reasons, such as fatigue cracking, rutting, low skid resistance, surface deterioration in the form of spalling and ravelling, etc. The procedure described herein is not intended to establish maintenance and repair needs and priorities or to predict the future need of an overlay; rather, it attempts to determine the required overlay thickness after the decision to overlay is made. The selection of an overlay thickness is made based on a fatigue cracking model developed from the AASHO Road Test data tempered by experience and other studies. The procedure does not consider rutting as a distress mechanism, primarily because rutting of overlayed pavements in the United States is most often associated with unstable paving mixes; nor is it intended to consider localized distress modes due to expansive soils or severe environmental stresses. The question of reflection cracking is addressed only indirectly in that badly cracked existing pavements which are most likely to develop reflection cracking generally require either very thick overlays, or as an alternative, a total or partial reconstruction or recycling may be more economical, thus minimizing the potential for reflection cracking.

Since the fatigue model is based primarily on AASHO Road Test data, this procedure infers that the overlay materials and construction specifications will not significantly differ from those now in use. However, overlays using reinforcing fabric and improved paving mixtures such as sulfur and latex-modified asphaltic materials can be accommodated by appropriate modification of the distress function.

1.3 DESIGN PHILOSOPHY

Although several design options are presented, the primary design procedure is based on determination of in-situ pavement layer properties from non-destructive deflection measurements on existing pavement. The procedure determines the overlay thickness requirement for each test location; consequently, the areas requiring significantly thicker overlays readily stand out, enabling the designer to consider partial or total reconstruction, recycling or other remedial measures, such as drainage improvement prior to overlay. The designer can vary the overlay thickness along the highway as required by field conditions and also select an appropriate reliability level for design. With modern construction practices, variation in overlay thickness can readily be built, provided adequate transition length between sections is maintained for riding quality. In this design procedure, elastic layer theory is used as an analytical response model to make design computations. The computational procedures are completely computerized in which the output includes the overlay thicknesses in a graphic format as a function of locations along the roadway. On the basis of this test plot, the designer can then divide the overlay project into various sections with similar overlay requirements. A separate small computer program is used to determine the statistical significance of this division if required by the engineer.

1.4 EQUIPMENT REQUIREMENTS

The procedure is based on in-situ evaluation of material properties for a three-layered or a four-layered pavement system from measured surface deflection. Therefore, testing equipment capable of deflection profile measurements at least four distances from the applied load could be used. The design procedure has been developed for the Dynaflect, Road Rater and Falling Weight Deflectometer (FWD) testers since these testing devices have greater usage by State Departments of Transportation than any other models; however, the theory is general and the program can be modified for any other deflection testing device.

The computer program used in the design procedure has been written for the IBM 360 or 370 systems, but can be adapted, with slight modifications, to the CDC 6600 or the Univac 1108. The program is intended primarily for batch processing, but remote terminal operation is also feasible since the amount of data required for input is minimal.

1.5 SUMMARY OF PROCEDURE

The basic overlay design procedure is based on in-situ evaluation of pavement layer properties from measured surface deflections for a three-layer pavement system. There will be times, however, when the measured deflection data is inconsistent with a three-layer representation of the pavement structure. When this occurs, a four-layer analysis is carried out. Figure 1 is a simplified flow chart showing the steps and decisions used in the program. A detailed description of the program appears in Volume 1 (2) and Section 3.1 of this report.

Along with the basic procedure, four other options are offered:

A. The use of laboratory determined layer properties in a three-layer pavement system

B. The use of laboratory determined layer properties in a four-layer pavement system

C. The use of estimated layer properties (default values) in a three-layer pavement system

D. Determination of in-situ pavement layer properties for a four-layer pavement system.

The options A and B for the use of data obtained by laboratory testing are intended to serve the purpose of diagnosis and verification for those areas where laboratory test data for layer moduli is (or becomes) available. Option C using default values is included primarily for design purposes and may be used for the evaluation of the relative effectiveness of various base or pavement materials. Option D is made available so that the interested user can study the effects of combining the base and subbase layers into a single layer as is being done in the three-layer analysis. It should be pointed out, however, that this latter option is considerably more expensive to use.

Detailed input instructions for all modes of operation are given in Chapter 3 of this report.

FHWA-RII METHOD - OAF - PROGRAM

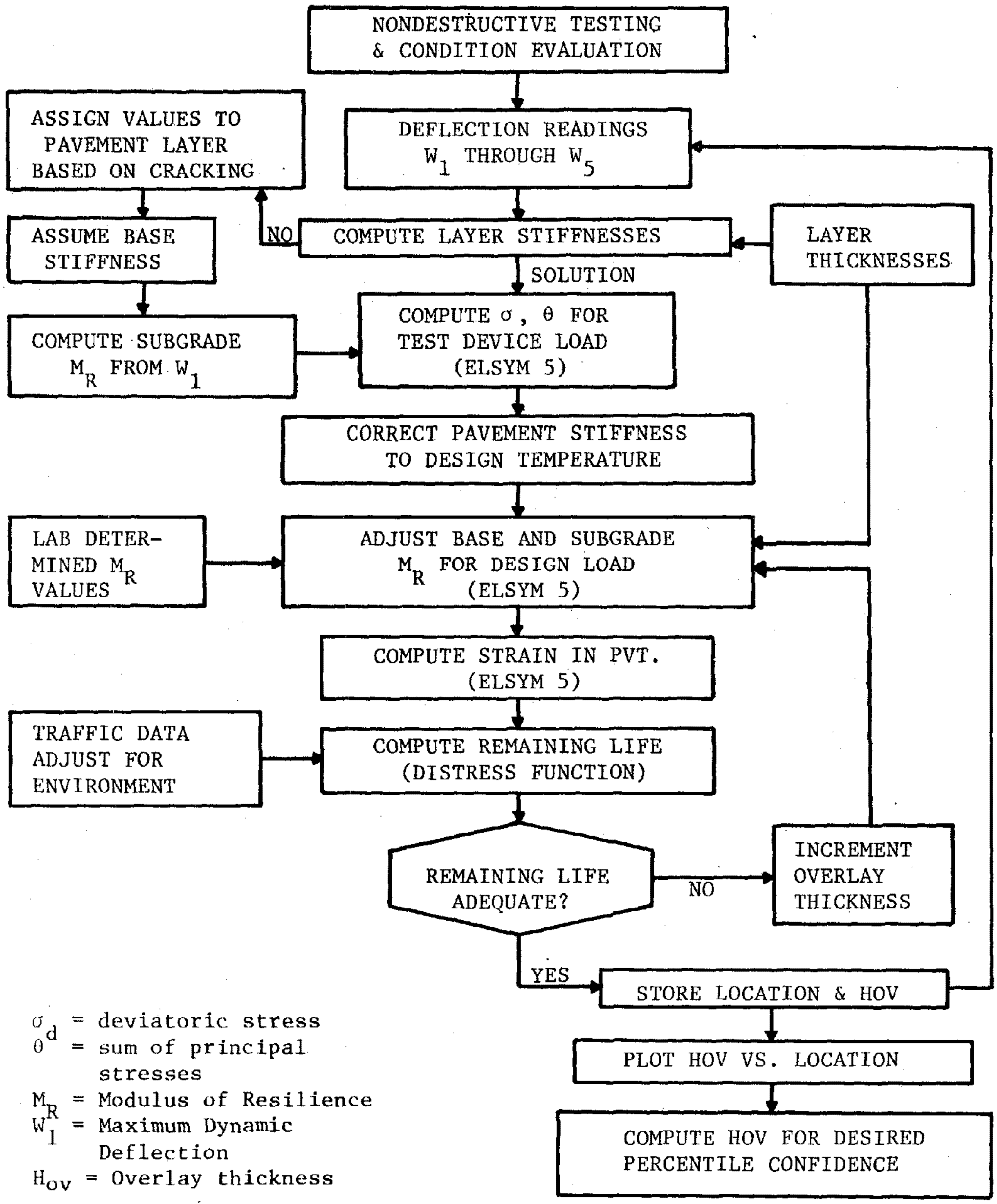


FIGURE 4. Simplified Flow Chart of OAF Program

CHAPTER 2
SELECTION OF INPUT DATA

In this chapter, the data input requirements for the overlay design procedures are presented. The choices of the data input are dependent on the design options selected. The basic design procedures in this chapter are based on measurement of dynamic deflections. For options A, B and C of Section 1.5, the data input requirements are somewhat different; these requirements are discussed in Sections 3.2.2 through 3.2.5.

In this design procedure, the data input are provided from the following areas:

1. Deflection data
2. Temperature measurements
3. Condition evaluation
4. Traffic data
5. Materials characterization

2.1 DEFLECTION DATA

Deflection testing is used to measure the structural adequacy of the in-service pavements and their responses to traffic loading. The measured surface deflection profiles are then used to calculate the in-situ stiffness of various pavement layers.

2.1.1 Equipment Type

As was stated in Chapter 1, the design procedure has been written for the Dynaflect, Road Rater, and Falling Weight Deflectometer testing devices. Since the design procedure makes use of at least four deflections and considers the actual loading and deflection measurement geometry, no satisfactory correlation exists between these testers and other devices such as the Benkelman Beam, California Traveling Deflectometer, Cox Device, or the WES device. It is, however, possible to modify the program for any other loading conditions or deflection measuring geometry; the only requirement is that the device measure deflection at at least four different distances from the applied load.

The testing device type is identified by the parameter DEVICE.

DEVICE = 1 for Dynaflect
DEVICE = 2 for Road Rater
DEVICE = 3 for trailer mounted Falling Weight Deflectometer (FWD)
DEVICE = 4 for van mounted FWD

If a tester other than the Dynaflect is used, the following additional information is needed:

1. Total static load applied by the loading head(s)
2. Static load applied by each trailer/van wheel
3. Distance from trailer/van wheels to first sensor location

4a. Amplitude and frequency for Road Rater
4b. Drop weight, drop height, and spring constant for the FWD.

Only item 1 needed for the Dynaflect tester. It should be kept in mind that for the Road Rater, the static load applied both by the loading heads and by the van wheels will be a function of amplitude and frequency as well as the weight (and weight distribution) of the van. For the FWD, the static loads depend on the size of the drop weight, the weight of the loading head assembly and the trailer weight or the van weight and weight distribution. If the above information is not available from the manufacturer, these values should be measured; however, care should be taken that all effects are included, and that the measuring process not introduce unwanted or unaccounted effects.

The program assumes that the tire pressure is 30 psi (207 kPa). If the actual tire pressure deviates significantly (30%) from this value, it is suggested that PRES = 30. be changed to PRES = actual tire pressure after statement with label 195, 263 and 348 or 295, 363 and 354 or 395, 463 and 356 (depending on Device type) in the main program.

2.1.2 Recommended Testing Conditions

The design procedure is based on measurements made during the time of the year when base and subgrade support values represent, as an approximation, average annual condition. Measurements made at other times (for example, worst condition encountered after spring thaw or best condition in late summer/early fall) may be accomodated through the use of a "seasonal factor" applied to the allowable axle loadings. This manual offers a guide (see Table 3 and Section 2.4.3) to the seasonal factor, but the user is encouraged to develop his own factor using procedures outlined in Appendix A. Measurements should not be made during the part of the year when any section of the pavement structure is in a frozen condition. It is also recommended that measurements not be taken during summer afternoons when average asphalt temperature exceeds about 100°F (38°C), especially for pavements with granular bases. Layer theory assumes that the materials are isotropic, i.e., that the modulus in bending is the same as compressive modulus. This, however, is not the case for most asphalt mixes at higher temperatures - as the temperature increases, the bending modulus decreases faster than the compressive modulus. The deflection directly under the load is a function of compressive modulus, but deflections away from the load depend on the load transfer efficiency of the pavement layer, or the bending modulus. This difference in moduli (bending and compressive) leads to nonlinear behavior, with measured deflections being higher under the load and lower away from the load than would be expected from isotropic materials.

2.1.3 Sampling Procedures and Frequency

The elastic layer theory used in evaluation of data assumes that the surface layer is continuous; i.e., capable of transmitting horizontal stresses, except for areas exhibiting Class 2 and Class 3 cracking (3) (these areas are treated somewhat differently in the program as described in Section 4.3.1, Volume 1 (2)). This is not the case when a large transverse crack is located between the point of load application and any of the deflection measuring sensors. It is therefore recommended that the testing device be positioned such that no major transverse cracks occur in the space occupied by the loading mechanism and deflection sensors.

The evaluation procedure utilizes both maximum deflection and the shape of the deflection basin to determine layer properties. The relationship between critical pavement parameters and measured deflection basin is quite complex, requiring considerable experience and understanding of the significance of measurements for an on-the-spot evaluation. Since this analysis is generally beyond the scope of an average technician doing the testing, reliance on his judgment to determine variability of field conditions is not recommended. Consequently, a shorter testing interval is used than is the case with most existing strategies. The recommended testing procedures include evaluation of at least one deflection profile along the outer wheel path of the existing roadway. Deflection measurements should be made at intervals between 50 and 150 feet (15 and 45 m) as outlined in Table 1. For two-directional roadways, it is desirable to obtain two staggered lines of deflection readings, one on either side of the centerline in the outer wheel path, such that if a 50-foot (15 m) spacing is used, each line should have measurements spaced 50 feet (15 m) apart, but staggered 25 feet (7.5 m). For divided highways deflection profiles are required in the outer lanes of both roadways. For undivided highways, the two profiles should be combined into one that represents the entire width of the roadway. However, for divided highways, the pavements on either side of the median should be considered to have separate deflection profiles.

Areas with Class 2 or Class 3 cracking should be delineated by one measurement on either side of the failure, as well as at least one measurement in the failed area, independent of the proposed measuring interval.

TABLE 1
GUIDELINE FOR DEFLECTION MEASUREMENTS

Condition of Location	Spacing of Measurements
Rolling terrain	50 feet (15 m)
Numerous cut to fill transitions	50 feet (15 m)
Level with uniform soil	100-150 feet (30-45 m)
Numerous failure areas	50 feet* (15 m)

* Plus measurements on either side and middle of each failure.

The analysis scheme assumes that the deflection measurements are representative of the roadway. It is, therefore, very important that care be taken in making and recoding measurements. The following scheme greatly improves the confidence in individual readings:

a) Stop machine at desired location and record readings.
b) Move ahead 1 or 2 feet (300 to 600 mm) and repeat measurements.
c) If readings agree within the resolution of the readout device, average the measurements and then move on.
d) If discrepancy is greater than readout resolution, move ahead 1 or 2 feet (300 to 600 mm) and repeat measurements.
e) Average the 2 sets of readings closest to each other.

While this procedure is not mandatory, it is recommended that it be followed at least until the machine-operator reproduceability is verified.

2.2 TEMPERATURE MEASUREMENTS

Since asphaltic concrete modulus is temperature dependent, it is necessary to determine the average pavement temperature at the time of testing.

Temperature determination could be carried out in one of two ways:

a) Direct determination of average temperature in the asphalt layer with temperature sensors buried at various depths in the pavement.

b) Indirect determination of temperature using procedures such as the Southgate Method (4).

While direct temperature measurements at various pavement depths are most accurate, they are impractical, since this procedure requires considerable time for sensor installation. The Southgate procedure (4), which requires the following information:

a) Air temperature measurement
b) Surface temperature measurement
c) Time of day measurement
d) Mean previous 5-day air temperature, obtained from the nearest weather station
e) Thickness of asphalt layer

is therefore recommended. The average pavement temperature is determined graphically from a series of graphs, as outlined in Appendix B.

The time interval between temperature measurements can vary considerably depending on weather conditions, time of day and length of testing time. At the very minimum, temperatures should be measured at the start and end of each test section, if testing time is greater than 1/2 hour. On bright sunny days or days with changes in air temperature, measurements should be made hourly; for overcast conditions with relatively constant air temperature, this interval may be extended to 3 to 4 hours.

2.3 CONDITION SURVEY

While the only condition information required by the overlay design scheme is whether Class 2 or Class 3 cracking (3) exists at a particular test site, the condition of the existing pavement should be documented. It is suggested that qualitative visual observations be made at the time of testing and recorded on the deflection data sheets. A sample data sheet for recording these observations is shown in Figure 2. Such a survey will serve as a valuable guide when maintenance alternatives are considered.

2.3.1 Cracking

Cracking shall be defined and recorded according to the AASHO definitions (3), i.e., Class 2, Class 3, etc. Class 2 cracking is defined as that which has progressed to the stage where cracks have been connected together to form a grid type

DISTRICT____ COUNTY_____ ROUTE_____ SECTION_____ PROJECT_____ DIRECTION_____ PVT.TYPE_____ DATE__/__/__ WEATHER_____

Page___of___

LOCATION	Cut/Fill/Grade	SENSOR DEFLECTIONS #1	#2	#3	#4	#5	Class of cracking	COMMENTS
1 2 3 4 5 6 7 8 9	10	11 12 13 14 15	16 17 18 19 20	21 22 23 24 25	26 27 28 29 30	31 32 33 34 35	36	37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

FIGURE 2. TYPICAL DYNAFLECT DATA SHEET

pattern and is commonly referred to as alligator cracking. Class 3 cracking is the progression from Class 2 in which the Class 2 cracks spall more severely at the edges, lose integrity between blocks, and the segments of the pavement surface loosen, move or rock under traffic. Photographs of these classes are shown in Figure 3.

If the testing scheme outlined in Section 2.1.3 is followed, it is not necessary to estimate the extent of cracking since the testing method delineates the start and the end of all cracked areas.

2.3.2 General Observations

The condition survey should include all relevant information such as conditions of drainage, cut/fill/grade transitions, and the presence of rutting, ravelling and spalling. This data, along with computed layer stiffness, serves as input to consideration of trade-offs between overlay thickness, drainage improvement, recycling or reconstruction. In many situations, it may be possible to improve drainage which will in turn improve material properties and result in reduced overlay thickness. In other areas, it may be more economical to reconstruct a section than to apply a thick overlay. Economic comparisons should be made between these alternatives.

2.4 TRAFFIC DATA

The overlay program requires as input the following traffic information:

a) Present daily equivalent 18 kip (80 kN) single axle loads in design lane, modified by regional and seasonal factors, DTN

$$DTN = DLT * RF * SF \qquad (2\text{-}1)$$

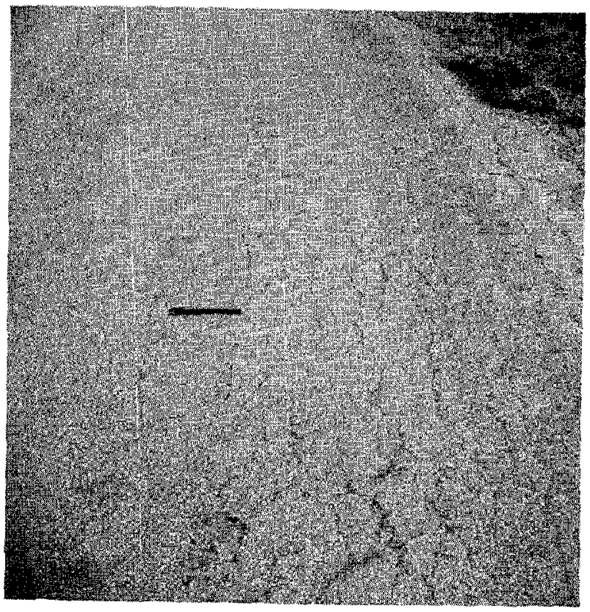
where

DLT = Design Lane Traffic, Section 2.4.1
RF = Regional Factor, Section 2.4.2
SF = Seasonal Factor, Section 2.4.3

b) Design period in years, NUMYR
c) Annual growth rate expected (in percent/100), GF

2.4.1 Design Lane Traffic

The procedure outlined in AASHO Interim Guide for the Design of Pavement Structures - 1972 (5) should be used to determine the design lane traffic in terms of equivalent 18 kip (80 kN) single axle loads. If the traffic projection



Class 2 Cracking

Class 3 Cracking

Figure 3. Photographs of Class 2 and Class 3 Cracking

represents the total of all lanes in both directions of travel, the traffic must be distributed by direction and lane as follows:

$$DLT = W_{t18} * DDF * LDF \qquad (2-2)$$

$$W_{t18} = N_t \sum_{i=1} P_i e_i$$

where

W_{t18} = total number of equivalent 18 kip (80 kN) axles

N_t = total number of axles

P_i = percent of axles in load group i

e_i = traffic equivalent factor for load group i

DDF = direction distribution factor

LDF = lane distribution factor

Directional distribution is normally made by assigning 50 percent to each direction unless special considerations dictate some other distribution. In regard to lane distribution, the critical lane is usually the outside lane. Unless the user agency has developed lane distribution factors for highways with two or more lanes in each direction, Table 2 should be used.

TABLE 2
LANE DISTRIBUTION FACTORS FOR MULTILANE ROADWAYS

Total Number of Lanes, One Direction	Lane Distribution Factor
2	1.0
3	0.8 - 1.0
3+	0.4 - 0.6

2.4.2 Regional Factor

Highway engineers have recognized that environmental conditions cause roads to deteriorate faster in some regions than in other climates under similar traffic conditions. The regional factor (6), RF, as defined in Figure 4, is proposed as the mechanism to account for differing environmental conditions and is used to modify the design lane traffic (as determined in Section 2.4.1) by multiplying DLT by RF.

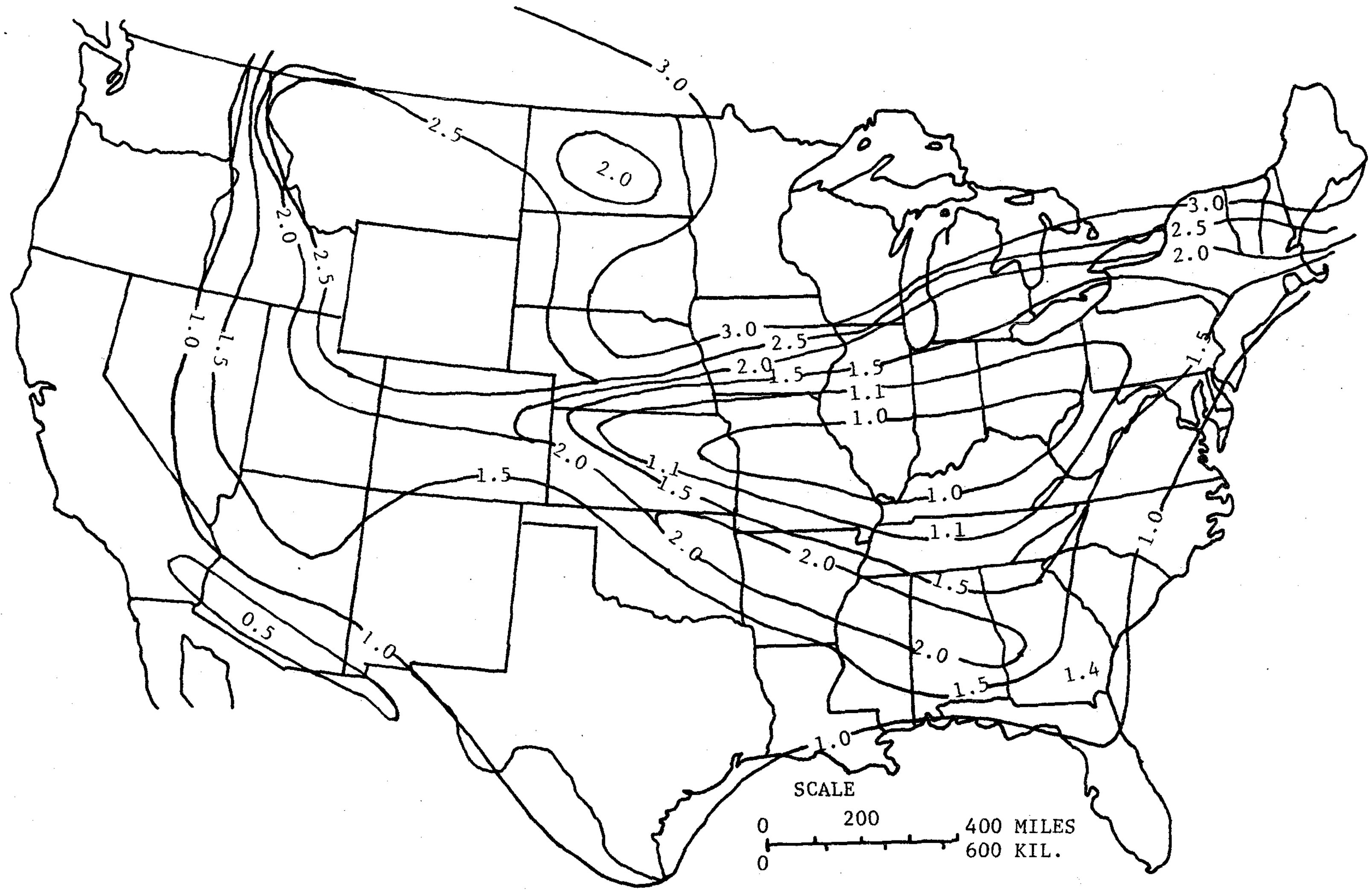


Figure 4. Contours of equal regional factors

2.4.3 Seasonal Factor

As was stated in Section 2.1.2, the procedure is based on measurements made during the time of year when moisture conditions in base and subgrade have stabilized and are representative of average annual conditions. Measurements made after spring thaw, or after extended wet or dry periods do not meet these requirements. One approach to this problem is avoiding any tests during this period, which of course severely restricts the available testing time. An alternative is to develop a seasonal factor (SF) to modify the design lane traffic to account for the weakened (or strengthened) condition of the pavement structure. Table 3 gives some suggested values of SF, but it should be emphasized that these values are based on local experience (Ohio) and may have little validity at other geographical areas. The user is encouraged to develop his own seasonal factor using the procedure outlined in Appendix A.

TABLE 3
DYNAFLECT SEASONAL FACTOR FOR OHIO PAVEMENTS

Month	Seasonal Factor (SF)*
January	1.11
February	1.20
March	0.85
April	0.39
May	0.63
June	0.90
July	1.20
August	1.49
September	1.35
October	1.08
November	0.96
December	0.96

*Developed using procedure discussed in Appendix A.

2.5 MATERIAL CHARACTERIZATION

The material characterization requirements include the thickness, Poisson's ratio and density of all layers, the asphalt modulus-temperature relationship, both for existing asphalt and proposed overlay mix, and the base, subbase and subgrade type so that proper stress-dependency relationships can be developed.

2.5.1 Thickness Requirements

The overlay program requires that all layer thicknesses be known, which can generally be obtained from construction records. Where such records are not available, pavement cores might be needed to determine these thicknesses.

The basic design scheme characterizes the existing pavement as a three-layer structure composed of an asphalt layer with thickness H_1, a base layer with thickness H_2, and subgrade which is semi-infinite in depth. Since at least some pavements are composed of more than three layers, it is necessary to combine some of the existing layers into one layer to fit the model.

The following scheme is used:

Layer 1 - H_1 will be equal to the sum of all existing asphalt layer thicknesses and will include surface course, leveling course, asphaltic concrete or asphalt treated base and previous overlays, if any.

Layer 2 - If the existing pavement is constructed with

a) Granular base and granular subbase, H_2 will be the sum of base and subbase thicknesses.
b) Cement-treated base on lime-stabilized subbase, H_2 will be the sum of base and subbase thicknesses.
c) Cement-treated base on granular subbase, H_2 will be the base thickness only.
d) Granular base on lime-stabilized subbase, H_2 will be the granular base thickness only.

The asphalt layer thickness is input as described above, but the base and subbase (if one exists) thicknesses are read in individually; the above layer thickness assignments are done internally in the program for the three-layer analysis, and used as they are for a four-layer analysis.

In the event that an existing pavement is constructed with only three layers and a four-layer analysis is used, the program assigns to layer two a thickness H_2 equal to two-thirds of the base thickness and to layer three a thickness equal to one-third of the base thickness plus six inches. The rationale for this choice is that often existing bases get contaminated with, and intrude into, the top layer of the subgrade, creating a soft layer which is a mixture of granular material and subgrade soil.

If the latter thickness assignment is used, this layer is considered as being stress-independent.

2.5.2 Poisson's Ratio

Materials characterization includes Poisson's ratio for each layer. These values are not assumed a priori in the program; rather, the user supplies them as part of the input data. Unless the user has specific values of Poisson's ratio for his materials, the values in Table 4 are suggested.

TABLE 4
SUGGESTED POISSON'S RATIOS OF MATERIALS

Material Type	Poisson's Ratio
Asphalt Layer	0.40
Granular Layer	0.37
Cement-treated Layer	0.15
Subgrade	0.45

2.5.3 Asphaltic Concrete Modulus-Temperature Relationship

Since pavement testing cannot always be conducted during the time period when average pavement temperature is the same as the design temperature, the in-situ asphalt stiffness (as computed in the program) has to be corrected for temprature effects. The program requires as input the modulus of the asphalt pavement at the design temperature (EDES), as well as the modulus of the proposed overlay mix at design temperature (EOV). If the same mix is used for overlay as was used in existing pavement, then EOV is the same as EDES.

Figure 5 shows a typical asphaltic concrete modulus-temperature relationship. If the user does not have such data for his mixes, the values from Figure 5 may be used; however, the list of references presented in Appendix C should be consulted to find the temperature relationship for a mix that most closely approximates the user's material.

It should be noted that there is an important difference between the in-situ layer 1 stiffness (E1) and EEXP. EEXP and EDES are moduli of asphaltic concrete determined either from laboratory-compacted specimens or from field cores of pavements that have seen little or no traffic, while E1 is the equivalent asphalt layer stiffness as it exists at the time of field testing. Consequently, a significant difference may exist between E1 and EEXP.

EEXP is determined from Figure 5 (or similar figures) by entering the horizontal axiswith the average pavement temperature during the test (determined in Section 2.2) and reading off the corresponding modulus value. EDES and EOV are determined similarly using the design temperature, which in this study is defined as the mean annual air temperature.

It should be pointed out that since dynamic modulus is frequency dependent, if the field testing is done at 8 Hz, the laboratory-determined asphalt moduli should be dynamic moduli determined at 8 Hz.

2.5.4 Stress Dependency of Base, Subbase and Subgrade Layers

Overwhelming evidence indicates that the modulus of most soils and granular materials is sensitive to stress, as well as to loading frequency and load repetitions. The modulus of resilience for granular material is generally expressed as:

$$M_R = A1\ \theta^{B1} \tag{2-3}$$

for subgrade soils as:

$$M_R = A2\ \sigma_d^{B2} \tag{2-4}$$

and for subbases as:

$$M_R = A3\ \theta^{B3} \tag{2-5}$$

where

θ is the sum of principal stresses, σ_d is the deviatoric stress, and A1, A2, A3, B1 B2, B3, are constants that depend on material properties.

Whenever field testing is conducted with loads that differ from design load, or when an overlay is placed on an existing pavement, the stresses experienced by the base, subbase (if one exists) and subgrade layers change. It is, therefore, necessary to correct the in-situ stiffness to account for the different stress states. The program computes the stresses σ_d and θ and the constants A1, A2 (and A3), but the constants B1, B2 (and B3) have to be supplied by the user. In Appendix C, tables and references are presented to serve as a guideline to the user for selection of these values. If the user is uncertain as to the material types existing in a particular pavement, it is suggested that conservative values, i.e., large B for subgrade and low B for base and subbase be used.

In the event that the three-layer analysis fails to find a solution for the layer stiffnesses and the four-layer analysis is used with a created subbase thickness (Section 3.1.1, H2 = 0.67H2+6.0), the subbase is assumed to be stress-independent, i.e., B3 is set to zero.

2.5.5 Layer Densities

Linear elasticity theory generally neglects body forces, i.e., forces due to gravity, since it is assumed that the stress-strain relationship for paving materials is linear. However, equations (2-3) through (2-5) state that the moduli of granular materials and subgrade soils exhibit stress-dependent behavior so that body forces can no longer be ignored. The effect of body forces is computed from the layer densities by the method outlined in Section 4.3.1, Volume 1 (2) of this report.

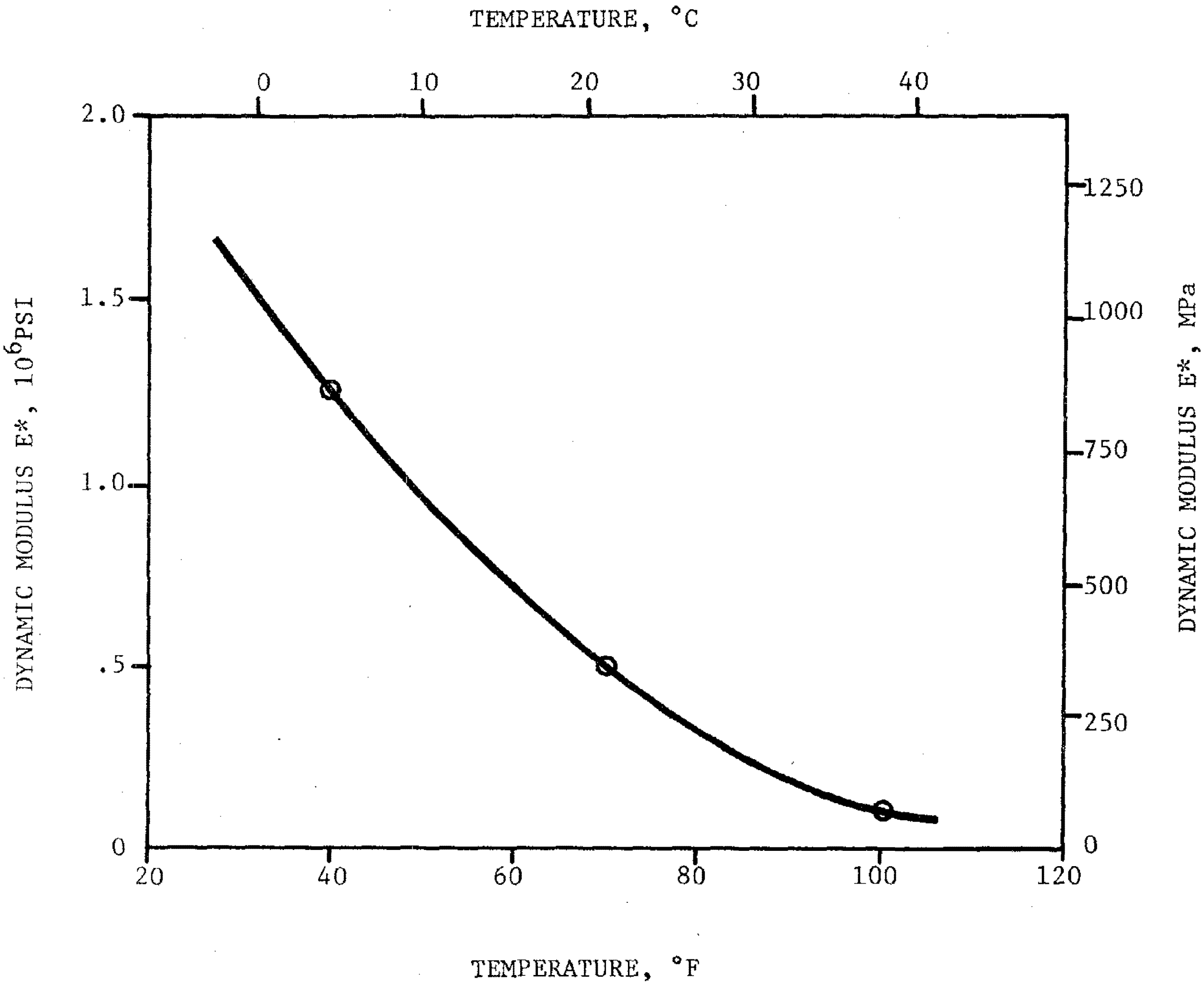


FIGURE 5. Typical Dynamic Test Results for an Asphaltic Concrete Specimen Tested at Three Temperatures.

CHAPTER 3
DESIGN PROCEDURE AND DATA INPUT GUIDE

This chapter provides the user with a ready reference of procedures and a guide to the input information required in the program, OAF. The steps used in the overlay design procedure are shown schematically in the flow chart in Figure 6; a detailed description appears in Chapter 3, Volume 1 (2) of this report.

3.1 PROGRAM DESCRIPTION

The overlay analysis program offers, in addition to the basic procedure, four other options or modes of analysis. The type of analysis used is determined by the variable KODE. As was stated in Section 1.5, the basic procedure considers the existing pavement as a three-layer structure and attempts to compute the in-situ layer stiffnesses at each test location from measured surface deflection. In the event that the three-layer analysis fails to find the layer stiffnesses, a four-layer analysis is used. For this mode of analysis, KODE=0 is specified. However, the program can also accept the layer properties as determined by laboratory tests, or use default values. When complete laboratory test data is available, including base and subgrade stress-dependent properties, KODE=1 or 2 is used. KODE=1 uses a three-layer structure as the analytical model and KODE=2 treats the pavement as a four-layer structure. If default values (estimated layer moduli for 18 kip (80 kN) axle loading) are used, KODE=3 is specified. KODE=4 offers the user the option to by-pass the three-layer analysis in determining the in-situ layer stiffnesses from measured surface deflections and go straight to a four-layer analysis . It should be pointed out, however, that the four-layer analysis is considerably more time consuming than the three-layer analysis.

KODE=0 and KODE=4 are usable with four types of testing devices, specified by DEVICE

a) Dynaflect, DEVICE=1
b) Road Rater. DEVICE=2
c) Falling Weight Deflectometer, trailer mounted, DEVICE=3
d) Falling Weight Deflectometer, van mounted, DEVICE=4

The following major steps (which will be described in the following section) are used in the analysis program:

1. Determine layer properties

a) from measured surface deflections, KODE=0 or KODE=4
b) from laboratory test data, KODE=1 or 2
c) from estimated (default) values, KODE=3.

2. Adjust layer stiffness for temperature and stress effect.
3. Compute remaining life, RLIFE.
4. Increment overlay thickness (HOV), readjust layer stiffnesses for changed stress states and recompute remaining life.

Step 4 is used and repeated until the remaining life (RLIFE) is within 25% of the design life, HOV is then interpolated.

Steps 1 through 4 are repeated for each test location. After the last overlay calculation, the required thicknesses are plotted as a function of test location and a statistical analysis performed. The statistical analysis computes the average overlay thickness along with the 67, 77, 87 and 97 percentile values. The program does not attempt to group the overlay project into sections having similar overlay needs - this is left for the design engineer.

Once the user has delineated his sections, he may wish to test the statistical significance of this division using a separate small program TVAL. Appendix D describes the input requirements for this program.

3.1.1 Determination of Layer Properties From Measured Surface Deflections (KODE=0 or 4, DEVICE=1, 2, 3 or 4)

The following input data (described in Chapter 2) is required for this mode of analysis:

a) Surface deflection measurements
b) Base type, i.e. granular or cement-treated
c) Layer thicknesses
d) Poisson's ratios of all layers
e) Modulus of pavement asphalt at test temperature and design temperature, EEXP and EDES
f) Modulus of overlay asphalt, EOV
g) Whether Class 2 or Class 3 cracking (3) exists.

As can be seen from the flow chart in Figure 6, pavements with cement-treated bases are analyzed somewhat differently from pavements with granular bases. For pavements with granular bases, subroutine DYNAFL or RDRWD depending on testing device type, is used to compute the in-situ layer stiffnesses from measured deflections and the shape of the deflection basin, as defined by the spreadability (SP):

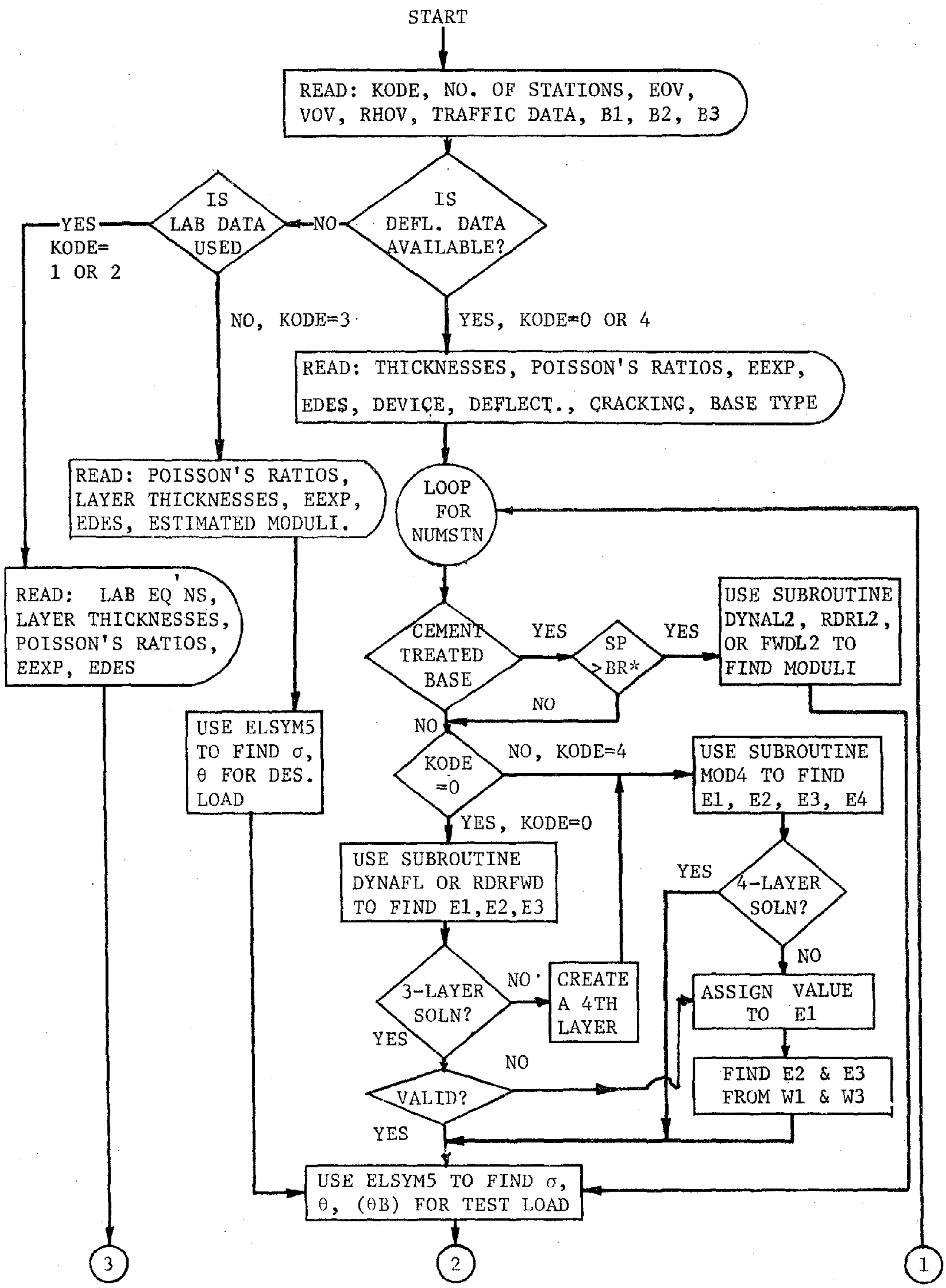


FIGURE 6. FLOW CHART OF OAF.

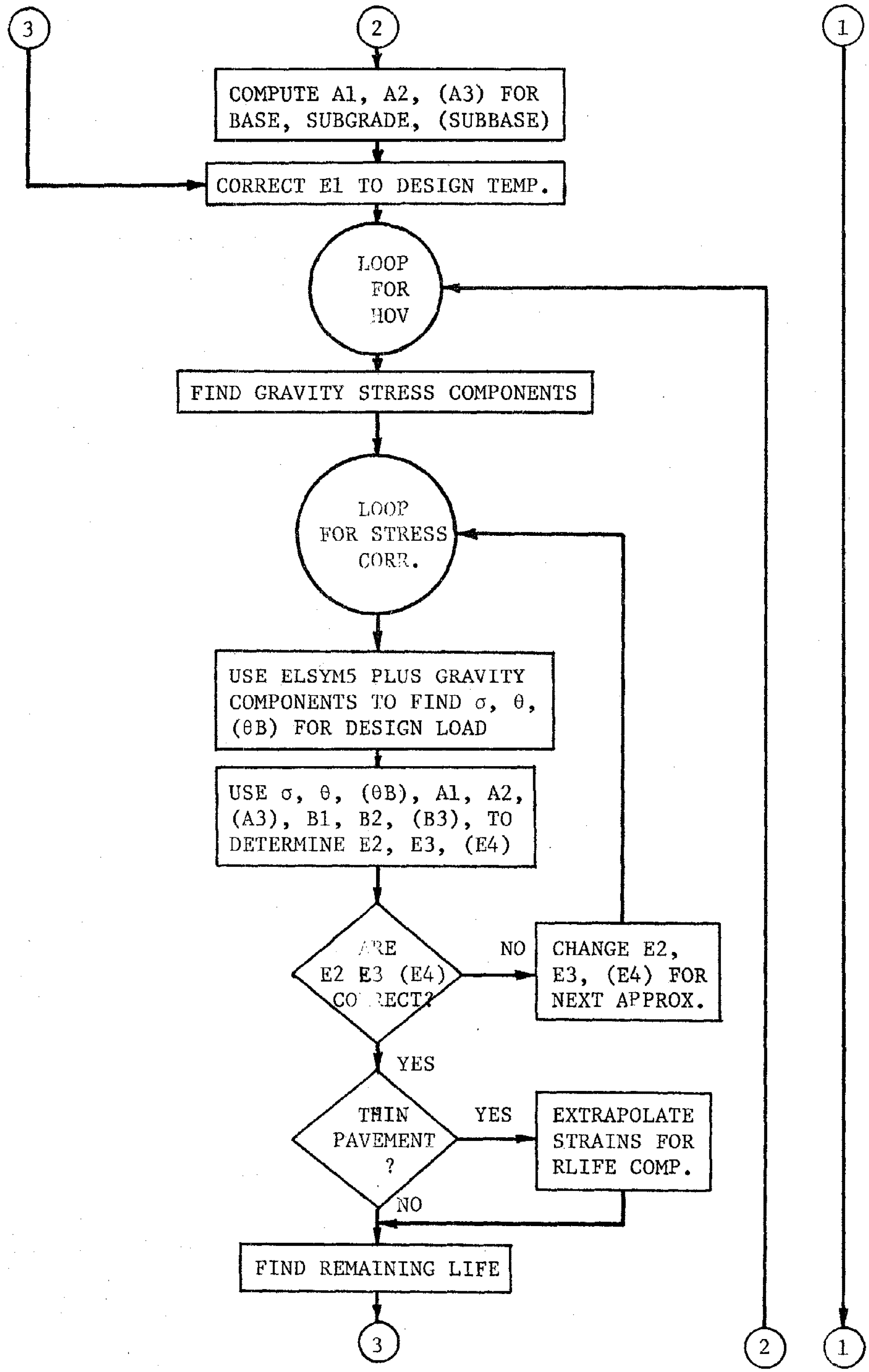


FIGURE 6. FLOW CHART OF OAF (CONTINUED).

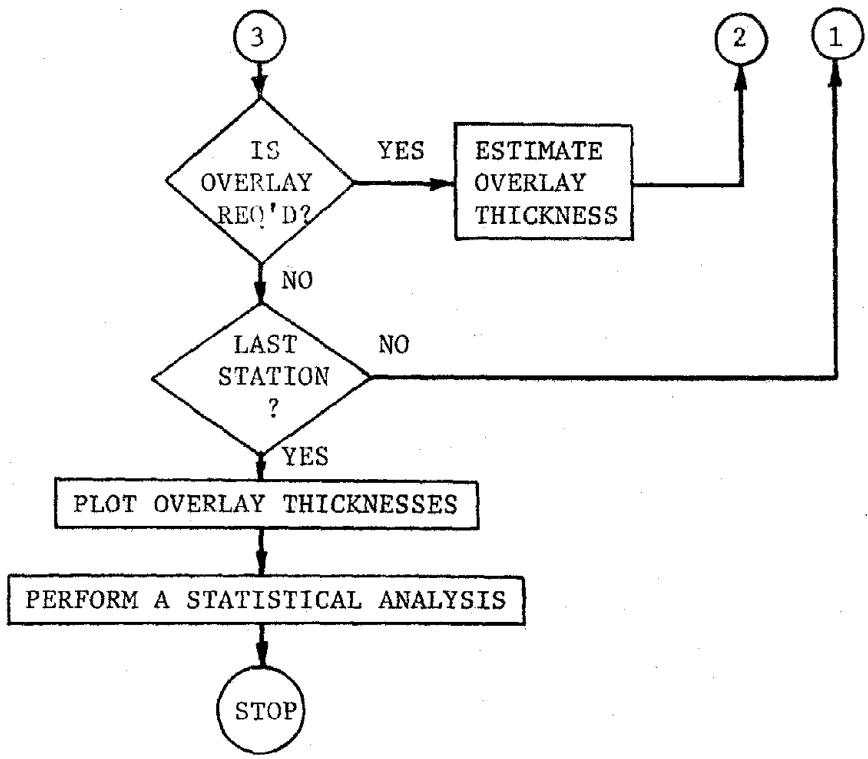


FIGURE 6. FLOW CHART OF OAF (CONTINUED).

$$SP = 100 * (\sum_{i=1}^{5} W_i)/5W_1 \quad (3-1)$$

for the Dynaflect, and

$$SP = 100 * (\sum_{i=1}^{4} W_i)/4W_1 \quad (3-2)$$

for the Road Rater and both types of Falling Weight Deflectometer

where

W_i are the measured deflections at variable distances from the load and W_1 is the maximum deflection.

The layer stiffnesses are determined using two strategies:

a) matching measured and computed W1, W2, SP
b) matching measured and computed W1, W3, SP.

If both schemes result in a solution (these will not always be the same), the one that produces E1 (effective modulus) closest to EEXP is used. However, some measured deflection data cannot be represented by a three-layer analytical model; in that case, a four-layer analysis is used. If the existing pavement is built with both a base and a subbase, the layer thicknesses are taken to be as-built thicknesses, i.e., as they are read in. In the event that the existing pavement is composed of only three layers (no subbase), the program creates an artificial subbase layer with the following thickness assignments:

a) asphalt layer thickness equal to sum of all asphalt layers (Section 2.5.1)
b) base layer thickness equal to two-thirds of as-built thickness
c) subbase thickness equal to six inches (150 mm) plus one-third of as-built base thickness
d) subgrade thickness semi-infinite

As was stated in Section 2.5.1, existing granular bases often get contaminated with, and intrude into the subgrade, creating a layer that is a mixture of granular material and subgrade soil. While the creation of an artificial subbase layer is somewhat arbitrary, it is felt that this approach is more rational than the default model described later in this section.

The layer stiffnesses in the four-layer analytical model are determined by matchiing measured and computed W1, W2, W3 and SP. In general, more than one combination of layer stiffnesses will match the above parameters; consequently, the program attempts to find several solutions. All solutions (layer stiffness values) found are printed out; however, only the solution that results in E1 closest to EEXP is used in overlay determination, just as in the three-layer model.

Although the four-layer model results in solutions most of the time, some measured deflection data will also be inconsistent with a four-layer analytical model and no solutions result. In this case, the program prints out the message "Default Option--No 4-Layer Solution" and a default model is used.

This default option characterizes the existing pavement as a three-layer structure and uses an iterative scheme to determine the base and subbase stiffnesses by matching measured and computed W1 and W3 (first and third sensor readings). The constraints that the subgrade modulus is not allowed to exceed 1,000,000 psi (6890 MPa) and the base stiffness is not allowed to exceed the smaller of two values: 0.65 E(1) or 150,000 psi (1034 MPa) are placed on the solution so that a solution consistent with the expected engineering properties of the layers can be found (see section 4.3.1 Volume 1 (2) for details). The iteration process is started by assigning arbitrary stiffness values to the base and subbase layers, and EEXP or 70,000 psi (482 MPa) (depending on whether the asphalt layer is uncracked or has class 2 or 3 cracking (3), respectively) to the asphalt layer.

For pavements with intact cement-treated bases, the critical strain occurs in the bottom of the base layer rather than in the asphalt layer. However, at the present time no satisfactory distress equation exists relating tensile strain in the base layer to the number of 18 kip (80 kN) axle loads to failure. In order to overcome this difficulty, these pavements are characterized by a two-layer analytical model composed of an equivalent full-depth asphalt layer with thickness H1 + H2 resting directly on subgrade. Subroutine DYNAL2, RDRL2 or FWD2 (depending on testing device) is used to determine the effective asphalt and subgrade layer stiffnesses using a scheme that matches measured and computed spreadability (SP) and maximum deflection (W1) values.

When the base layer is already cracked, the critical strain moves upward toward the bottom of the asphalt layer; the program treats this case as if the base were composed of granular material, but with stress-independent modulus.

Dynaflect measurements made on pavements with relatively intact cement-treated bases result in spreadability values in excess of 55%. This value (55%) is used to differentiate between cracked and uncracked bases and the type of analysis used, i.e., two-layer evaluation or three-layer evaluation.

The branch value for Road Rater or FWD measurements is 50%.

After the layer stiffnesses have been determined, ELSYM5 is used to compute the stress σ_d and θ for the testing device load so that the constants A1, A2 and A3 can be determined

$$A1 = EB\ \theta^{-B1} \qquad (3\text{-}3)$$

$$A2 = ES\ \sigma_d^{\ B2} \qquad (3\text{-}4)$$

$$A3 = ESB\ \theta^{-B3} \qquad (3\text{-}5)$$

where EB, ES and ESB are the moduli of the base, subgrade and subbase layers, respectively. It should be noted that in this analysis compressive stresses are assumed to be positive.

Layer theory sometimes predicts tensile bulk stresses (negative θ) in the base and/or subbase layers. In that event equations 3-3 and/or 3-5 are not defined and the intercepts A1 and/or A3 cannot be determined. In order to overcome this difficulty, the program assumes that for these cases the granular material stiffnesses can be determined from

$$E_i = A_i(.99 + .01\theta) \qquad i=1 \text{ or } 3 \qquad (3\text{-}6)$$

so that the intercepts can be evaluated from

$$A_i = 100\ E_i/(99+\theta) \quad i=1 \text{ or } 3 \qquad (3\text{-}7)$$

The reasons for this choice are discussed more fully in Section 4.3.4, Volume 1 (2) of this report.

Since the measured surface deflections are dynamic deflections, they are functions of only the dynamic load applied by the testing device. This, however, is not true of the stresses σ_d and θ. All the testing devices considered in this procedure apply a static load in addition to the dynamic load; also, the Road Rater and the Falling Weight Deflectometer have the vehicle/trailer wheels close to the point of load application. Additionally, overburden pressure (self-weight of the layers) contributes to σ_d and θ (see Section 4.3.4, Volume 1 (2) for details). It is therefore necessary to include all factors when computing these stresses; for these reasons, the parameters discussed in Sections 2.1.1 and 2.5.5 are part of the input data.

3.1.2 Determination of Layer Properties from Laboratory Test Data (KODE=1 or 2)

When complete laboratory test data are available for materials characterization, the initial sections of the program are bypassed. The required data are read in and the program proceeds directly to step 2 (Section 3.1). References to laboratory testing methods are presented in Appendix B, Volume 1 (2) of this report.

In this mode the pavement is characterized either by a three-layer (KODE=1) or a four-layer (KODE=2) analytical model, depending on whether a subbase exists.

The layers in the three-layer model were defined in Section 2.5.1; the four-layer model is composed of the following layers:

1) Asphalt layer with thickness H; as defined in Section 2.5.1
2) Base layer with thickness H2 equal to base thickness
3) Subbase layer with thickness H3 equal to subbase thickness
4) Subgrade layer with semi-infinite thickness.

In addition to the layer thicknesses, the following information is required for input:

a) Poisson's ratio and density of all layers
b) Modulus of overlay asphalt at design temperature, EOV
c) Modulus of existing asphalt at design temperature, EDES
d) Constants A1 and B1 to determine the base modulus from

$$E_B = A1\ \theta^{B1} \qquad (3\text{-}8)$$

or from

$$E_B = A1(.99 + .01\theta) \qquad (3\text{-}9)$$

when θ is in tension (negative)

e) Constants A2 and B2 to determine the subgrade modulus from

$$E_S = A2\ \sigma_d^{B2} \qquad (3\text{-}10)$$

f) If subbase is used, the constants A3 and B3 to determine the subbase modulus from

$$E_{SB} = A3\ \theta^{B3} \qquad (3\text{-}11)$$

or from

$$E_{SB} = A3(.99 + .01\theta) \qquad (3\text{-}12)$$

when θ is in tension (negative)

In the above equation, θ is the sum of the principal stresses and σ_d is the deviatoric stress.

3.1.3 Determination of Layer Properties from Default Values (KODE=3)

When neither dynamic measurements nor complete laboratory test data are available, the user may estimate the layer moduli based on experience and published data. In this mode, the pavement is characterized by the three-layer analytical model and requires, in addition to layer thicknesses, the following input information:

a) Poisson's ratio and density of all layers
b) Modulus of overlay asphalt at design temperature, EOV
c) Modulus of existing asphalt at design temperature, E(1)
d) Base modulus for 18 kip (80 kN) axle loading, E(2)
e) The constant B1, equation 3-8
f) Subgrade modulus for 18 kip (80kN) axle loading, E(3)
g) The constant B2, equation 3-10.

After the above information has been read in, ELSYM5 is used to determine σ_d and θ for 18 kip (80 kN) axle loading, the constants A1 and A2 are determined from equations 3-3 and 3-4 (or from equation 3-7 if the bulk stress in base and/or subbase is in tension) and the program skips to step 3 (Section 3.1). The effect of self-weight is included in the stress computation.

3.1.4 Temperature and Stress Correction, Step 2

In this step, the layer 1 stiffness is adjusted from measurement temperature to design temperature (if lab data or default values are specified at design temperature, no correction is needed) using the following relationship:

$$E(1) = E1 * EDES/EEXP \qquad (3-12)$$

where

E(1) = effective asphalt stiffness at design temperature

E1 = effective asphalt stiffness at test temperature

EDES = modulus of original paving asphalt at design temperature

EEXP = modulus of original paving asphalt at test temperature

which assumes that the effective (in-situ) asphalt stiffness has a temperature dependency that is parallel to that of the original paving mix (see Section 2.5.3).

The temperature correction section is by-passed when the existing A.C. layer has Class 2 or Class 3 cracking (3) since the stiffness of a cracked A.C. layer is not expected to change significantly with temperature. Also, if E1 is less than 100,000 psi (690 MPa) for an uncracked pavement, the temperature correction is not used to lower the A.C. stiffness, since this would result in an uncracked A.C. stiffness that may be lower than the value assigned to a cracked layer.

Following temperature correction of layer 1, the moduli of base and subgrade are computed for the state of stress existing in the pavement under an 18 kip (80 kN) axle load at the design temperature. A modified Newton-Raphson (7) iterative procedure is used:

a) Initial values for the base and subgrade stiffnesses are assumed.
b) The stresses σ_d and θ are computed using ELSYM5. These stresses include gravity (self-weight) and static load effects.
c) Base and subgrade stiffnesses are computed from equations 3-8 and 3-10 (or 3-6 if θ is negative) using the θ and σ_d values from (b)
d) New base and subgrade stiffnesses are computed using the modified Newton-Raphson procedure.

Steps (b), (c) and (d) are repeated until the base and subgrade stiffnesses determined in steps (c) and (d) differ by less than 2% and 5%, respectively. This procedure is discussed in detail in Section 4.3.4, Volume 1 (2) of this report.

3.1.5 Remaining Life Determination, Step 3

The design procedure is based on the "effective stiffness" concept in which the existing pavement is characterized by layers having as-built thicknesses but with altered layer stiffnesses, i.e., a "new" pavement with in-situ layer sitffnesses as determined from dynamic testing. In the analysis model used, the new pavement is treated as having all of its life remaining; consequently, estimation of previous traffic experienced is not necessary.

The remaining life of uncracked pavements having in-situ stiffness greater than 70,000 psi (482 MPa)(the value used to characterize asphalt layers having Class 2 cracking (3)) is determined by computing the maximum horizontal tensile strain (ε) at the bottom of the existing asphalt layer (with ELSYM5) and using this strain to compute N_f (number of equivalent 18 kip (80 kN) axle loadings to failure, or remaining life) from

$$N_f = 7.56 \times 10^{-12} \, (1/\varepsilon)^{4.68} \qquad (3\text{-}13)$$

For existing pavements exhibiting Class 2 or Class 3 cracking (3) or having an in-situ stiffness (at the test point) less than 70,000 psi (482 MPa), the maximum horizontal tensile strain (ε) is calculated both at the bottom of the existing pavement and at the bottom of the overlay, and the larger value selected. Equation 3-13 is again used to compute the remaining life.

It should be pointed out that equation 3-13 is not the same equation developed by ARE (1). It has been developed based on the same 27 failed sections of the AASHO Road Test (3) used by ARE (1), with the following differences (see Sections 3.1.1 and 3.1.2, Volume 1 (2) for details):

a) ε is the maximum horizontal tensile strain at the bottom of the asphalt layer which occurs in the direction of traffic rather than in the direction of the axles.
b) Equations of the form of 3-8 through 3-11 were developed from the lab test data of AASHO materials published in Appendix B, Volume 1 of ARE report (1) so that the layer moduli in the strain analysis would have the same stress dependency as the lab testing data indicates.
c) Gravity forces (self-weight effects) were included in stress correction of layer moduli.

Equation 3-13 was redeveloped because the authors felt that since the FHWA-RII overlay design procedure uses stress-dependent moduli for base, subbase and subgrade layers in overlay thickness determination, it would be totally inconsistent to use a distress function that was not developed using the same criteria.

3.1.6 Determination of Required Overlay Thickness, Step 4

If the remaining life determined in the previous step is less than the design life, an overlay thickness is projected. A new value for overlay thickness is computed from the last two values for remaining life, and if the new remaining life is not within 25% of the design life, a third value for overlay thickness is computed from the last two values. Generally, the remaining life is within the convergence criterion after the third iteration. The required overlay thickness is then interpolated from the last two values of remaining life.

As a result of adding an overlay to the existing pavement, the state of stress experienced by the base and subgrade layers changes. It is therefore necessary to readjust these layer stiffnesses to correspond to the changed stresses; the procedure outlined in step 2, Section 3.1.4 is used. Once the layer stiffness corresponding to the new stresses have been found, the horizontal tensile strain is computed, either at the bottom of the existing asphalt layer for uncracked pavements or at the bottom of the overlay and at the bottom of the existing asphalt layer (the larger of the two strains is used) for cracked pavements, and remaining life determined from equation 3-13.

Although considerable care has been exercised in finding realistic in-situ layer stiffnesses, it is possible that the field deflection measurements result in a pavement structure having a very stiff base layer. When this occurs, the horizontal strains under the asphalt layer may be small or compressive; i.e., the pavement may have a very high and unrealistic remaining life. Therefore an acceptability criterion is used to reject these solutions, the message "Default Option 3-Layer Solution Unacceptable" is printed out, and a default model very similar to the one described in Section 3.1.1 is used in the analysis (see Section 4.3.1 Volume 1 (2) for details).

3.2 INPUT INSTRUCTIONS

The input requirements for program OAF are shown in Figure 7 and Tables 5 and 6. Figure 7 shows a sample data deck. The blocks allocated to each variable are shown in Table 5, and Table 6 gives the formats along with a variable description list and reference to the sections where these variables are defined.

Although the program offers five modes of analysis, each with somewhat different input requirements, the first four cards of the data set are the same for each analysis mode. These cards contain the following information:

Card 1 TITLE Identifying the project or section considered

Card 2 KODE, NUMSTN, NLS, DEVICE
KODE is specified as 0, 1, 2, 3 or 4 depending on the type of analysis used -- see Section 3.1.
NUMSTN is psecified as 1 for KODE=1, 2, 3 and as the number of locations at which dynamic deflection measurements were made for KODE=0 and

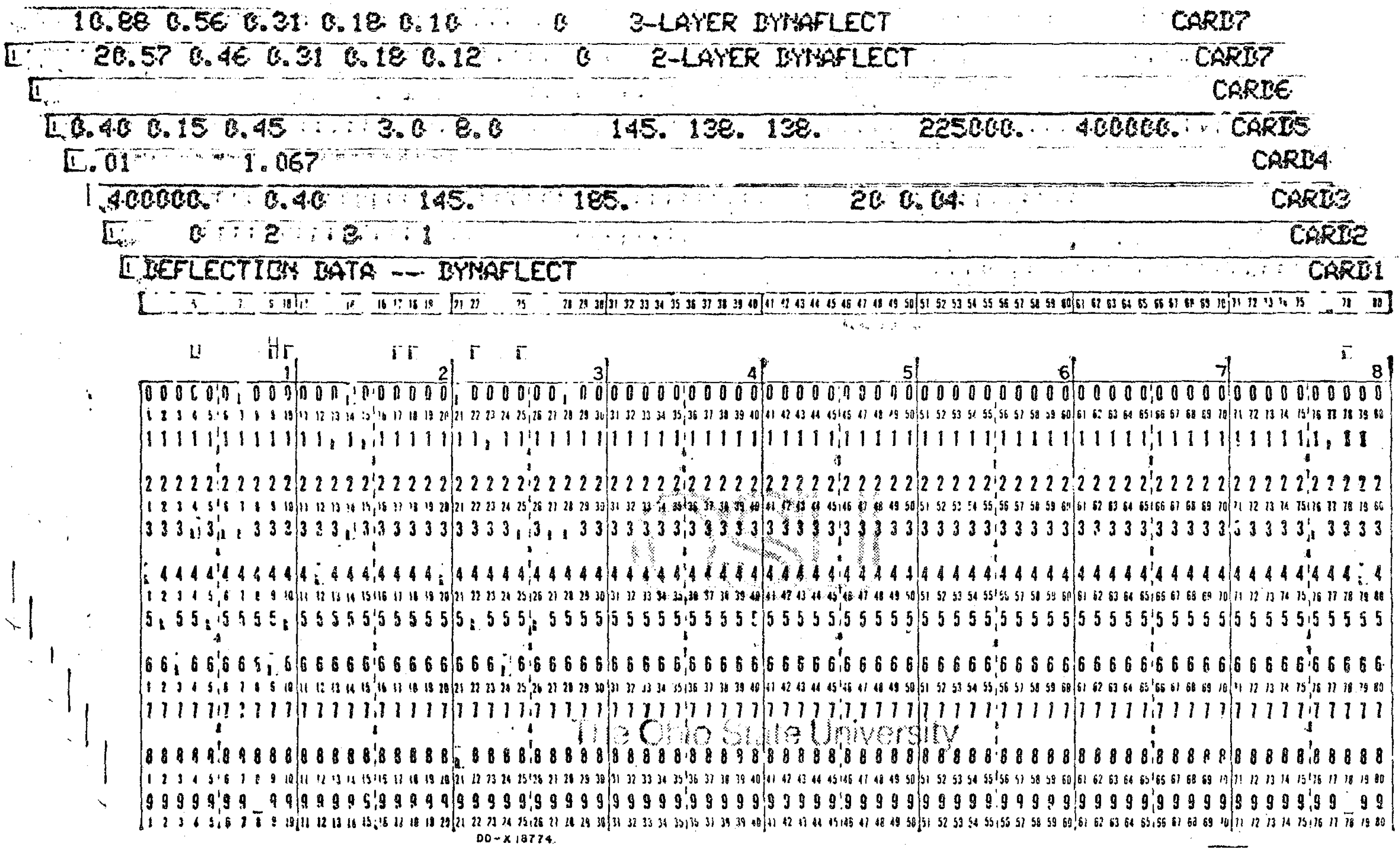


FIGURE 7. A Sample Data Set for KODE=0, DEVICE=1

KODE=4. NLS defines the number of layers used to characterize the existing pavement and must be assigned the following values:

NLS=3 for KODE=0, 1, 3
NLS=4 for KODE=2,4

DEVICE is used to identify the type of testing device used; it needs to be specified only when KODE=0 or 4:

DEVICE=1 for Dynaflect
DEVICE=2 for Road Rater
DEVICE=3 for trailer mounted FWD
DEVICE=4 for van mounted FWD

Card 3 EOV, VOV, RHOV, DTN, NUMYR, GF

EOV, VOV AND RHOV are the modulus, Poisson's ratio and density (in pcf), respectively, of the overlay layer at the design temperature. The program requires that moduli and densities be read in British units, i.e., psi for modulus and pcf for density. DTN is the number of daily equivalent 18 kip (80 kN) axle loadings (Section 2.4.1), GF is the annual growth rate expected in traffic (expressed as % divided by 100), and NUMYR is the number of years in the design period.

Card 4 B1, B2, B3 - the slopes of the base, subgrade and subbase stress-dependency relationship (equations 3-3 through 3-5). If KODE other than 2 or 4 is used, B3 need not be defined.

NOTE: The program requires that the slopes B1 (and B3) be positive if the base (subbase) modulus increases with increasing θ and B2 be positive if the subgrade modulus decreases with increasing deviatoric stress. Some computers do not like zeros as exponents. It is therefore suggested that for base, subbase or subgrade materials with stress-independent moduli, the values for B be specified as 0.001 rather than 0.

The rest of the input requirements are different for each analysis mode, consequently they will be described separately.

It should be pointed out that while the output appears in both British and metric units, the inputs, except for the FWD parameters, are all in British units; moreover, the Dynaflect and Road Rater deflections are read in in mils (.001 ins). To convert to British units:

1 psi = 6.895 kPA
1 lb = 4.44 N
1 pcf = 62.35 x specific gravity
1 in = 25.4 mm
1 mil = .0254 mm = 25.4 micrometers

3.2.1 Input Requirements Using Dynaflect Deflection Data, KODE=0 or KODE=4, DEVICE=1

In addition to the data described in Section 3.2, the following additional information is required for this mode of analysis.

Card 5 NN1, NN2, NN3, NN4, TH1, TH2, TH3, RHO(1), RHO(2), RHO(3), RHO(4), EEXP, EDES, LTYPE
NN1 through NN4 are the Poisson's ratios of the layers from top to bottom layer, respectively, and TH1, TH2, TH3 are the thicknesses of the top three layers. RHO(1) through RHO(4) are the densities (in pcf) of the pavement layers and EEXP and EDES are the moduli of the original asphalt mix at test and design temperatures, respectively. Note that if KODE=0, the pavement is represented by three layers; therefore NN4, TH3 and RHO(4) need not be defined (may be left blank). LTYPE is used to distinguish granular bases from cement-treated bases. LTYPE=0 for granular bases; any non-zero number may be used for cement-treated bases.

Card 6 STATIC is the total static load applied by the trailer to the pavement; for most Dynaflects this value is 1500 lbs. (6.7 kN)

Card 7 NUMB, D1, D2, D3, D4, D5, KRACK, COMM
NUMB identifies the location at which deflection measurements were made and must be read in as an integer. D1 through D5 are the measured Dynaflect deflections in mils, KRACK specifies if any cracking exists at the test site, and COMM is left for appropriate comments, such as drainage conditions, presence of rutting or patching, time of day and temperature measurements, and other general observations.

KRACK=2 denotes Class 2 cracking (3),
KRACK=3 denotes Class 3 cracking (3), and
KRACK=0 (or blank) denotes that no cracking exists.

Card 7 is repeated for every measurement location and the entire data set (cards 1 through 7) is repeated for every test section, or whenever the average test temperature changes sufficiently to make a 10% change in EEXP.

The program is currently limited to 40 test locations per data set. This limitation is defined by the dimension of HOV and NSTN arrays in the statement:

```
COMMON/PLOT/HOV (40), NSTN (40), NUMSTN
```

which occurs at the beginning of the main program and again in the subroutine PLOT. If the user wishes to extend this limit, the dimensions of HOV and NSTN arrays may be redefined in the above COMMON statements.

No inherent limit exists on the number of data sets (cards 1 through 7) that may be processed at one time beyond the limits of available processing time on the computer.

3.2.2 Input Requirements Using Road Rater Deflection Data, KODE=0 or KODE=4, DEVICE=2

In addition to the data described in Section 3.2, the following additional information is required for this mode of analysis:

Card 5 NN1, NN2, NN3, NN4, TH1, Th2, TH3, RHO(1), RHO(2), RHO(3), RHO(4), EEXP, EDES, LTYPE
This card is identical to card 5 described in Section 3.2.1.

Card 6 FORC, AMP, FR, STATIC, XDIST, XSENS
FORC is the static load (in pounds) applied by each van wheel, and STATIC is the total static load (in pounds) applied by the loading head to the pavement surface - see Section 2.1.1. AMP and FR are the amplitude and frequency used in generating the dynamic load; AMP must be read in in mils (.001 inches). XDIST is the center-to-center distance (in inches) between the front tires of the van, and XSENS is the center-to-center distance (in inches) from the first sensor to the van front wheel.

Card 7 NUMB, S1, S2, S3, S4, RN, KRACK, COMM
NUMB, KRACK, and COMM are as defined in Card 7, Section 3.2.1. RN is the range multiplication factor of the readout instrument, and S1 through S4 are instrument readings of sensors 1 through 4. RN must be defined such that deflections are in mils (.001 inches), i.e., so that D1=RN*S1 has units of mils. Also, RN may vary from test location to test location BUT MUST BE THE SAME FOR ALL SENSORS AT THE SAME TEST LOCATION.

Card 7 is repeated for every measurement location and the entire data set (cards 1 through 7) is repeated for every test section, or whenever the average test temperature changes sufficiently to make a 10% change in EEXP. (See Section 3.2.1 for restrictions.)

Note that card 6 is read once per data set; if AMP or FR are changed, a new data set consisting of cards 1 through 7 has to be defined.

3.2.3 Input Requirements Using Falling Weight Deflectometer Data, KODE=0 or KODE=4, DEVICE=3 or DEVICE=4

In addition to the data described in Section 3.2, the following additional information is required for this mode of analysis:

Card 5 NN1, NN2, NN3, NN4, TH1, TH2, TH3, RHO(1), RHO(2), RHO(3), RHO(4), EEXP, EDES, LTYPE
This card is identical to card 5 described in Section 3.2.1.

Card 6 FORC, WGTM, HGTM, SPRM, STATIC, XDIST, XSENS
FORC is the static load applied by each trailer/van wheel (DEVICE=3/4) when the drop weight is resting on the loading head, and STATIC is the static load applied by the loading head with the drop weight elevated - see Section 2.2.1. WGTM and HGTM are the mass and drop height of the drop weight, respectively, and SPRM is the spring constant of the spring between the loading head and drop weight. XDIST is the center-to-center distance (in inches) between the trailer wheels (or the rear van wheels), and XSENS is the center-to-center distance (in inches) from the first sensor to the trailer/van wheel.

Card 7 NUMB, D1, D2, D3, D4, KRACK, COMM
NUMB, KRACK and COMM are defined in card 7, Section 3.2.1, and D1 through D4 are sensor readings in millimeters. Since the FWD testers do not have well-defined sensor locations, the program REQUIRES that the sensors be located at 0, 30, 60, 100 cm from the center of the loading head. OTHER SENSOR LOCATIONS WILL NOT WORK AND WILL REQUIRE EXTENSIVE MODIFICATION TO THE PROGRAM.

Card 7 is repeated for every measurement location and the entire data set (cards 1 through 7) is repeated for every test section, or whenever the average test temperature changes sufficiently to make a 10% change in EEXP. (See Section 3.2.1 for restrictions.)

Note that card 6 is read once per data set; if any of the parameters on card 6 are changed, a new data set consisting of cards 1 through 7 has to be defined.

3.2.4 Input Requirements Using Laboratory Data in Three-Layer Model (KODE=1)

Laboratory test data is assumed to be available on a limited basis and is therefore not processed through the loop for NUMSTN, i.e., NUMSTN=1 is specified. If more than one set of laboratory data is available, the entire data set of 6 cards is repeated.

The following additional information is required for this mode of analysis:

Card 5 E(1), CBASE, CSUB
Here E(1) is the modulus of the asphalt layer at test temperature, CBASE, CSUB are the constants A1, A2 of equations 3-3 and 3-4, respectively, and represent the intercepts of the stress-dependency relationship.

Card 6 NN1, NN2, NN3, NN4, TH1, TH2, TH3, RHO(1), RHO(2), RHO(3), RHO(4), EEXP, EDES, LTYPE
This card is identical to card 5 described in Section 3.2.1, except that only granular bases are permitted. The values of NN4, TH3, and RHO(4) are ignored in this analysis and may be left blank.

3.2.5 Input Requirements Using Laboratory Data in Four-Layer Model (KODE=2)

The input requirements for this mode of analysis are the same as for the three-layer analytical model, except that the cards in the data set are made out as follows:

Card 5 E(1), CBASE, CSUB, CSBS
The first three variables are the same as defined under card 5 in Section 3.2.4 and CSBS is the intercept A3 (of equation 3-5) in the subbase stress-dependency relationship.

Card 6 NN1, NN2, NN3, NN4, Th1, Th2, TH3, RHO(1), RHO(2), RHO(3), RHO(4), EEXP, EDES, LTYPE
This card is identical to Card 5 described in Section 3.2.1, except that only granular bases are permitted for this mode of analysis.

3.2.6 Input Requirements Using Estimated (Default) Values (KODE=3)

The data set for this mode of analysis consists of six data cards. The first four cards are prepared as described in Section 3.2 and Card 6 is the same as the sixth card in Section 3.2.5. The remaining card (Card 5) contains the estimated (default) layer moduli for 18 kip (80 kN) axle loading.

Card 5 E(1), E(2), E(3)

The entire data set of six cards is repeated for each set of estimated moduli values.

TABLE 5. INPUT GUIDE FOR OAF

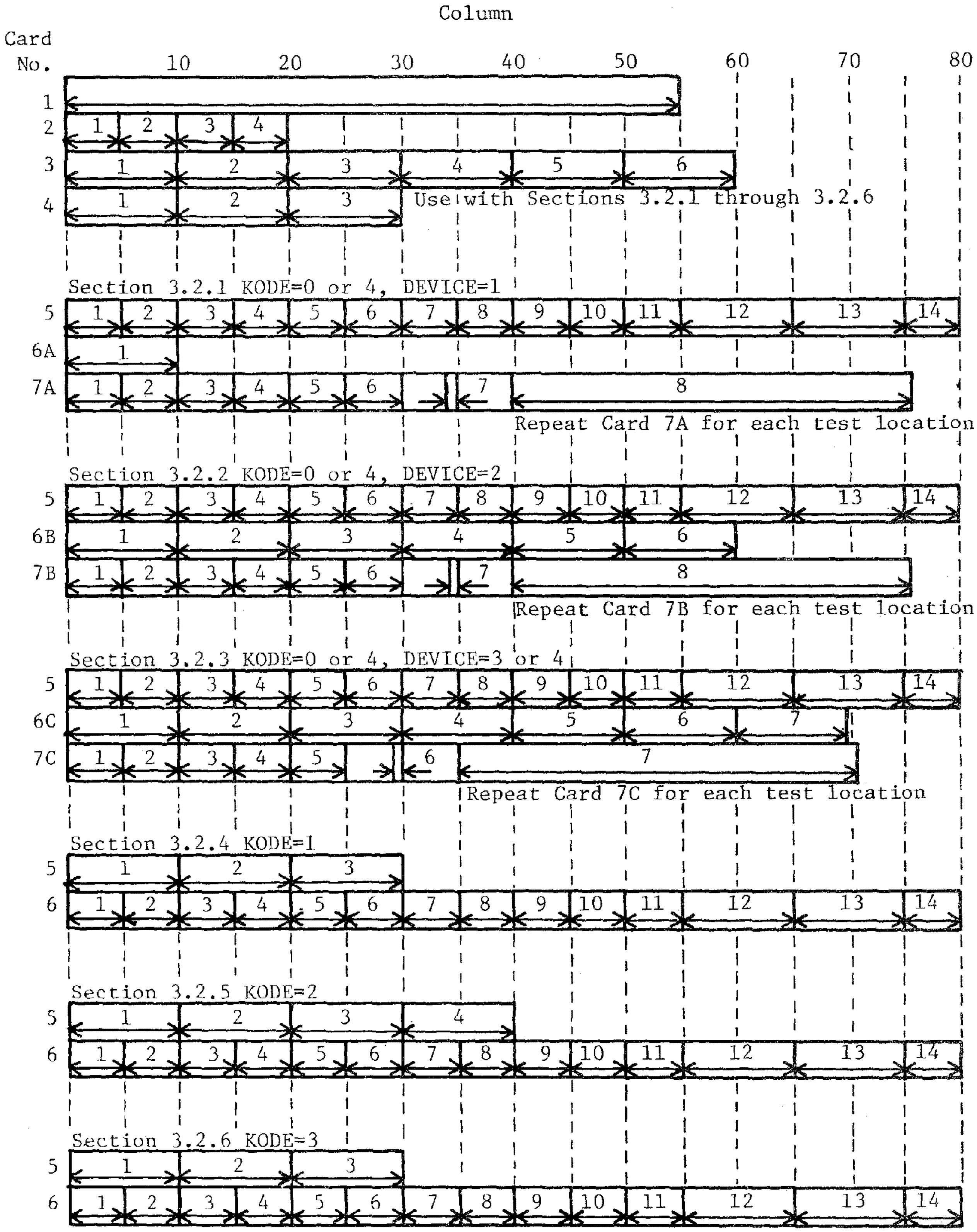


TABLE 6. INPUT FORMATS

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
1	14A4	1. TITLE	ALPHANUMERIC HEADING	3.2
2	4I5	1. KODE	SWITCH FOR TYPE OF ANALYSIS =0 DEFLECTION DATA, 3-LAYER ANALYSIS =1 3-LAYER LAB DATA =2 4-LAYER LAB DATA =3 ESTIMATED (DEFAULT) VALUES =4 DEFLECTION DATA, 4-LAYER ANALYSIS	3.1, 3.2
		2. NUMSTN	NUMBER OF LOCATIONS WHERE DEFLECTIONS ARE MEASURED	3.2
		3. NLS	NUMBER OF LAYERS USED IN ANALYTICAL MODEL =3 FOR KODE=0, 1, 3 =4 FOR KODE=2, 4	3.2
		4. DEVICE	SWITCH FOR TYPE OF TESTER =1 FOR DYNAFLECT =2 FOR ROAD RATER =3 FOR TRAILER-MOUNTED FWD =4 FOR VAN-MOUNTED FWD	3.2
3	4F10.0, I10, F10.0	1. EOV	MODULUS OF OVERLAY AT DESIGN TEMPERATURE	2.5.3
		2. VOV	POISSON'S RATIO OF OVERLAY	2.5.2
		3. RHOV	DENSITY OF OVERLAY	2.5.5, 3.2

TABLE 6. INPUT FORMATS (continued)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
3		4. DTN	AVERAGE EQUIVALENT DAILY 18KIP (80KN) AXLE LOADINGS	2.4
		5. NUMYR	NUMBER OF YEARS IN DESIGN PERIOD	2.4
		6. GF	EXPECTED ANNUAL TRAFFIC GROWTH RATE	2.4
4	3F10.0	1. B1	SLOPE FOR BASE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2, 3.2
		2. B2	SLOPE FOR SUBGRADE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2, 3.2
		3. B3	SLOPE FOR SUBBASE STRESS-DEPENDENCY RELATIONSHIP	3.1.2, 3.2, 2.5.4

ONLY ONE OF THE FOLLOWING FOUR SECTIONS ARE REQUIRED, DEPENDING ON THE TYPE OF ANALYSIS

<u>SECTION 3.2.1, KODE=0 or KODE=4</u>

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
5	11F5.0, 2F10.0, I5	1. NN1	POISSON'S RATIO OF LAYER 1	2.5.2, 3.1.2
		2. NN2	POISSON'S RATIO OF LAYER 2	2.5.2, 3.1.2
		3. NN3	POISSON'S RATIO OF LAYER 3	2.5.2, 3.1.2
		4. NN4	POISSON'S RATIO OF LAYER 4 IF SUBBASE IS PRESENT	2.5.2, 3.1.2

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
5		5. TH1	THICKNESS OF LAYER 1	2.5.1
		6. TH2	THICKNESS OF LAYER 2	2.5.1
		7. TH3	THICKNESS OF LAYER 3, IF SUBBASE IS PRESENT	2.5.1
		8. RHO(1)	DENSITY OF LAYER 1 IN PCF	2.5.5, 3.2
		9. RHO(2)	DENSITY OF LAYER 2 IN PCF	2.5.5, 3.2
		10. RHO(3)	DENSITY OF LAYER 3 IN PCF	2.5.5, 3.2
		11. RHO(4)	DENSITY OF LAYER 4 IN PCF IF SUBBASE IS PRESENT	2.5.5, 3.2
		12. EEXP	MODULUS OF ORIGINAL ASPHALT MIX AT TEST TEMPERATURE	2.5.3
		13. EDES	MODULUS OF ORIGINAL ASPHALT MIX AT DESIGN TEMPERATURE	2.5.3
		14. LTYPE	SWITCH FOR BASE TYPE =0 FOR GRANULAR BASE =1 FOR CEMENT-TREATED BASE	3.2.1

NOTE: CARDS 6A, 6B and 6C USED FOR DYNAFLECT, ROAD RATER AND FALLING WEIGHT DEFLECTOMETER, RESPECTIVELY; DEVICE 1, 2, or 3 AND 4.

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
6A	F10.0	1. STATIC	TOTAL STATIC LOAD APPLIED BY TRAILER, LBS	2.1.1, 3.2.1
6B	6F10.0	1. FORC	STATIC LOAD PER VAN FRONT WHELL, LBS	2.1.1, 3.2.2
		2. AMP	AMPLITUDE USED IN DYNAMIC FORCE GENERATION, MILS	2.1.1, 3.2.2
		3. FR	FREQUENCY OF DYNAMIC FORCE, Hz	2.1.1, 3.2.2
		4. STATIC	TOTAL STATIC LOAD APPLIED BY LOADING HEAD, LBS	2.1.1, 3.2.2
		5. XDIST	DISTANCE BETWEEN VAN FRONT WHEELS (CENTER-TO-CENTER), IN.	3.2.2
		6. XSENS	DISTANCE FROM #1 SENSOR TO VAN WHEEL, IN.	3.2.2
6C	7F10.0	1. FORC	STATIC LOAD PER TRAILER/VAN WHEEL, NEWTONS	2.1.1, 3.2.3
		2. WGTM	WEIGHT OF DROP WEIGHT, NEWTONS	3.2.3
		3. HGTM	HEIGHT OF DROP, METERS	3.2.3
		4. SPRM	SPRING CONSTANT, NEWTONS/METER	3.2.3
		5. STATIC	STATIC LOAD APPLIED BY LOADING HEAD, NEWTONS	2.1.1,3.2.3
		6. XDIST	DISTANCE BETWEEN TRAILER/VAN WHEELS (CENTER-TO-CENTER), IN.	3.2.3
		7. XSENS	DISTANCE FROM #1 SENSOR TO TRAILER/VAN WHEEL (CENTER-TO-CENTER), IN.	3.2.3

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
NOTE:	CARD 7A IS USED WITH DYNAFLECT, DEVICE=1 CARD 7B IS USED WITH ROAD RATER, DEVICE=2 CARD 7C IS USED WITH FWD, DEVICE=3 or 4 CARD 7 IS REPEATED FOR EACH MEASUREMENT LOCATION, i.e., NUMSTN times			
7A	I5, 5F5.0, 4X, I1, 5X, 9A4	1. NUMB	LOCATION OF TEST SITE MUST BE AN INTEGER	3.2.1
		2. D1	SENSOR 1 DEFLECTION, MILS	3.2.1
		3. D2	SENSOR 2 DEFLECTION, MILS	3.2.1
		4. D3	SENSOR 3 DEFLECTION, MILS	3.2.1
		5. D4	SENSOR 4 DEFLECTION, MILS	3.2.1
		6. D5	SENSOR 5 DEFLECTION, MILS	3.2.1
		7. KRACK	SWITCH FOR TYPE OF CRACKING = 0 or BLANK FOR UNCRACKED PAVEMENT = 2 FOR CLASS 2 CRACKING = 3 FOR CLASS 3 CRACKING	2.3.1, 3.2.1
		8. COMM	SPACE FOR GENERAL COMMENTS	2.3.1, 3.2.1
7B	I5, 5F5.0, 4X, I1, 5X, 9A4	1. NUMB	SAME AS IN CARD 7A	3.2.1
		2. S1	SENSOR 1 DEFLECTION, METER UNITS*	3.2.2

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
		3. S2	SENSOR 2 DEFLECTION, METER UNITS*	3.2.2
		4. S3	SENSOR 3 DEFLECTION, METER UNITS*	3.2.2
		5. S4	SENSOR 4 DEFLECTION, METER UNITS*	3.2.2
		6. RN	RANGE OF INSTRUMENT SCALE	3.2.2
		7. KRACK	SAME AS IN CARD 7A	2.3.1, 3.2.1
		8. COMM	SPACE FOR GENERAL COMMENTS	2.3.1, 3.2.1
7C	I5, 4F5.0, 4X, I1, 5X, 9A4	1. NUMB	SAME AS IN CARD 7A	3.2.1
		2. D1	SENSOR 1 DEFLECTION, MILI-METERS	3.2.3
		3. D2	SENSOR 2 DEFLECTION, MILI-METERS	3.2.3
		4. D3	SENSOR 3 DEFLECTION, MILI-METERS	3.2.3
		5. D4	SENSOR 4 DEFLECTION, MILI-METERS	3.2.3
		6. KRACK	SAME AS IN CARD 7A	2.3.1, 3.2.1
		7. COMM	SPACE FOR GENERAL COMMENTS	2.3.1, 3.2.1

*NOTE: Meter units x RN = mils

TABLE 6 INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
SECTION 3.2.4, KODE=1				
5	3F10.0	1. E(1)	MODULUS OF EXISTING PAVEMENT AT TEST TEMPERATURE	2.5.3
		2. CBASE	INTERCEPT OF BASE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2
		3. CSUB	INTERCEPT OF SUBGRADE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2
6	11F5.0, 2F10.0, I5	1. NN1	POISSON's RATIO OF LAYER 1	2.5.2
		2. NN2	POISSON'S RATIO OF LAYER 2	2.5.2
		3. NN3	POISSON'S RATIO OF LAYER 3	2.5.2
		4. NN4	BLANK FOR KODE=1	3.2.4
		5. TH1	THICKNESS OF LAYER 1	2.5.1
		6. TH2	THICKNESS OF LAYER 2	2.5.1
		7. TH3	BLANK FOR KODE=1	3.2.4
		8. RHO(1)	DENSITY OF LAYER 1, PCF	2.5.5, 3.2
		9. RHO(2)	DENSITY OF LAYER 2, PCF	2.5.5, 3.2
		10. RHO(3)	DENSITY OF LAYER 3, PCF	2.5.5, 3.2

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
		11. RHO(4)	BLANK FOR KODE=1	3.2.4
		12. EEXP	MODULUS OF ORIGINAL ASPHALT MIX AT TEST TEMPERATURE	2.5.3
		13. EDES	MODULUS OF ORIGINAL ASPHALT MIX AT DESIGN TEMPERATURE	2.5.3
		14. LTYPE	=0, GRANULAR BASE	3.2.1,3.2.4

NOTE: CARD 6 IS IDENTICAL WITH CARD 5 SECTION 3.2.1 (KODE=0 or 4)

SECTION 3.2.5, KODE=2

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
5	4F10.0	1. E(1)	MODULUS OF EXISTING PAVEMENT AT TEST TEMPERATURE	2.5.3
		2. CBASE	INTERCEPT OF BASE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2
		3. CSUB	INTERCEPT OF SUBGRADE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2
		4. CSBS	INTERCEPT OF SUBBASE STRESS-DEPENDENCY RELATIONSHIP	2.5.4, 3.1.2
6	11F5.0, 2F10.0, I5	1. NN1	POISSON'S RATIO OF LAYER 1	2.5.2
		2. NN2	POISSON'S RATIO OF LAYER 2	2.5.2
		3. NN3	POISSON'S RATIO OF LAYER 3	2.5.2
		4. NN4	POISSON'S RATIO OF LAYER 4	2.5.2

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE		DESCRIPTION	REFERENCE SECTION
6		5.	TH1	THICKNESS OF LAYER 1	2.5.1
		6.	TH2	THICKNESS OF LAYER 2	2.5.1
		7.	TH3	THICKNESS OF LAYER 3	2.5.1
		8.	RHO(1)	DENSITY OF LAYER 1, PCF	2.5.5, 3.2
		9.	RHO(2)	DENSITY OF LAYER 2, PCF	2.5.5, 3.2
		10.	RHO(3)	DENSITY OF LAYER 3, PCF	2.5.5, 3.2
		11.	RHO(4)	DENSITY OF LAYER 4, PCF	2.5.5, 3.2
		12.	EEXP	MODULUS OF ORIGINAL ASPHALT MIX AT TEST TEMPERATURE	2.5.3
		13.	EDES	MODULUS OF ORIGINAL ASPHALT MIX AT DESIGN TEMPERATURE	2.5.3
		14.	LTYPE	=0, GRANULAR BASE	3.2.1, 3.2.5

NOTE: CARD 6 IS IDENTICAL WITH CARD 5, SECTION 3.2.1 (KODE=0 or 4)

SECTION 3.2.6, KODE=3

CARD	FORMAT	VARIABLE		DESCRIPTION	REFERENCE SECTION
6	3F10.0	1.	E(1)	ESTIMATED MODULUS OF LAYER 1	2.5.3, 3.1
		2.	E(2)	ESTIMATED MODULUS OF LAYER 2	2.5.3, 3.1
		3.	E(3)	ESTIMATED MODULUS OF LAYER 3	2.5.3, 3.1

TABLE 6. INPUT FORMATS (cont.)

CARD	FORMAT	VARIABLE	DESCRIPTION	REFERENCE SECTION
6	11F5.0, 2F10.0, I5	1. NN1	POISSON'S RATIO OF LAYER 1	2.5.2
		2. NN2	POISSON'S RATIO OF LAYER 2	2.5.2
		3. NN3	POISSON'S RATIO OF LAYER 3	2.5.2
		4. NN4	POISSON'S RATIO OF LAYER 4	2.5.2
		5. TH1	THICKNESS OF LAYER 1	2.5.1
		6. TH2	THICKNESS OF LAYER 2	2.5.1
		7. TH3	THICKNESS OF LAYER 3	2.5.1
		8. RHO(1)	DENSITY OF LAYER 1, PCF	2.5.5, 3.2
		9. RHO(2)	DENSITY OF LAYER 2, PCF	2.5.5, 3.2
		10. RHO(3)	DENSITY OF LAYER 3, PCF	2.5.5, 3.2
		11. RHO(4)	DENSITY OF LAYER 4, PCF	2.5.5, 3.2
		12. EEXP	MODULUS OF ORIGINAL ASPHALT MIX AT TEST TEMPERATURE	2.5.3
		13. EDES	MODULUS OF ORIGINAL ASPHALT MIX AT DESIGN TEMPERATURE	2.5.3
		14. LTYPE	=0, GRANULAR BASE	3.2.1, 3.2.5

NOTE: CARD 6 IS IDENTICAL WITH CARD 5, SECTION 3.2.1 (KODE=0 or 4)

CHAPTER 4
OUTPUT DESCRIPTIONS AND DATA INTERPRETATIONS

The output format of the OAF program has been designed to best inform the engineer as to anticipated pavement problems and provide guidance for various maintenance alternatives. Although the required overlay thickness is of ultimate interest to the user, the results of intermediate computations can also be of value when evaluating alternate maintenance strategies to overlay. For example, print-out of the in-situ layer stiffnesses showing relatively low values of the base and/or subgrade moduli at a particular test location might lead to a decision for drainage improvement which might well result in an improvement in these properties with a corresponding decrease in the amount of overlay required. Consequently, the output format has been designed with these considerations in mind.

4.1 OUTPUT DESCRIPTION

A sample section of the computer output for special case KODE=0, DEVICE=1 is reproduced in Table 7. The output is divided into four major sections delineated by the headings with asterisks as follows:

1. Input Information
2. Dynamic Deflection Data
3. Stress Correction Constants
4. Stress-Corrected Layer Stiffness

4.1.1 Input Information

This is a recapitulation of the input data and is the same for all modes of analysis, except that when the four-layer model (KODE=2 or KODE=4) is used, an extra line is added to the description of the existing pavement. The five analysis modes as presented in the previous section were:

KODE=0	Layer properties determined from dynamic deflections for a three-layer or a four-layer system depending on whether a 3-layer solution was found.
KODE=1	Input layer properties for a three-layer system using lab data
KODE=2	Input layer properties for a four-layer system using lab data
KODE=3	Input layer properties for a three-layer system using default values
KODE=4	Layer properties determined from dynamic deflections for a four-layer system.

```
* * * INPUT INFORMATION * * *

SWITCH FOR TYPE OF ANALYSIS = 0    (3-LAYER DEFLECTION DATA)
NUMBER OF TEST LOCATIONS IN ROAD SECTION =    4
NUMBER OF LAYERS USED IN ANALYTICAL MODEL =    3
TYPE OF TESTING DEVICE =  1   (DYNAFLECT)

MODULUS OF OVERLAY= 750000. PSI ( 0.517E 10 PA)
POISSON'S RATIO OF OVERLAY= .40
DENSITY OF OVERLAY=145.0 PCF
DAILY TRAFFIC NUMBER= 893. EAL
NUMBER OF YEARS FOR DESIGN PERIOD IS 20
THE GROWTH FACTOR FOR TRAFFIC IS 0.050
PROJECTED DESIGN LIFE= 0.1729653E 08


EXISTING PAVEMENT IS AS FOLLOWS:

LAYER 1 THICKNESS= 5.00 IN (127.0 MM),POISSON'S RATIO= 0.40
LAYER 1 DENSITY = 145.0 PCF (2321.4 KCM)
LAYER 2 THICKNESS= 9.00 IN (228.6 MM),POISSON'S RATIO= 0.37
LAYER 2 DENSITY = 138.0 PCF (2209.4 KCM)
LAYER 3 THICKNESS=SEMI-INFINITE,       POISSON'S RATIO= 0.45
LAYER 3 DENSITY = 135.0 PCF (2161.3 KCM)
TYPE OF BASE LAYER =  0

EXPECTED LAYER 1 MODULUS AT TEST TEMPERATURE   =   725000. PSI
                                               = 0.500E 10 PA
EXPECTED LAYER 1 MODULUS AT DESIGN TEMPERATURE =   750000. PSI
                                               = 0.517E 10 PA


DYNAFLECT LOAD PARAMETER:

DEVICE STATIC LOAD = 1500.0 LB (6672.0 N)



4TH LAYER CREATED FROM 3-LAYER DATA
EXISTING PAVEMENT IS AS FOLLOWS:

LAYER 1 THICKNESS= 5.00 IN (127.0 MM),POISSON'S RATIO= 0.40
LAYER 2 THICKNESS= 6.00 IN (152.5 MM),POISSON'S RATIO= 0.37
LAYER 3 THICKNESS= 9.00 IN (228.5 MM),POISSON'S RATIO= 0.37
LAYER 4 THICKNESS=SEMI-INFINITE,       POISSON'S RATIO= 0.45
TYPE OF BASE LAYER =  0

* * * * DYNAFLECT DEFLECTION DATA * * * *       STATION NO.       2

COMMENTS:

MEASURED VALUES OF DYNALECT DEFLECTIONS (MILS)
     0.7800     0.6000     0.4200     0.2970     0.2610
COMPUTED VALUES OF DEFLECTIONS (MILS)
     0.7800     0.6096     0.4141     0.2986     0.2308
```

TABLE 7. SAMPLE OUTPUT FROM PROGRAM OAF.

```
CALCULATED VALUES FOR THE MODULI ARE AS FOLLOWS:
LAYER 1 MODULUS       775,520 PSI ( 0.535E 10 PA)
LAYER 2 MODULUS        60,011 PSI ( 0.414E 09 PA)
LAYER 3 MODULUS        35,438 PSI ( 0.244E 09 PA)
LAYER 4 MODULUS        22,727 PSI ( 0.157E 09 PA)


* * * THE CONSTANTS IN STRESS CORRECTION ARE * * *

CONSTANT A FOR BASE=          31943.
CONSTANT A FOR SUBBASE=       35387.
CONSTANT A FOR SUBGRADE=      29569.
CONSTANT B FOR BASE=          0.450
CONSTANT B FOR SUBBASE=       0.001
CONSTANT B FOR SUBGRADE=      1.100

E(1) (TEMPERATURE CORRECTED)=     802,262 PSI ( 0.553E 10 PA)

* * * STRESS-CORRECTED LAYER STIFFNESSES ARE * * *

ITERATION NUMBER= 2
CORRECTED BASE STIFFNESS=            68,191 PSI ( 0.470E 09 PA)
CORRECTED SUBBASE STIFFNESS=         35,438 PSI ( 0.244E 09 PA)
CORRECTED SUBGRADE STIFFNESS=         9,335 PSI ( 0.644E 08 PA)
THICKNESS OF OVERLAY=  0.0 INCHES (   0.0 MM)
REMAINING LIFE OF THE PAVEMENT= 0.2264743E 08 CYCLES

* THE OVERLAY REQUIRED FOR THIS STATION IS 0.00 INCHES (   0.0 MM)

* * * * DYNAFLECT DEFLECTION DATA * * * *        STATION NO.      22

COMMENTS:

MEASURED VALUES OF DYNAFLECT DEFLECTIONS (MILS)
    0.7000     0.6000     0.4200     0.2970     0.2520
COMPUTED VALUES OF DYNAFLECT DEFLECTIONS (MILS)
    0.7000     0.6000     0.4378     0.3087     0.2223

CALCULATED VALUES FOR THE MODULI ARE AS FOLLOWS:
LAYER 1 MODULUS     4,014,651 PSI ( 0.277E 11 PA)
LAYER 2 MODULUS        20,105 PSI ( 0.139E 09 PA)
LAYER 3 MODULUS        26,877 PSI ( 0.185E 09 PA)


* * * THE CONSTANTS IN STRESS CORRECTION ARE * * *

CONSTANT A FOR BASE=          10964.
CONSTANT A FOR SUBGRADE=      24992.
CONSTANT B FOR BASE=          0.450
CONSTANT B FOR SUBGRADE=      1.100

E(1) (TEMPERATURE CORRECTED)=  4,153,088 PSI ( 0.286E 11 PA)

* * * STRESS-CORRECTED LAYER STIFFNESSES ARE * * *

ITERATION NUMBER 2
CORRECTED BASE STIFFNESS=            22,413 PSI ( 0.155E 09 PA)
CORRECTED SUBGRADE STIFFNESS=        11,236 PSI ( 0.775E 08 PA)
THICKNESS OF OVERLAY=  0.0 INCHES (   0.0 MM)
REMAINING LIFE OF THE PAVEMENT= 0.7601248E 09 CYCLES

* THE OVERLAY REQUIRED FOR THIS STATION IS 0.00 INCHES (   0.0 MM)
```

TABLE 7. SAMPLE OUTPUT FROM PROGRAM OAF (CONT).

The only computed quantity in this section is the design life determined from

$$DESL = 365 * DTN * NUMYR * (1. + GF)^{NUMYR} \quad (4\text{-}1)$$

4.1.2 Dynamic Deflection Data

This section appears only when measured deflections are used in the analysis (KODE=0 or 4). In this section the measured dynamic deflections, as well as location information and any appropriate comments appearing on the input card, are reproduced. The in-situ stiffnesses (for DEVICE loading) determined from the deflection data (Section 3.1.1) are printed out along with the theoretical deflections computed from the three-layer analytical model with the above stiffnesses. A comparison of the measured and computed deflections may be used as a measure of how well the model represents the actual pavement. In the example presented in Table 7, the match between these deflections is fairly good, suggesting that the analytical model is a fair representation of the existing pavement. In the absence of cracks in the space occupied by the sensors and loading wheels, differences greater than about 4% (or .03 mils (.0008 mm), whichever is greater) in corresponding deflection values may indicate that the analytical model does not accurately represent the pavement structure. However, it should be kept in mind that the analytical model assumes that the layer thicknesses are constant throughout the project. If the as-built thicknesses vary from the assumed (design) thicknesses, this variation is reflected not only in the effective layer stiffnesses, but also in the shape of the deflection basin, or the degree of correspondence between measured and computed deflections. The analysis method also assumes that the measured deflections are precise; however, the readout resolution of the Dynaflect meter is at best ± .01 mils (.00025 mm) for deflection values below 1 mil (.025 mm) and ± .03 mils (.0008 mm) for deflections between 1 and 3 mils (.025 and .08 mm). (The other testing devices considered by this analysis program have similar resolution ranges). This resolution problem coupled with operator-induced errors contributes to the discrepancy between two sets of deflections and may alter the effective layer 1 and layer 2 stiffnesses significantly, particularly for pavements with relatively low (0.5 to 0.6 mils (.013 to .015 mm)) maximum deflections. It is for these reasons that the duplicate measurement scheme has been proposed in Section 2.1.3.

In this section the effective in-situ asphalt layer stiffness at design temperature is printed out. A comparison of this value with EDES may be used to assess the existing asphalt layer condition; however, it should be emphasized that both layer 1 and layer 2 stiffnesses are "effective stiffnesses" and reflect thickness variations as well as the inherent errors in measurement due to limited readout resolution.

4.1.3 Stress Correction Constant

In this section the constants A, B, used in the stress-correction equations, are printed. The constants B are read in as part of the input data, along with the A's for KODE=1 or 2. However, for KODE=0, KODE=3 or KODE=4, the A's are computed as outlined in Sections 3.1.1 and 3.1.3.

4.1.4 Stress-Corrected Layer Stiffnesses

The final section headed by "Stress-Corrected Layer Stiffnesses Are" prints out the incremented overlay thickness, the remaining life for that thickness of overlay, as well as the layer stiffnesses corresponding to the stress state for that particular geometry. The required overlay thickness for the particular design life is also printed out here.

If laboratory-determined data or estimated (default) values are used (KODE=1, 2, 3) in the analysis, the output ends at this point. When deflection data are used, however, the last three sections are repeated for each measurement location; the required overlay thicknesses are plotted as a function of measurement location as shown in Figure 8; and the overlay thicknesses for various percentiles (Table 8) are printed.

TABLE 8
PERCENTILE LEVELS AND THEIR
CORRESPONDING OVERLAY THICKNESSES

PERCENTILE	THICKNESS REQUIRED
0.67	0.6 in. (15mm)
0.77	0.8 in. (20mm)
0.87	1.8 in. (46mm)
0.97	3.1 in. (79mm)

AVERAGE OVERLAY THICKNESS FOR PROFILE = 0.6 in. (15mm)

The significant data in this section, other than the final overlay required, are the corrected base and subgrade stiffnesses for the 0 overlay case, i.e., the base and subgrade conditions of the existing pavement for an 18 kip (80 kN) axle loading. Comparison of these values along the roadway can help formulate alternative maintenance strategies, as was mentioned earlier.

```
              0     20     20    100      1      1      0
              0      0      0     20      2      0      3      1
              0      0      0      0      0      0      0      0
              0      0      0      0      0      0      0
              0      0
```

1 PLOT OF OVERLAY THICKNESSES

```
                                  OVERLAY REQUIRED-INCHES
                    -0.1      0.6       1.2       1.8       2.4       3.1
DISTANCE    OVERLAY  I---------I---------I---------I---------I---------I
STATION NO.  INCHES  I
      1         0.0  I*
                     I
      2         0.0  I*
                     I
      3         0.0  I*
                     I
      4         0.0  I*
                     I
      5         0.0  I*
                     I
      6         0.0  I*
                     I
      7         0.1  I *
                     I
      8         0.8  I            *
                     I
      9         0.6  I          *
                     I
     10         0.0  I*
                     I
     11         3.1  I                                                 *
                     I
     12         1.8  I                            *
                     I
     13         0.3  I    *
                     I
     14         0.0  I*
                     I
     15         0.1  I *
                     I
     16         0.7  I           *
                     I
     17         2.9  I                                              *
                     I
                     I---------I---------I---------I---------I---------I
                    -0.1      0.6       1.2       1.8       2.4       3.1
```

Figure 8. Plot of overlay thickness

It should be re-emphasized that the analysis model used elastic theory to represent the existing pavement. Although this layer theory has general acceptance, particularly when coupled with the concept of dynamic modulus, there are times when the theory predicts unrealistic conditions, for instance the layer theory in some cases predicts tensile horizontal stresses in granular bases. It is, therefore, important that comprehensive visual observations be recorded at the time of measurement so that these observations can be used to evaluate the validity of the computed overlay thicknesses.

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APPENDIX A

GUIDE FOR DEVELOPMENT OF A SEASONAL FACTOR

The overlay design program assumes that the base and subgrade support conditions have stabilized and approximates average annual values. Since the base and subgrade stiffness vary seasonally with moisture conditions, deflection readings taken at other times during the year may result in over or under estimation of the amount of overlay required. An approach to deal with this problem is suggested below:

1. Select several projects that represent the range of environmental conditions and soil types encountered. These projects should be selected so that they encompass the range of pavement geometry used (layer thicknesses and types) and should be relatively new with most of their life remaining.

2. Make deflection measurements periodically. The period may be variable depending on the variation in local climate conditions, but at least seven surveys should be conducted during the part of the year when no part of the pavement is in frozen conditions. It is suggested that the multiple measuring scheme proposed in Section 2.1.3 be used and at least 30 locations per project be tested.

3. Assume a low DTN so that no overlay will be required and compute the remaining life at each test location using program OAF.

4. For each section and each survey, discard the two highest and two lowest RLIFE values along with any based on the default model (when the message "Does Not Fit 4-Layer System" appears). Compute the average and standard deviation of RLIFE. Discard any values that are beyond the average ± two standard deviations and recompute the average RLIFE.

5. Determine for each section the mean yearly RLIFE by summing the average for each survey (from step 4) and dividing by the number of surveys, and normalize the averages by dividing by the mean annual value.

6. Plot the normalized values for each section as a function of measurement time and draw a smooth curve through these points.

The curve developed above is the seasonal adjustment factor SF discussed in Section 2.4.3.

APPENDIX B
DETERMINATION OF MEAN ASPHALTIC CONCRETE TEMPERATURE

The mean temperature of an asphalt layer 2 inches (50.8 mm) thick or over is affected by the ambient temperature during the previous time period. The Kentucky procedure, developed by Southgate (1), compensates for this phenomenon by using the previous 5 day mean air temperature history at the test location to estimate the pavement temperature at mean pavement depth. The method also takes into consideration the time of day the test was taken, which has proven significant. For pavements less than 2 inches (50.8mm) thick the surface temperature and the time of day are adequate in estimating temperature at various depths.

In the above the 5 day mean air temperature is defined as the arithmetic mean of the daily high and low air temperature occurring during the 5 day period prior to testing. The daily temperatures are available from the U.S. Weather Bureau. It is suggested that information from three weather stations which form a triangle enclosing the test location be used. The mean 5 day temperatures are assigned weighing factors inversely proportional to the distance from the test location. If the altitude of the weather station is significantly different, weighing factors are also used based on the difference in elevation between the weather station and test locations. The procedure used is explained in the following example.

The test location is at an altitude of 1000 ft. (305m). Three nearby weather stations are located as follows:

A - Altitude 800 ft. (244m), air distance 24 miles (38.6 km), Temperature $T_A = 60^oF$ (15.6^oC)

B - Altitude 1500 ft. (457m), air distance 30 miles (48.3km), Temperature $T_B = 55^oF$ (12.8^oC)

C - Altitude 1200 ft. (366m), air distance 60 miles (96.6km), Temperature $T_C = 58^oF$)14.4^oC)

The distance weighing factors are computed from

$$f_a = \frac{\text{maximum distance of station}}{\text{distance of station A}} = \frac{60}{24} = 2.5$$

$$f_b = \frac{\text{maximum distance of station}}{\text{distance of station B}} = \frac{60}{30} = 2.0$$

$$f_c = \frac{\text{maximum distance of station}}{\text{distance of station C}} = \frac{60}{60} = 1.0$$

The altitude weighing factors are computed similarly

$$g_a = \frac{\text{maximum difference in elevation}}{\text{elevation difference of station A}} = \frac{500}{200} = 2.5$$

$$g_b = \frac{\text{maximum difference in elevation}}{\text{elevation difference of Station B}} = \frac{500}{500} = 1.0$$

$$g_c = \frac{\text{maximum difference in elevation}}{\text{elevation difference of station C}} = \frac{500}{200} = 2.5$$

The mean 5 day air temperature at test location is then

$$T = \frac{(f_a + g_a)T_a + (f_b + g_b)T_b + (f_c + g_c)T_c}{f_a + f_b + f_c + g_a + g_b + g_c} = 58.1^{\circ}F \; (14.5^{\circ}C)$$

The average temperature of an asphalt pavement greater than 2 inches (50.8mm) thick is obtained by adding the mean 5 day air temperature to the measured surface temperature, entering the graph appropriate to the test hour, and reading the temperature from the curve corresponding to half thickness of asphalt layer.

For a thin pavement, 2 inches (50.8mm) thick or less, the average temperature is obtained directly by entering the appropriate graph with the measured surface temperature and reading the temperature from the curve corresponding to the half thickness of the asphalt layer.

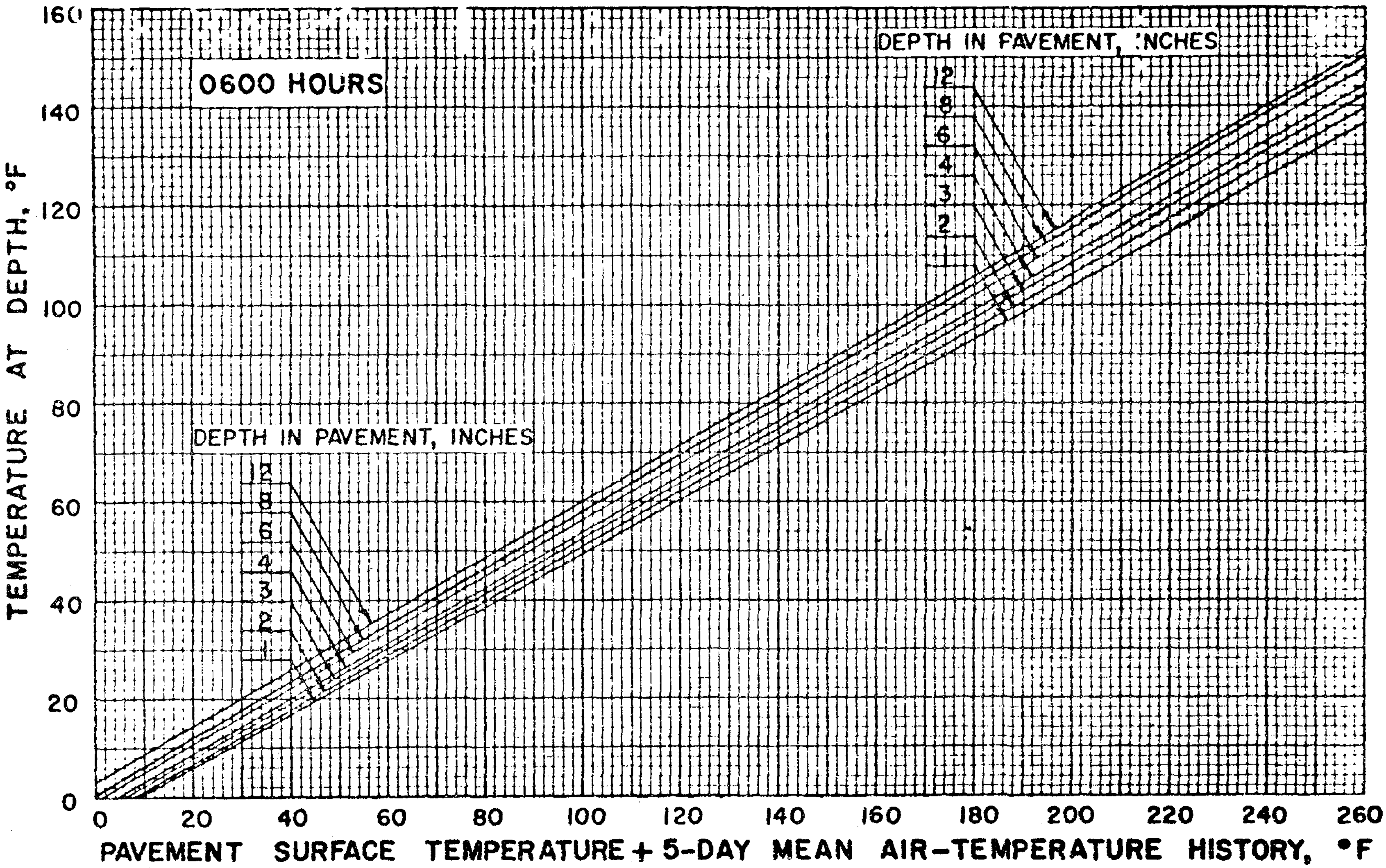

FIGURE 9. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{O}F = 1.8(^{O}C) + 32^{O}$

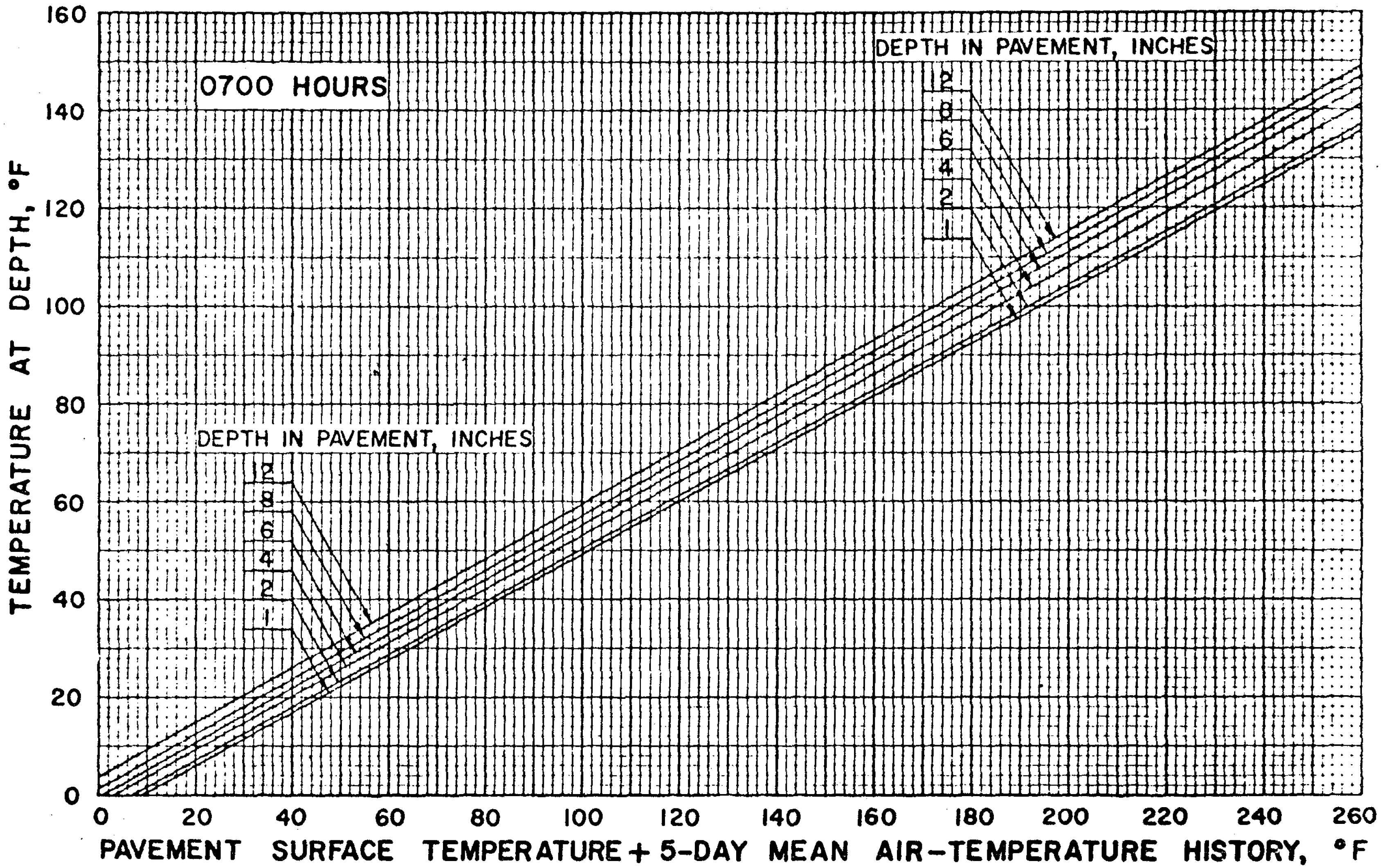

FIGURE 10. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

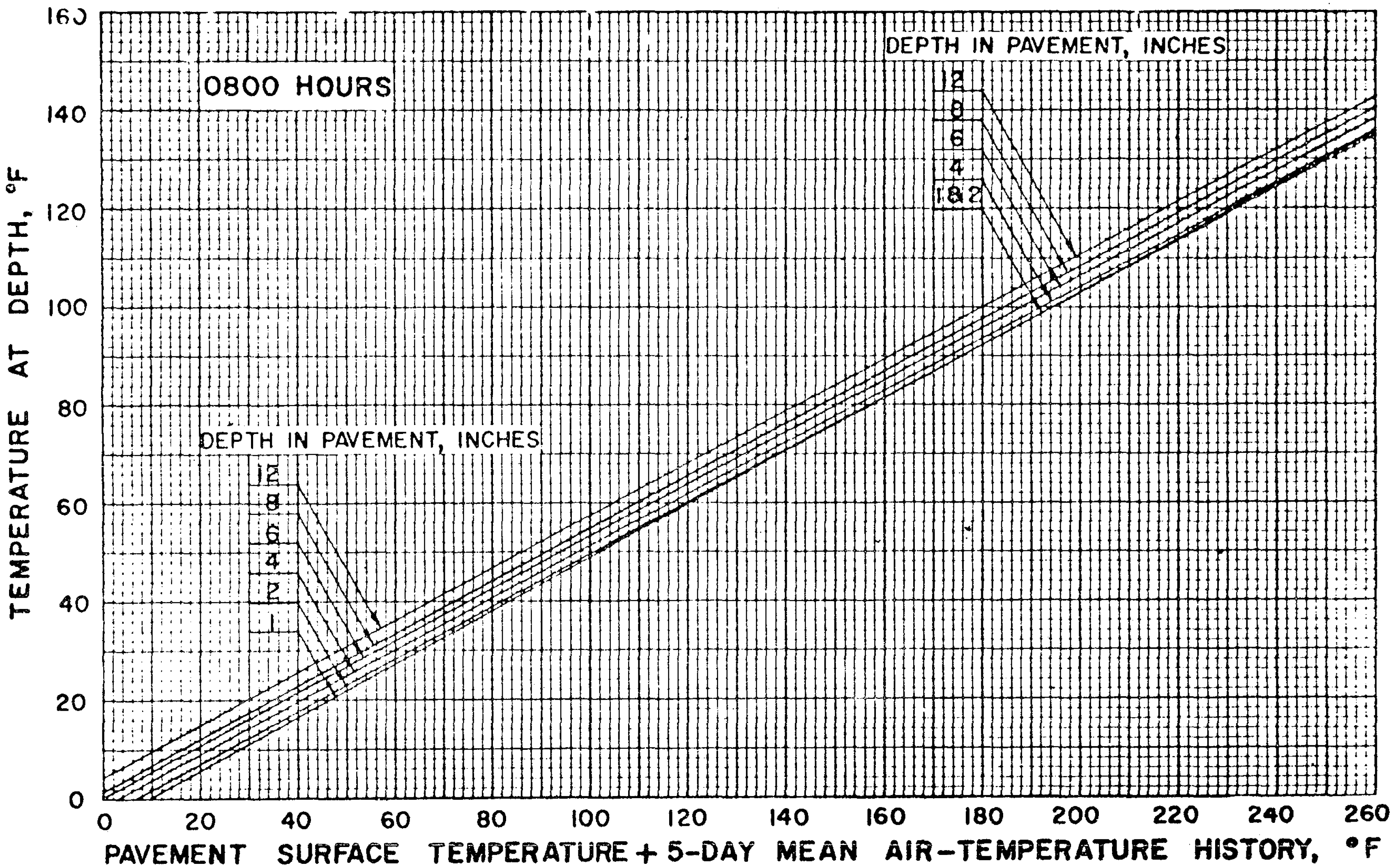

FIGURE 11. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{o}F = 1.8(^{o}C) + 32^{o}$

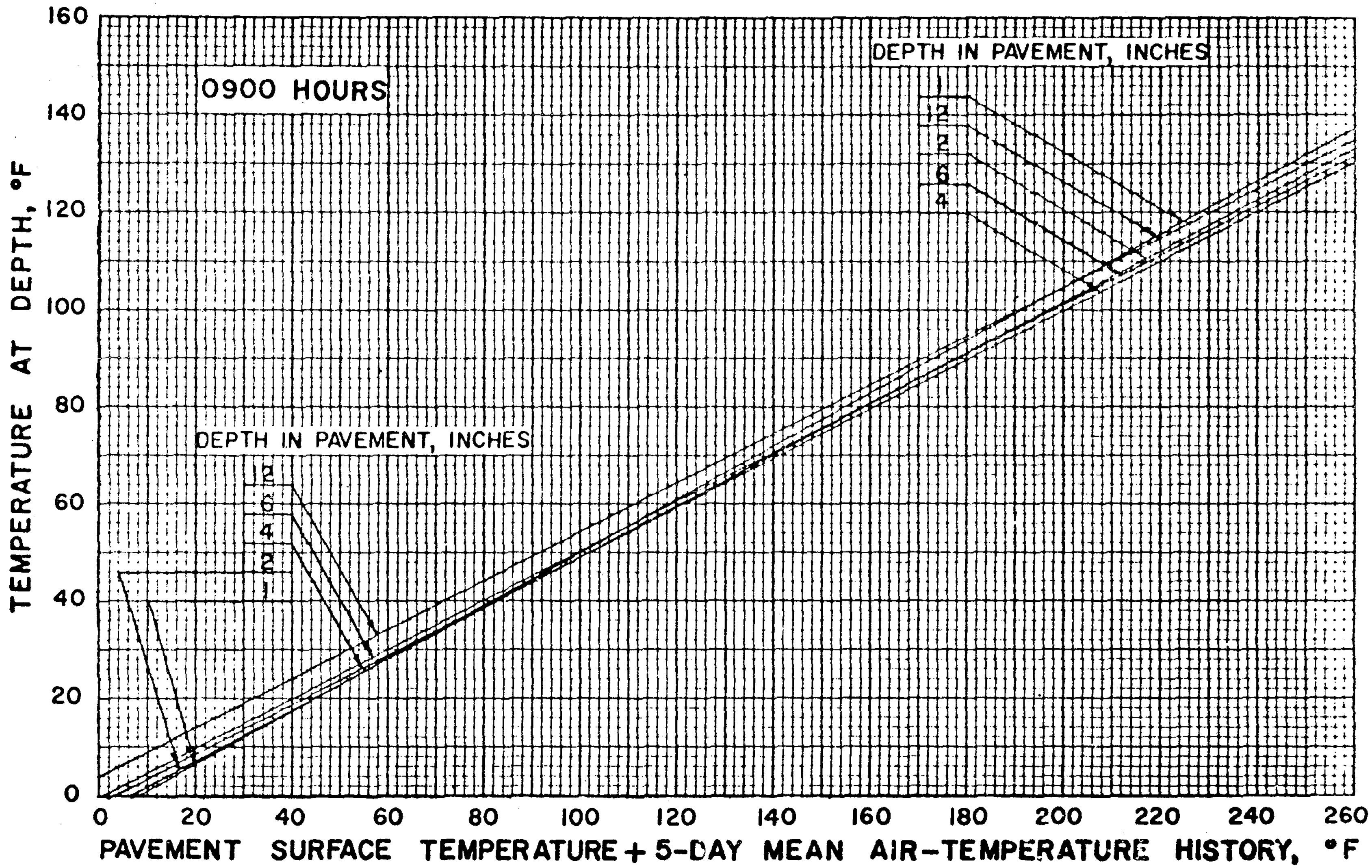

FIGURE 12. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in., = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32$

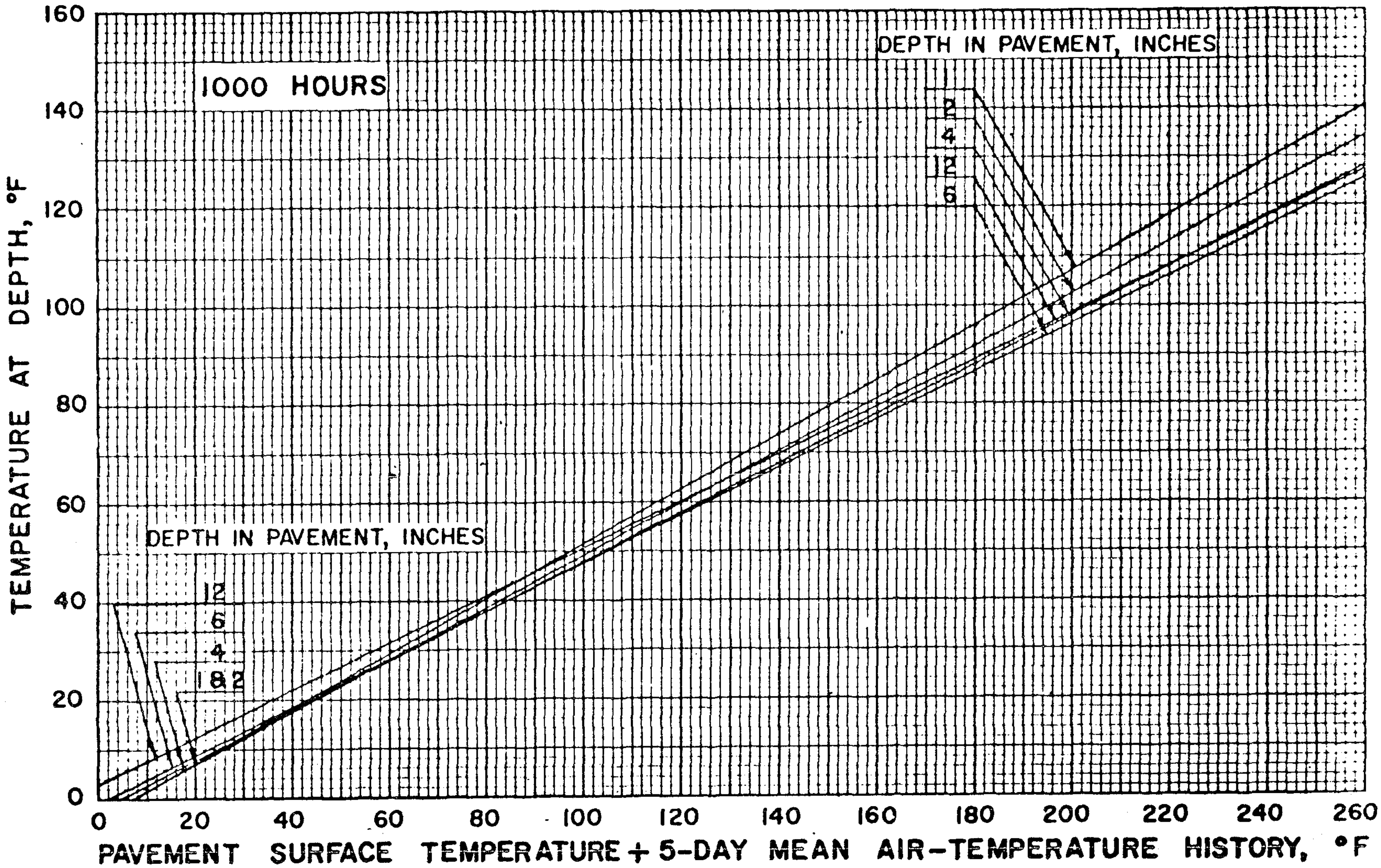

FIGURE 13. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{O}F = 1.8(^{O}C) + 32^{O}$

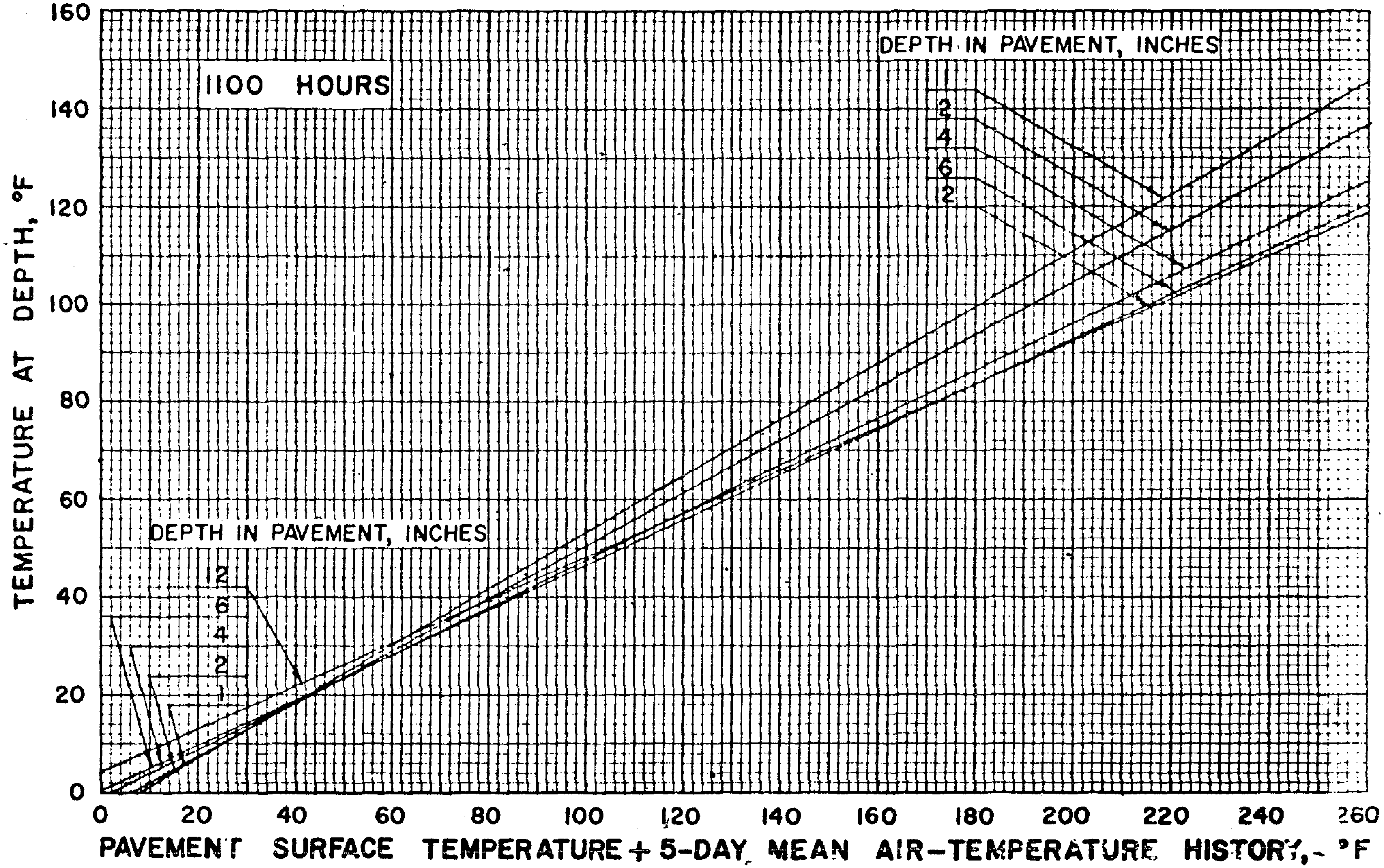

FIGURE 14. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

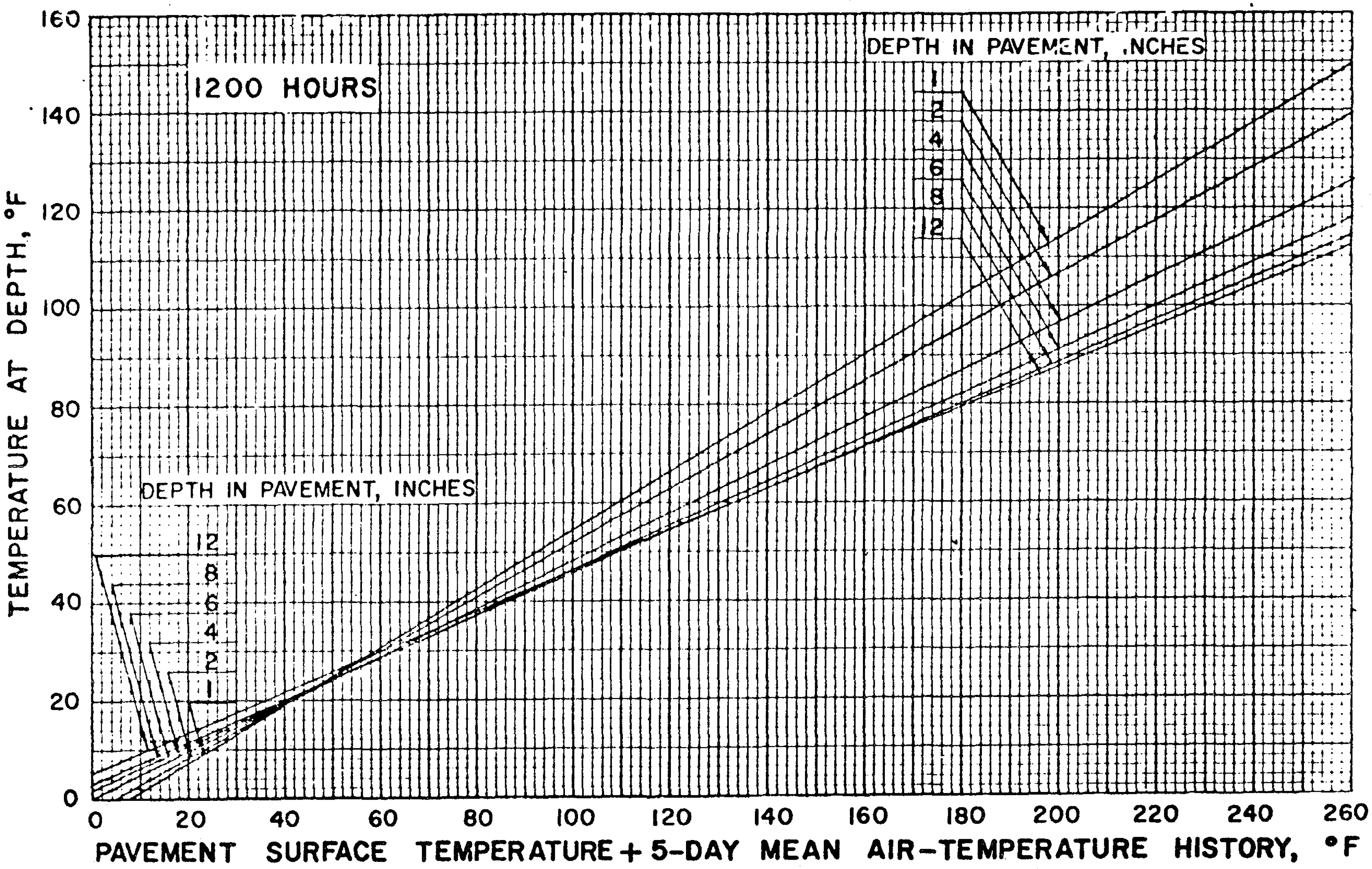

FIGURE 15. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm
$1^{O}F = 1.8(^{O}C) + 32^{O}$

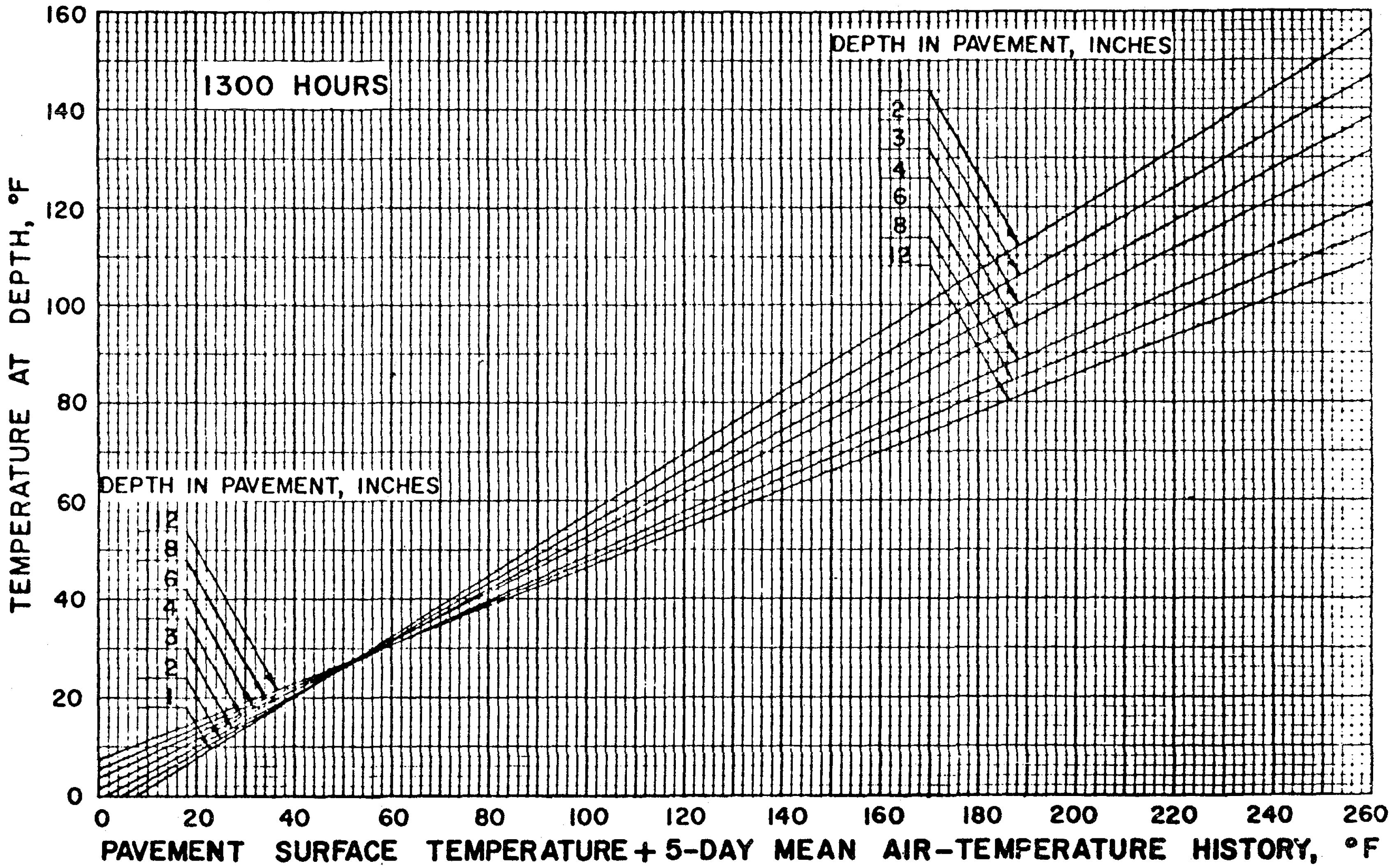

FIGURE 16. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

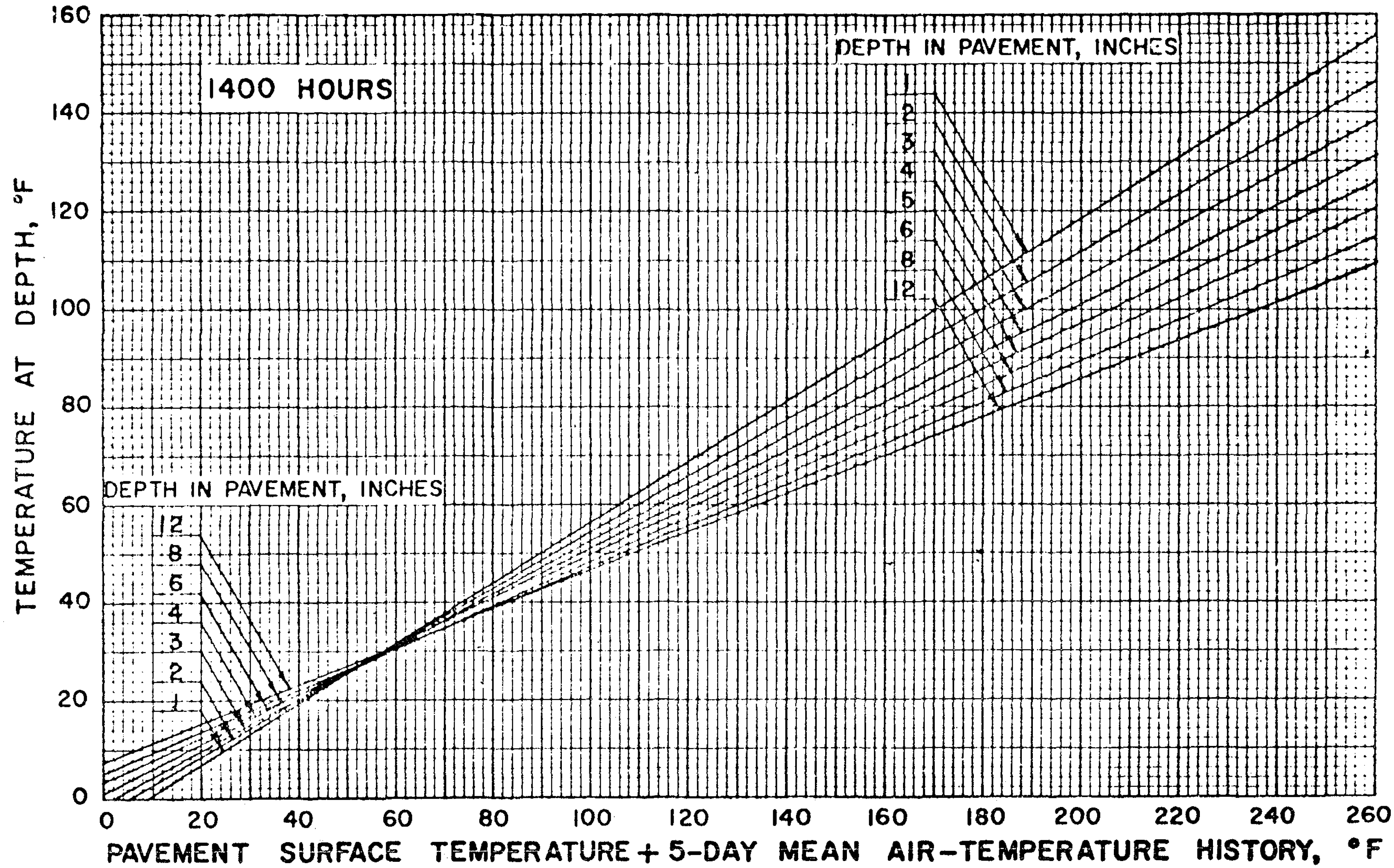

FIGURE 17. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm
$1^{O}F = 1.8(^{O}C) + 32^{O}$

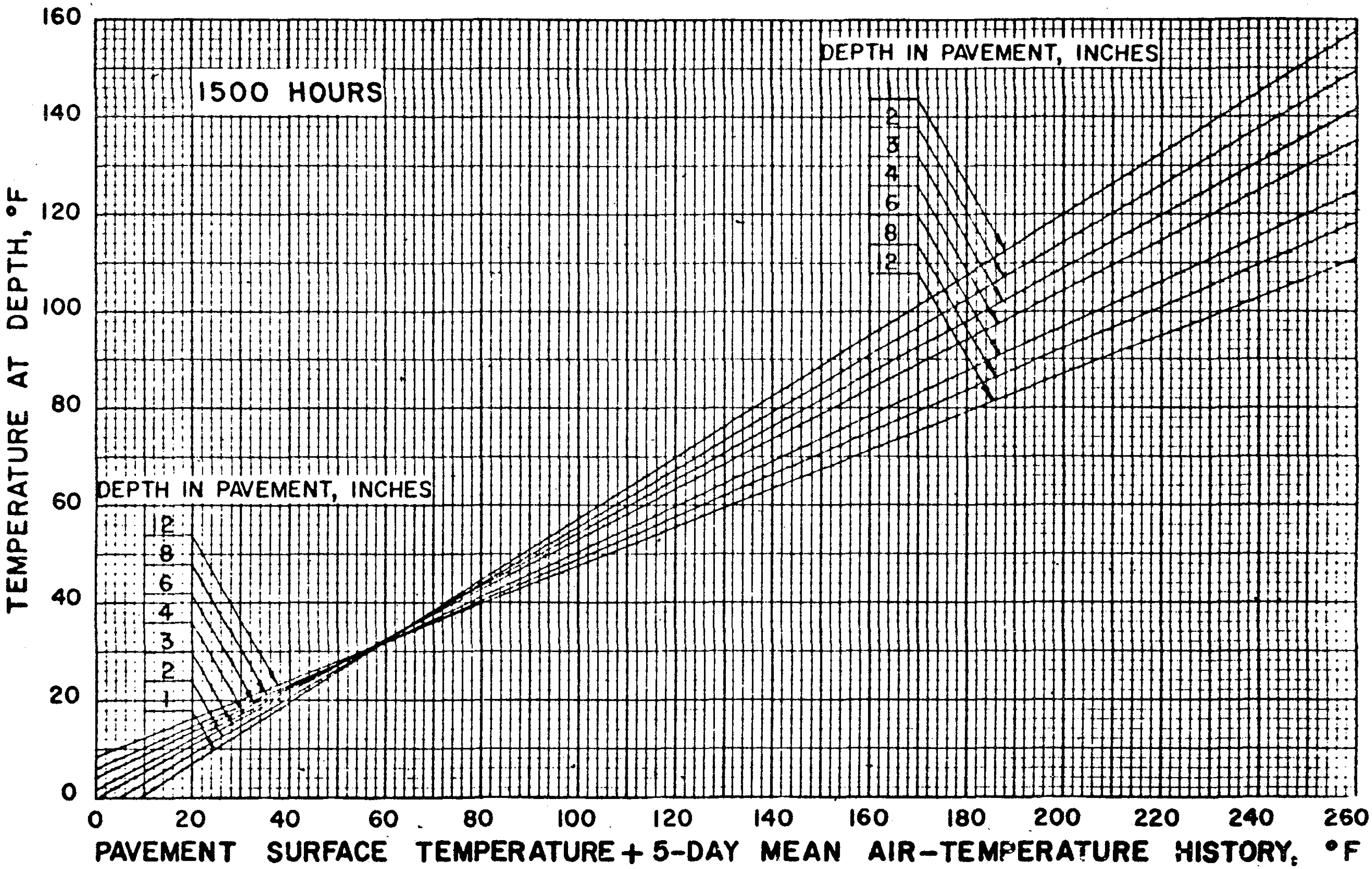

FIGURE 18. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

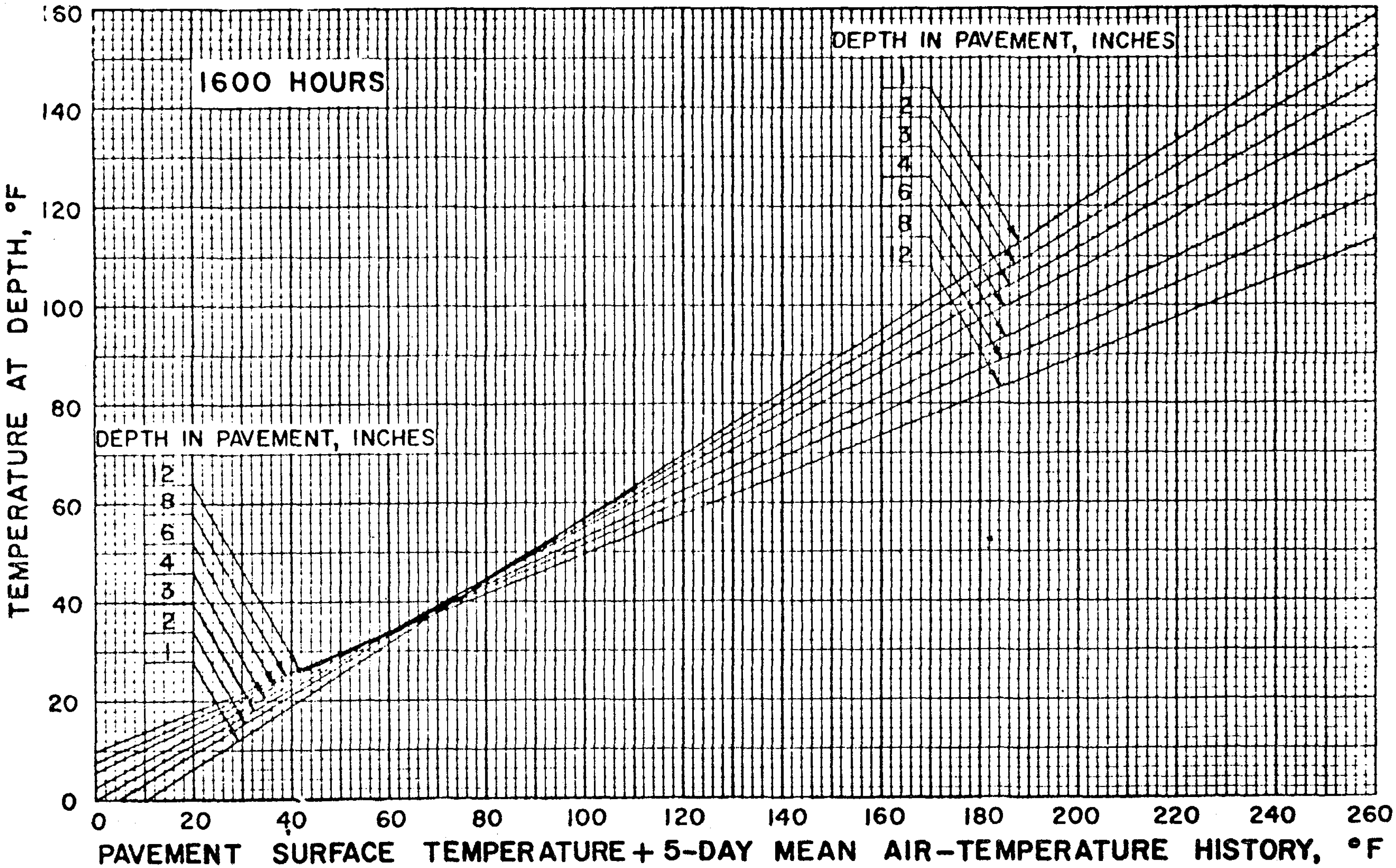

FIGURE 19. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{o}F = 1.8(^{o}C) + 32^{o}$

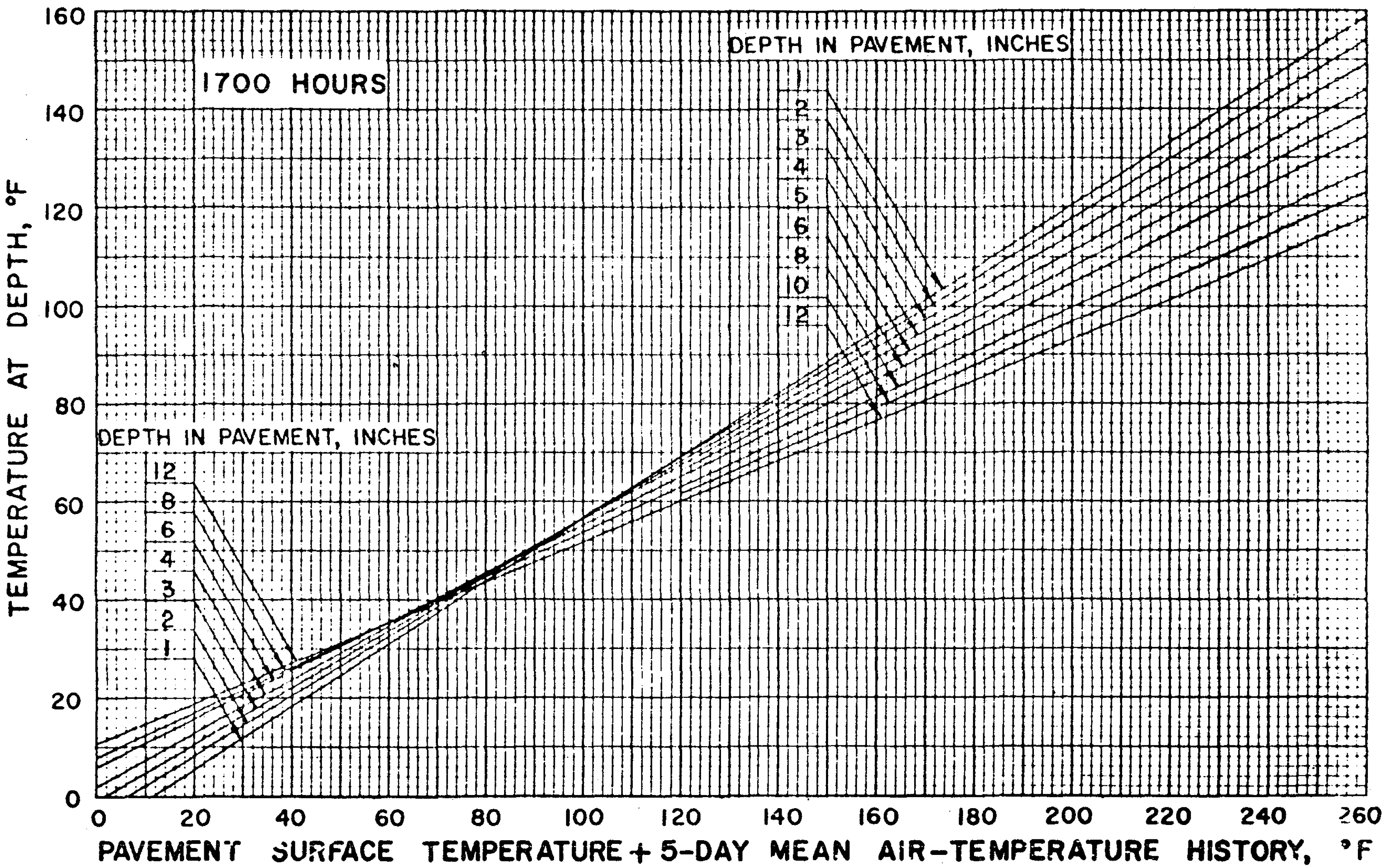

FIGURE 20. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

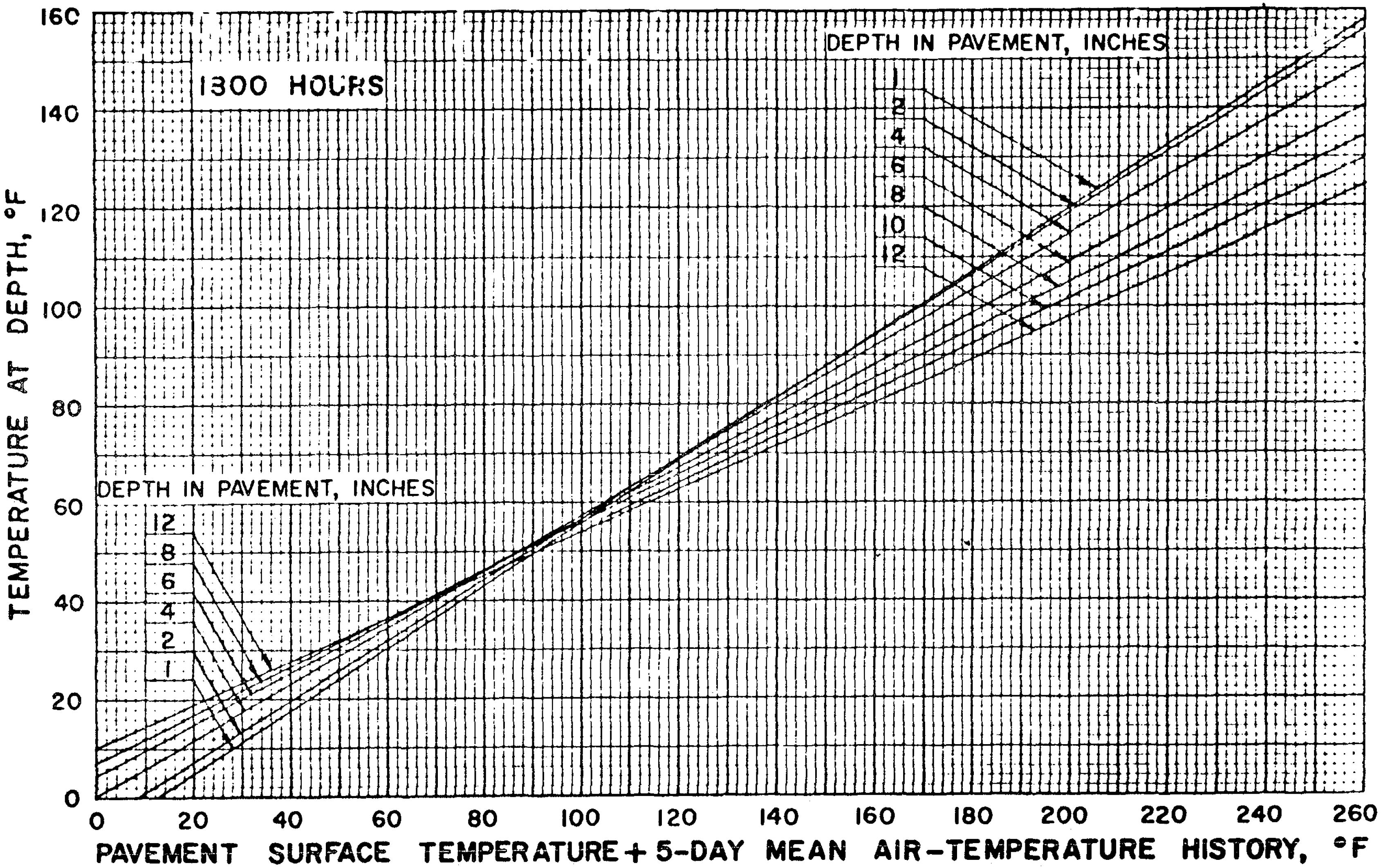

FIGURE 21. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

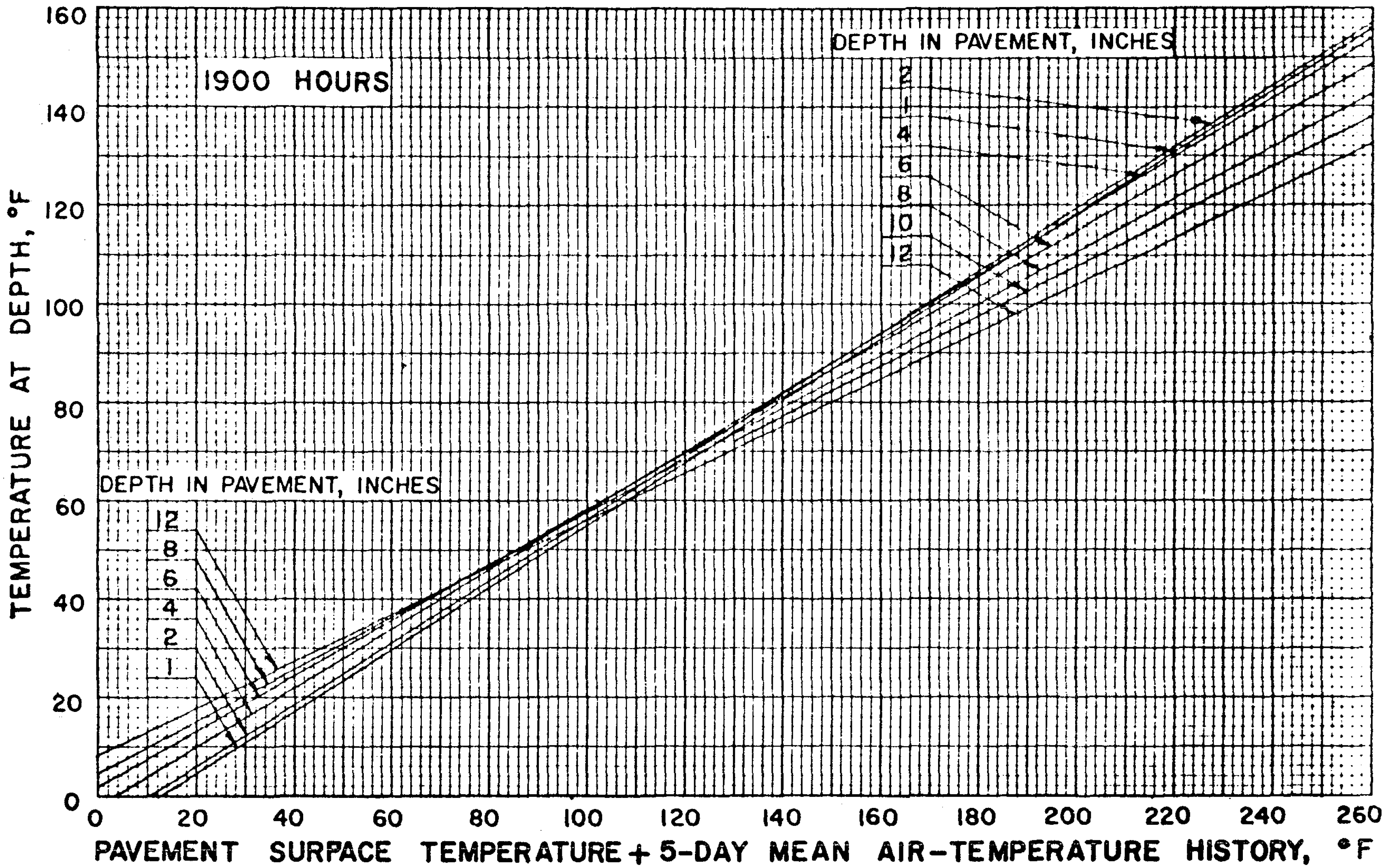

FIGURE 22. **Temperature Prediction Graph for Pavement Greater Than 2 Inches Thick**

1 in. = 25.4mm

$1^{o}F = 1.8(^{o}C) + 32^{o}$

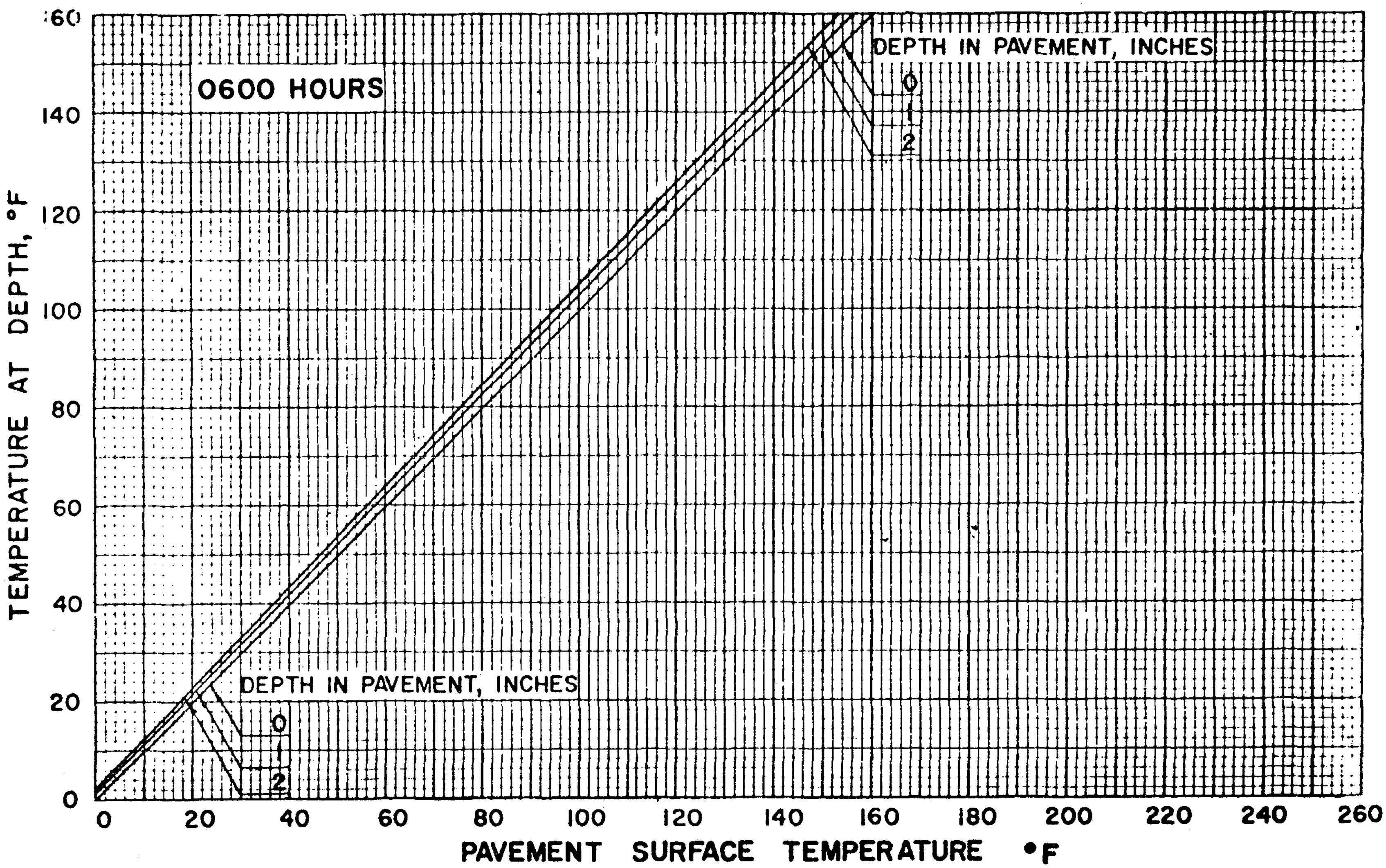

FIGURE 23. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

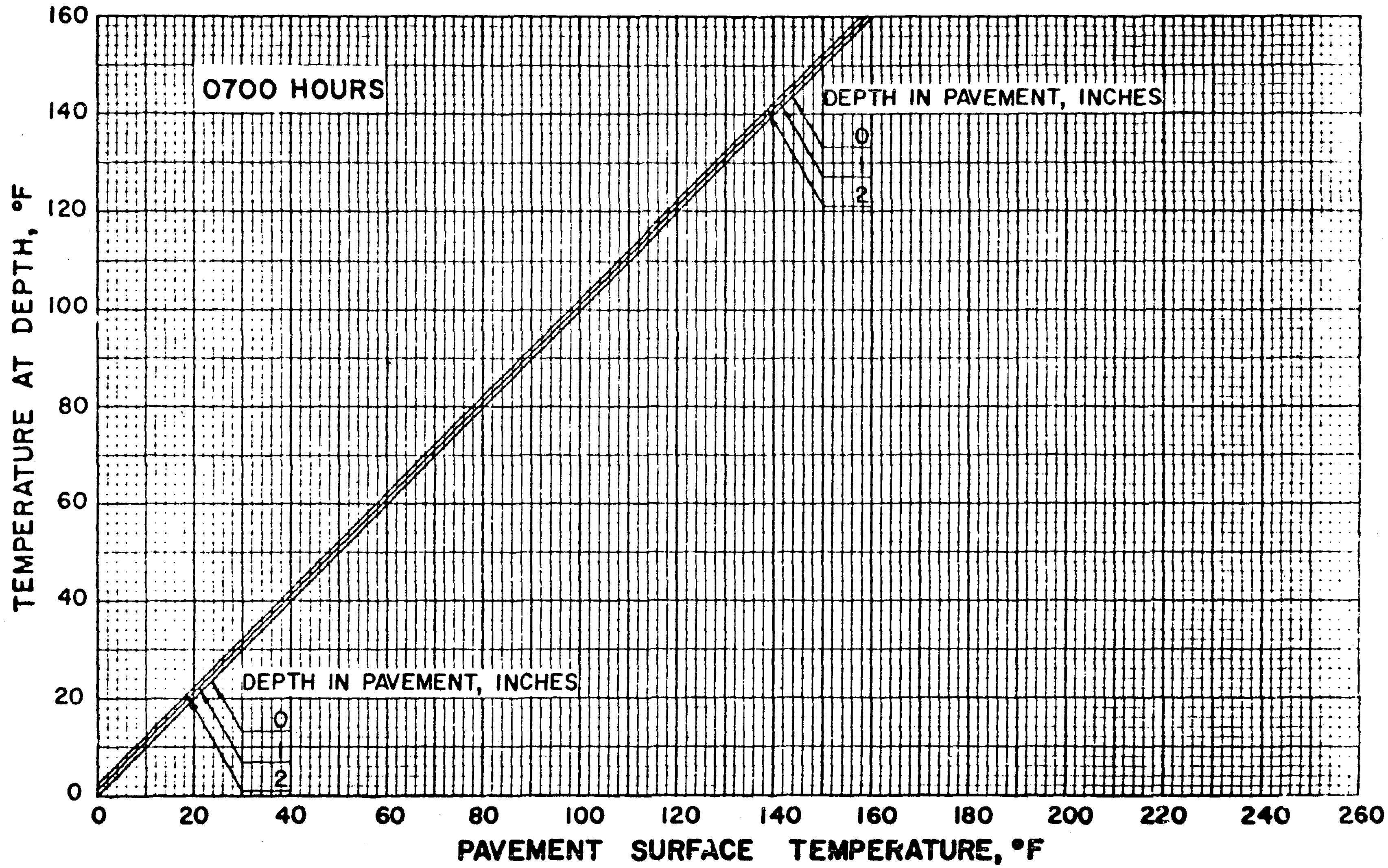

FIGURE 24. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4 mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

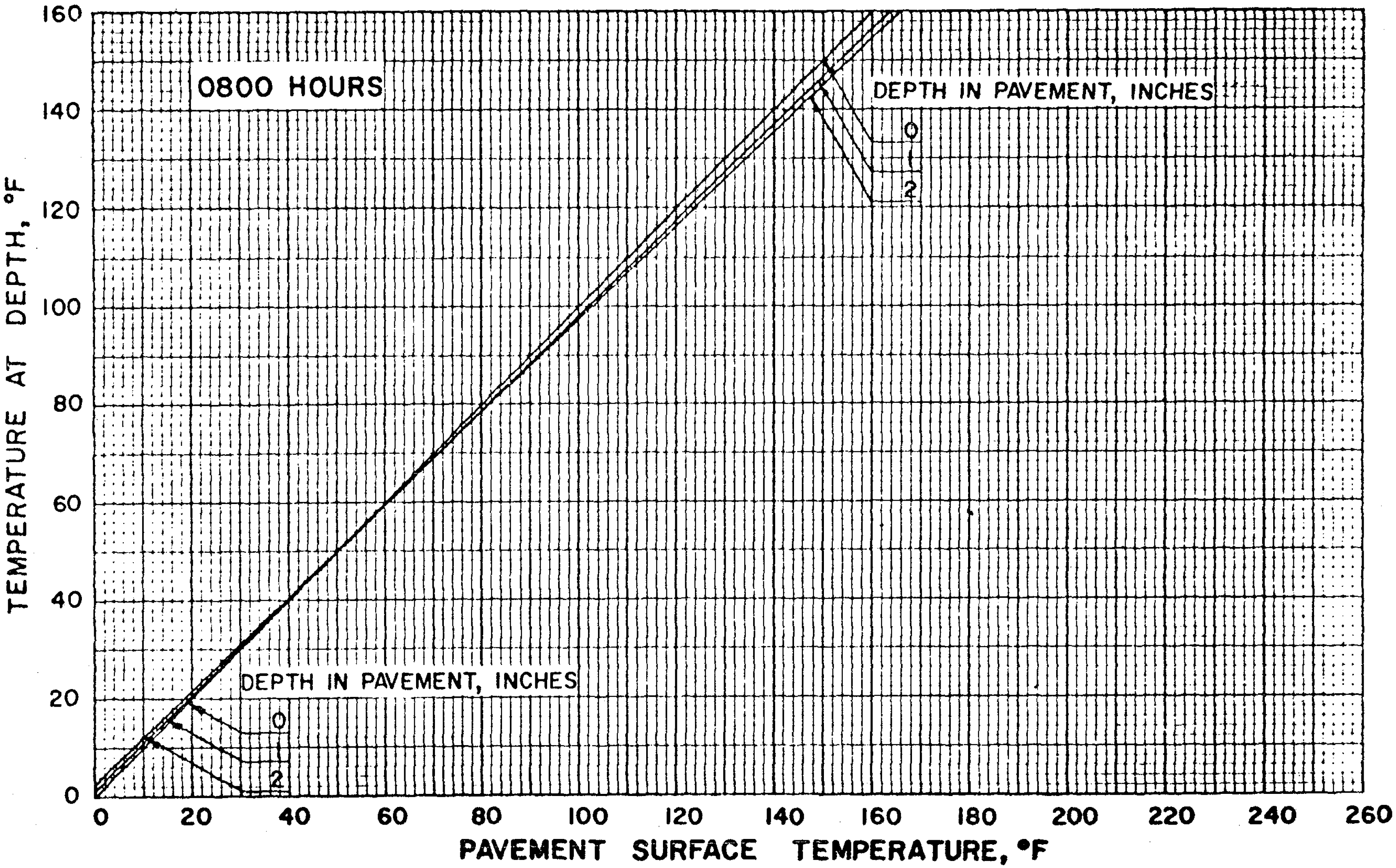

FIGURE 25. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{O}F = 1.8(^{O}C) + 32^{O}$

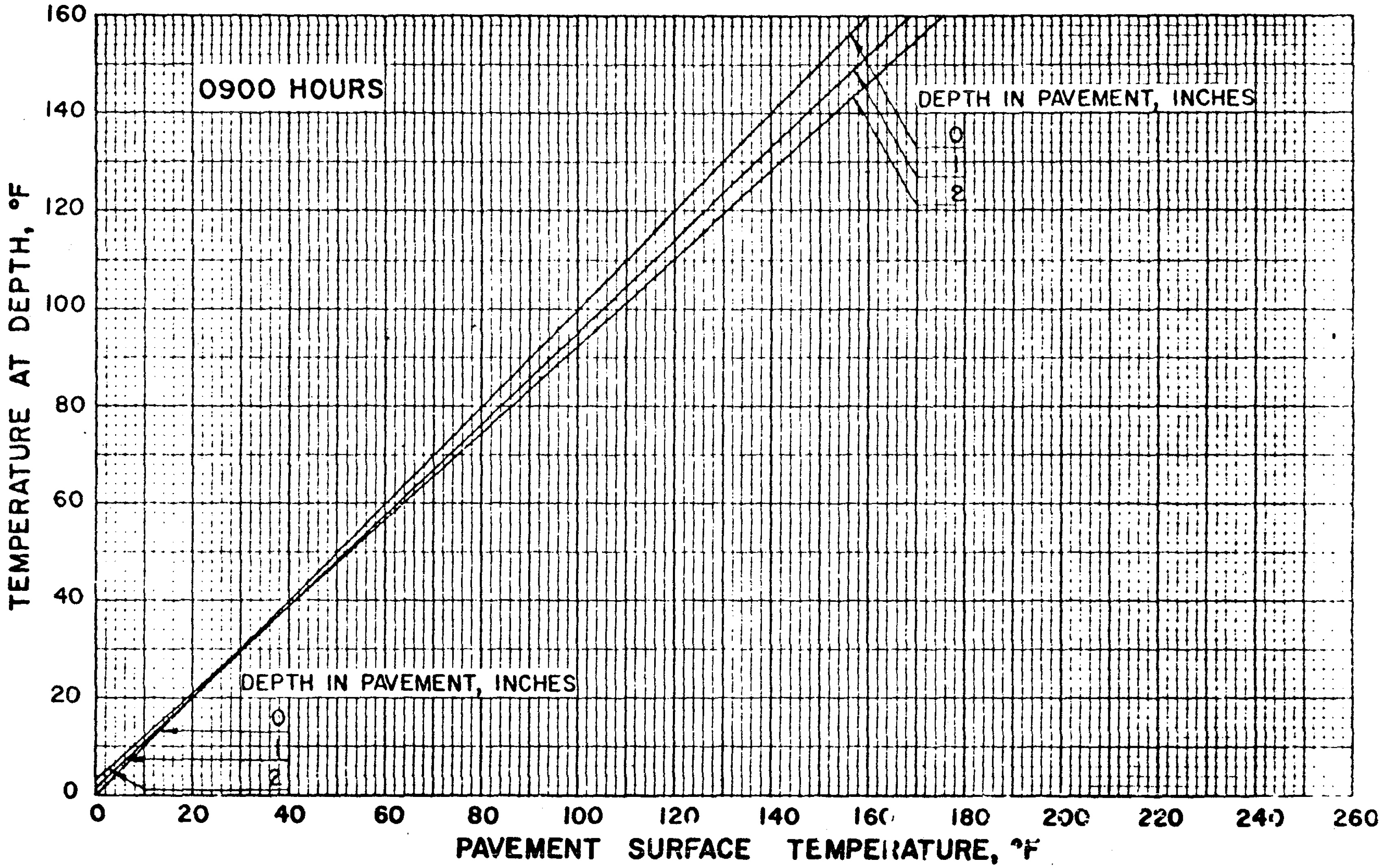

FIGURE 26. **Temperature Prediction Graphs for Paveme... Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
1°F = 1.8(°C) + 3

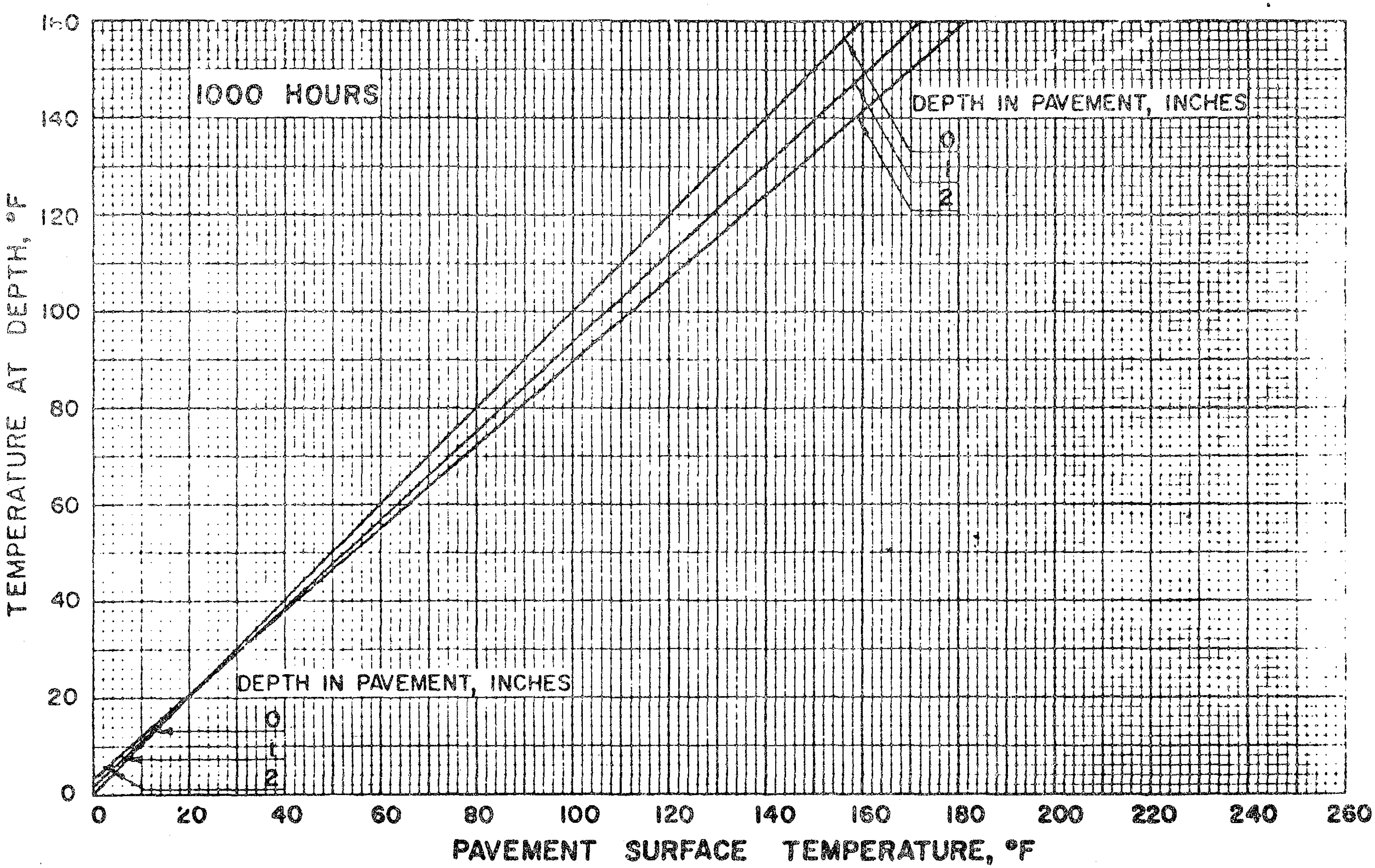

FIGURE 27. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{o}F = 1.8(^{o}C) + 32^{o}$

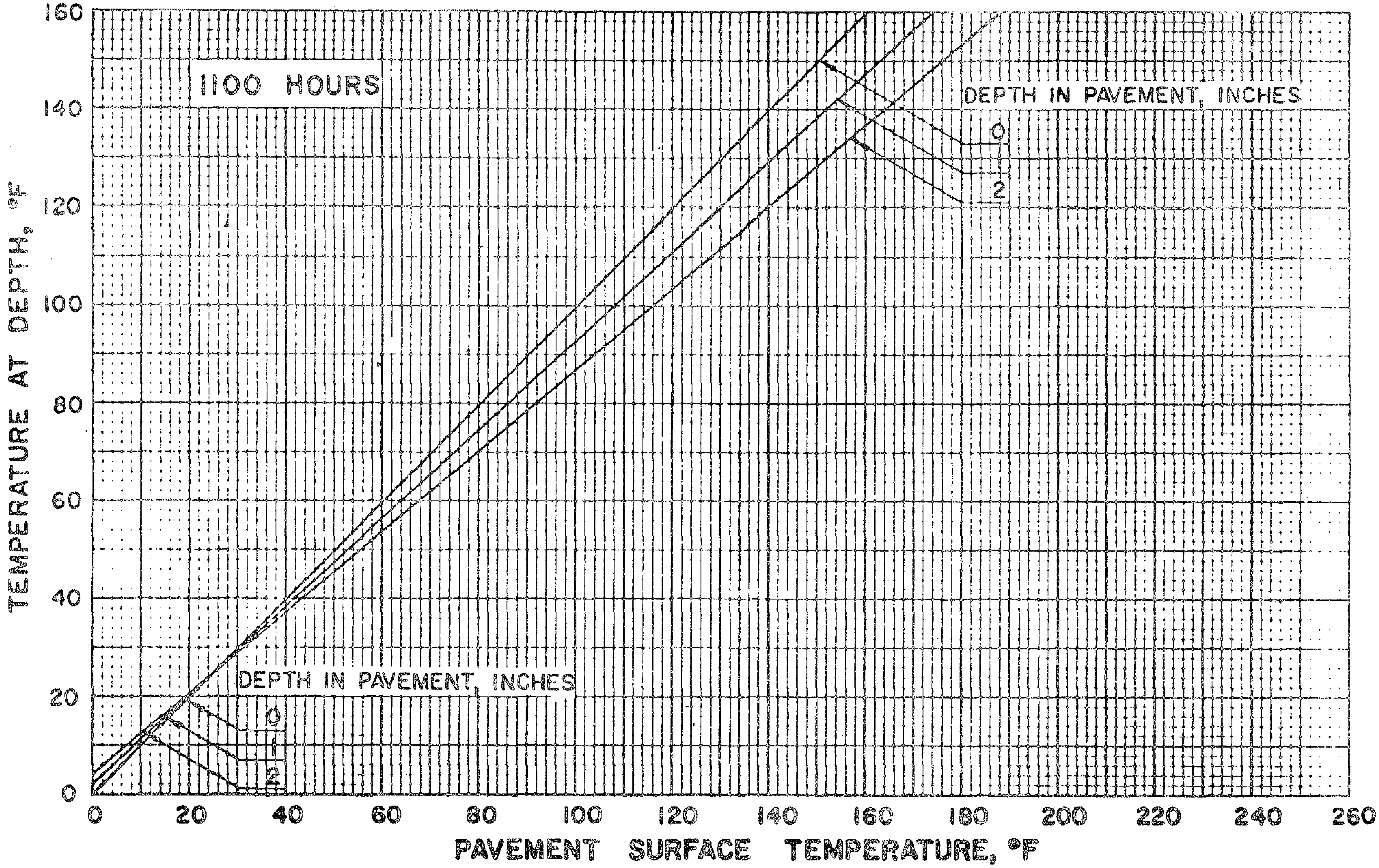

FIGURE 28. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

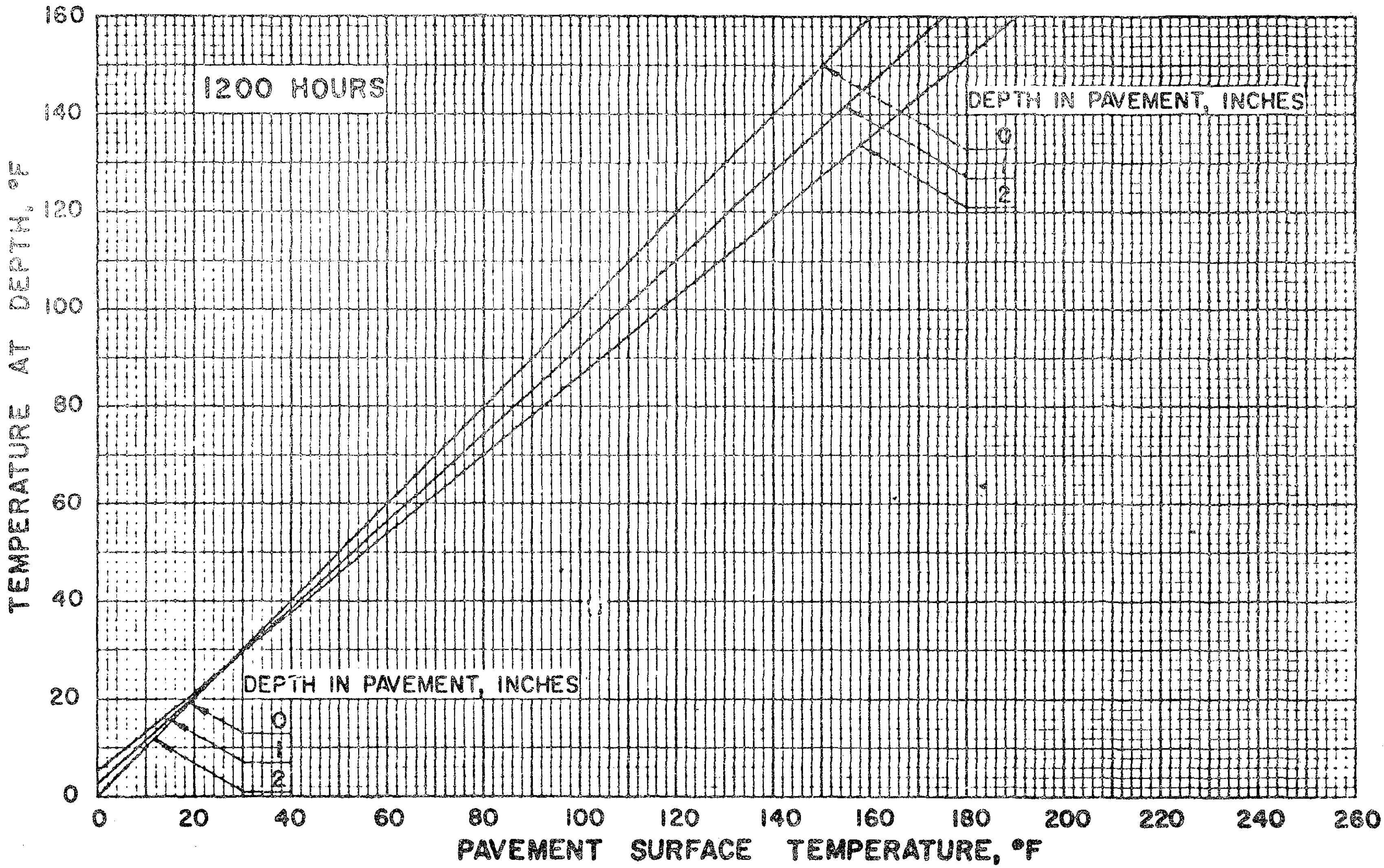

FIGURE 29. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

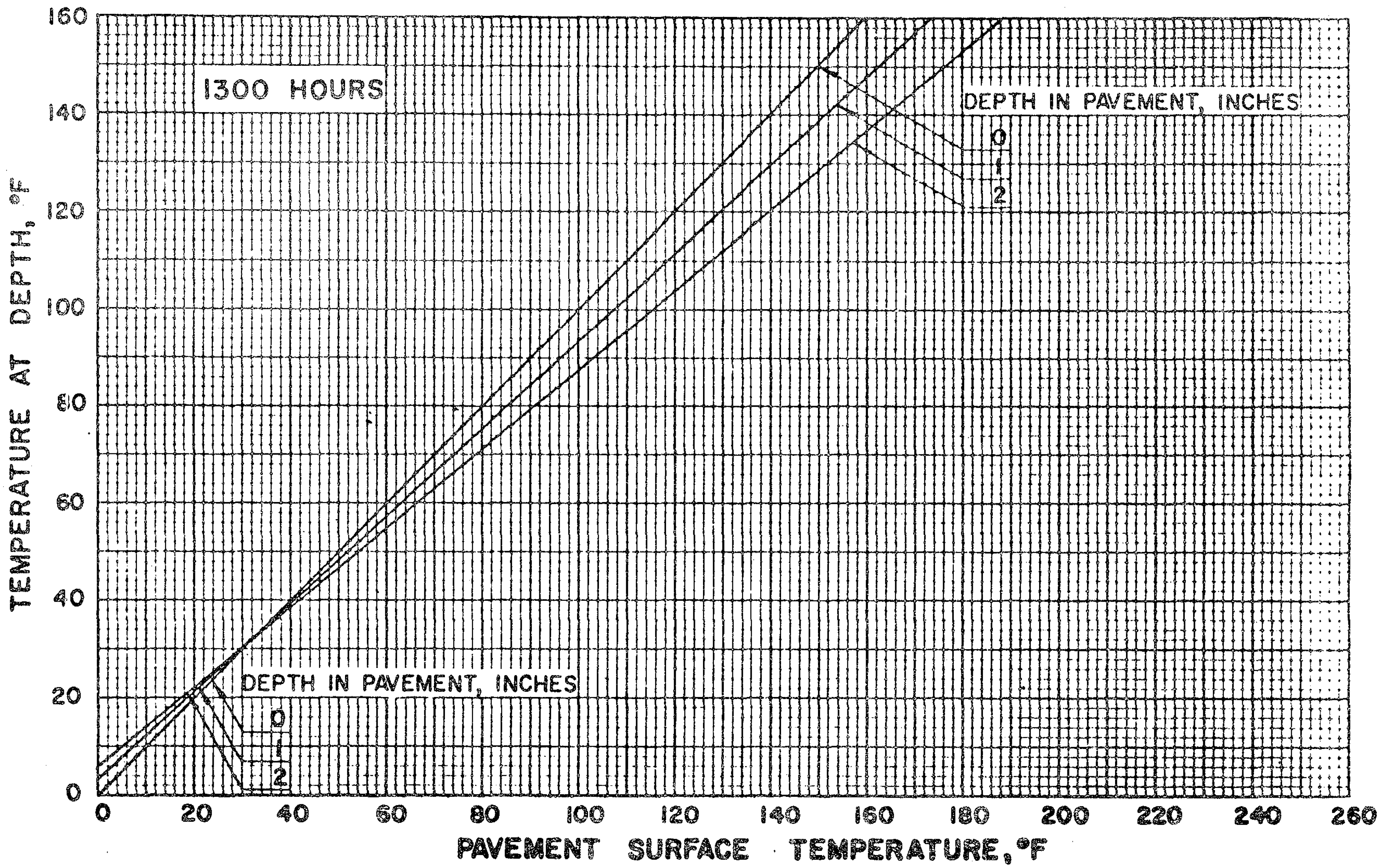

FIGURE 30. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4 mm

$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

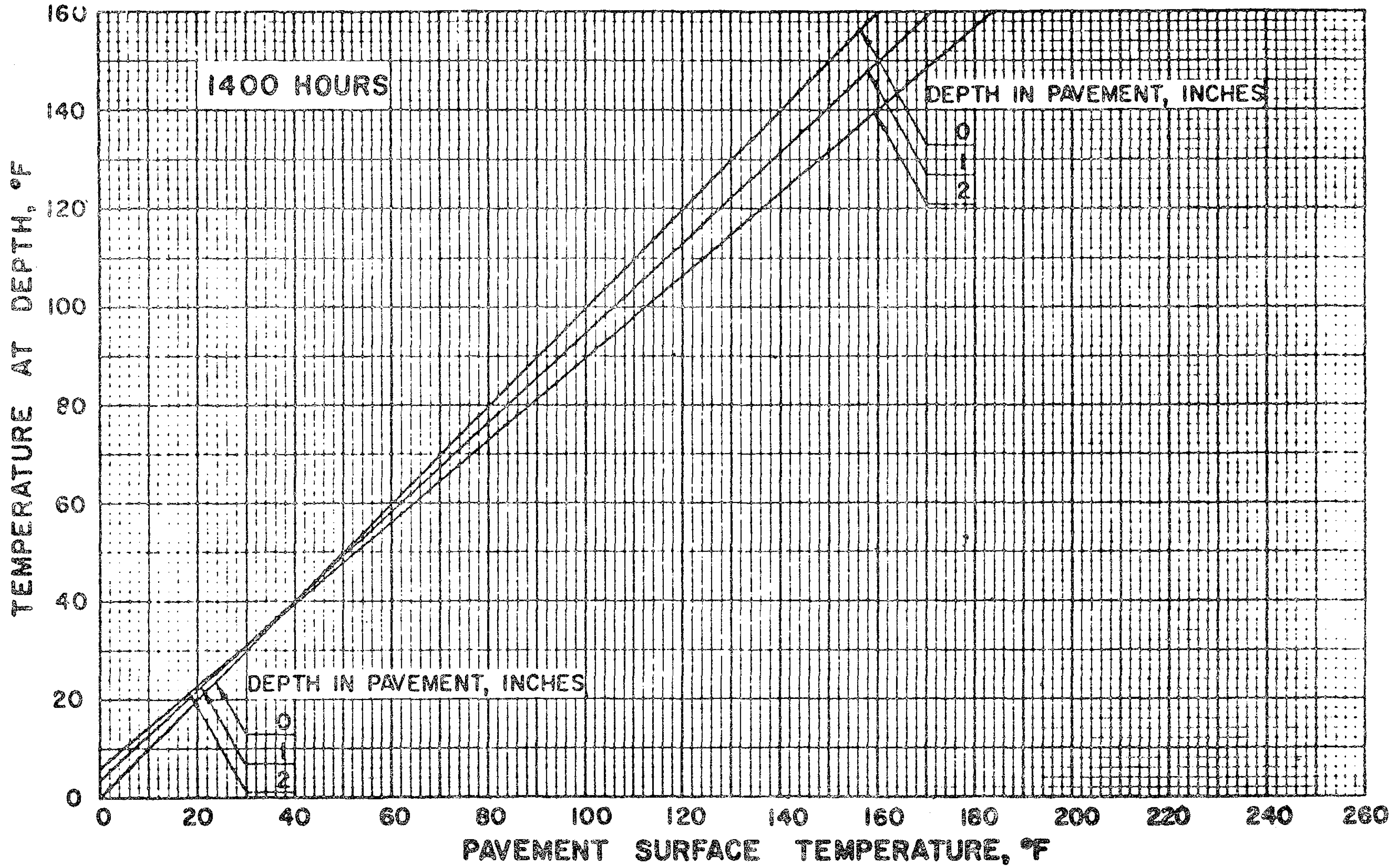

FIGURE 31. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm

$1^{O}F = 1.8(^{O}C) + 32^{O}$

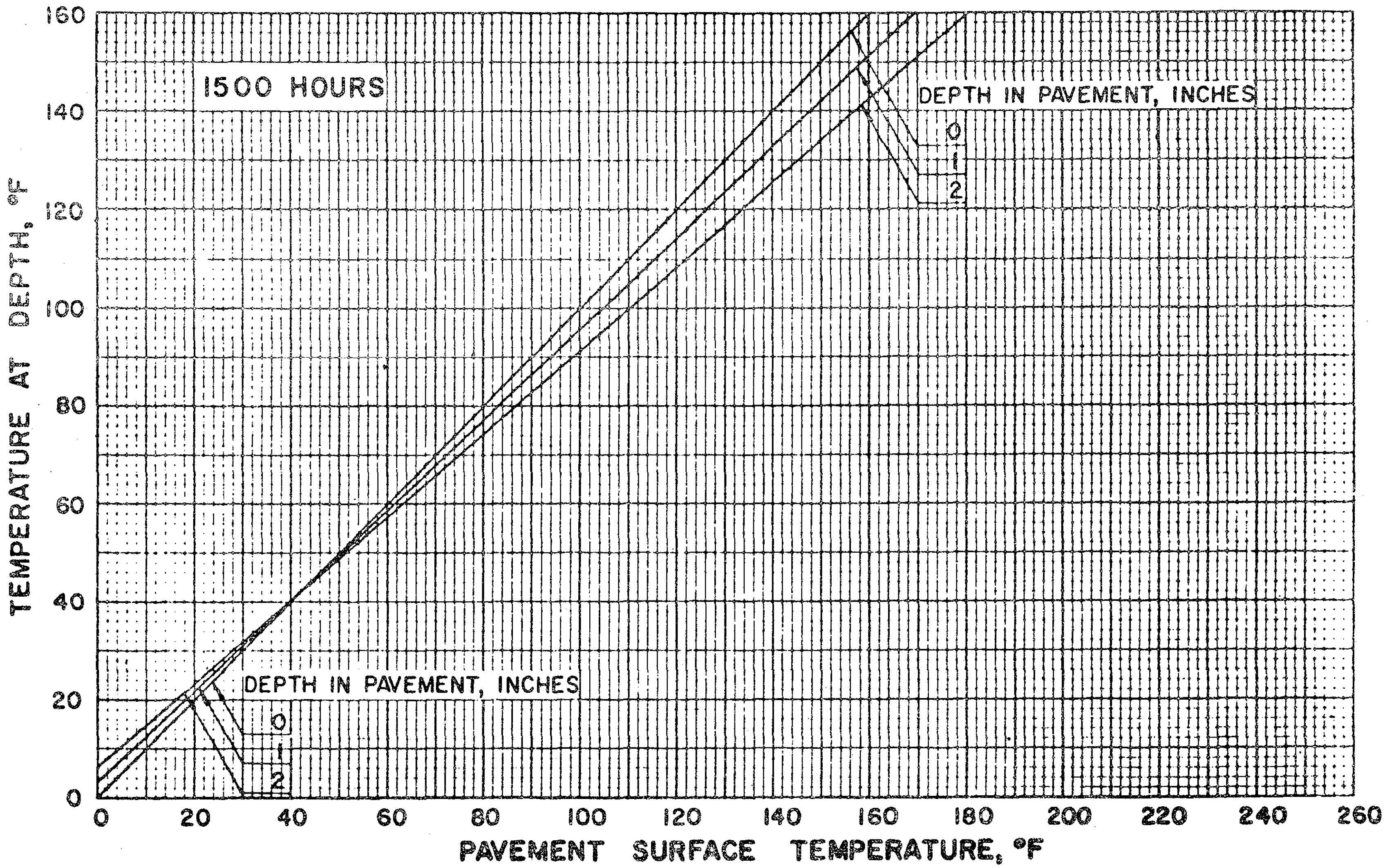

FIGURE 32. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
1°F = 1.8(°C) + 32°

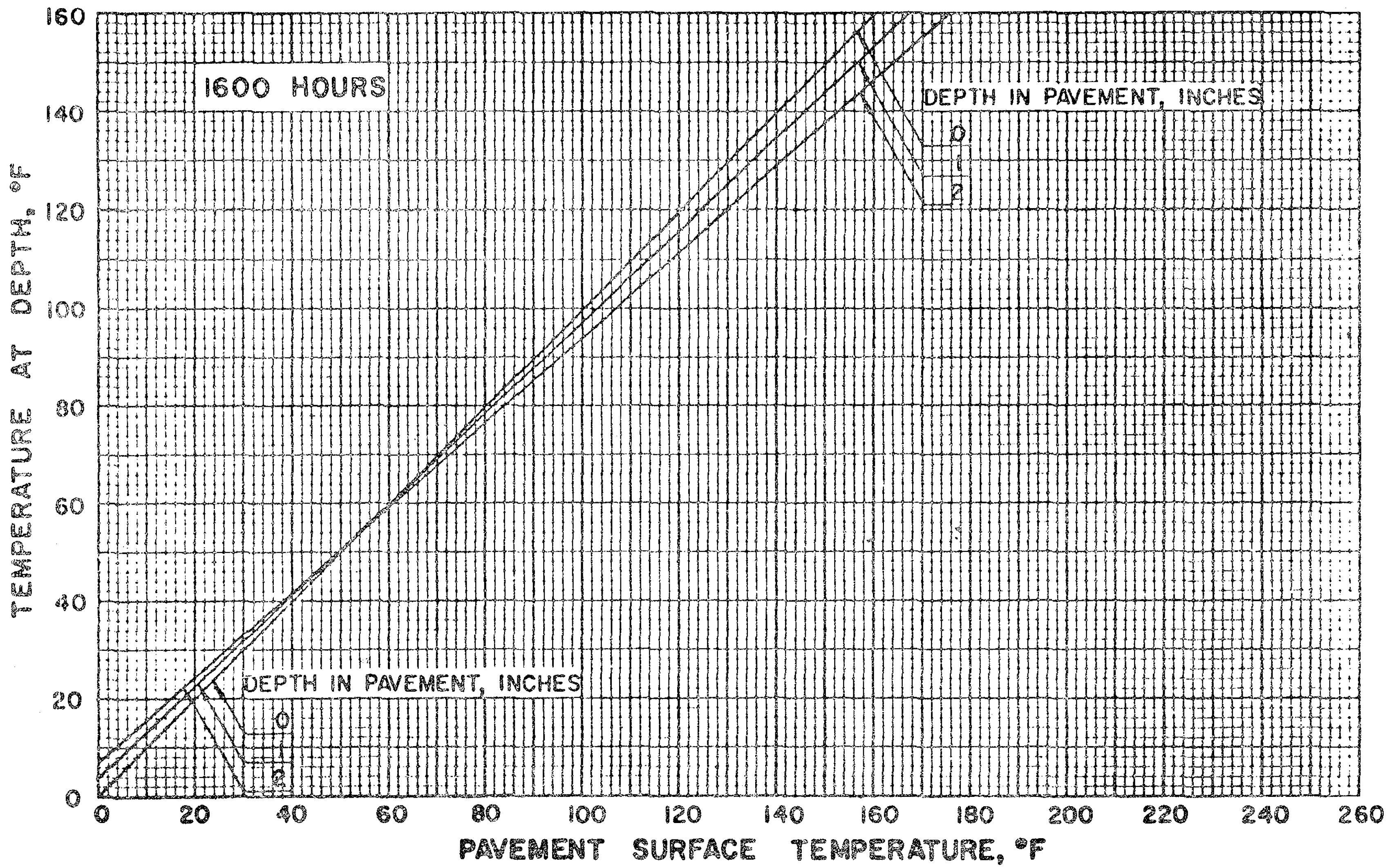

FIGURE 33. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

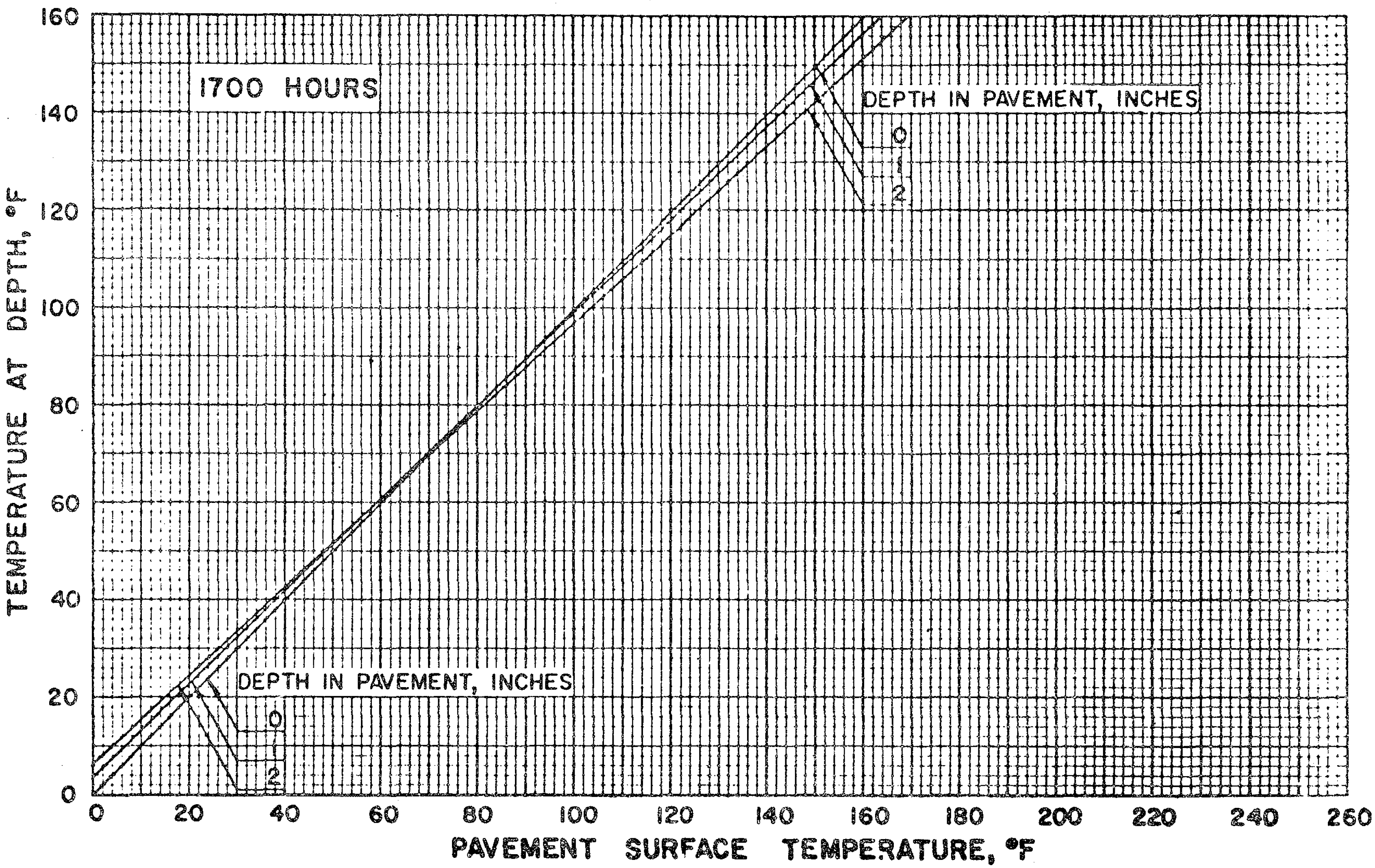

FIGURE 34. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4 mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

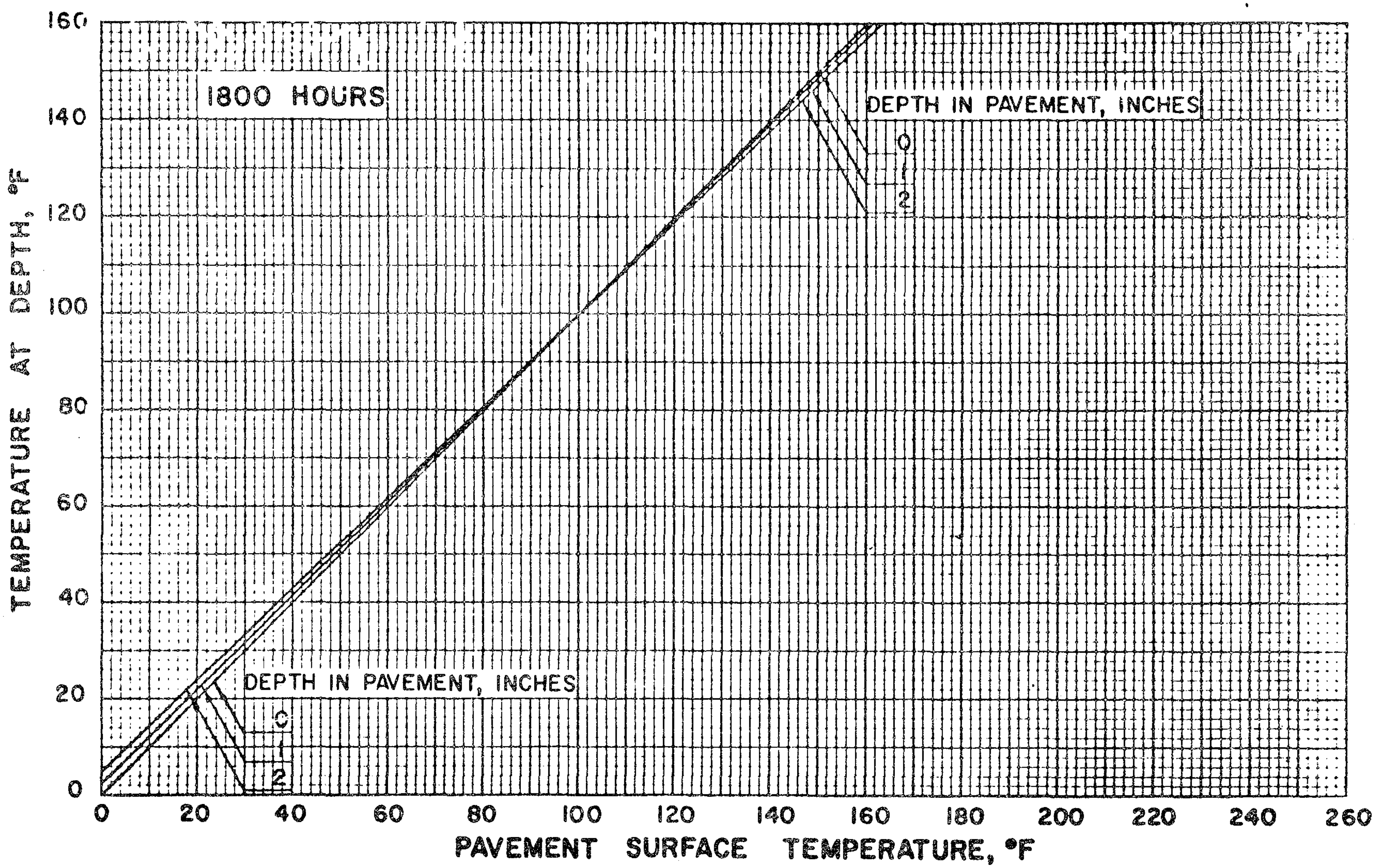

FIGURE 35. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{\circ}F = 1.8(^{\circ}C) + 32^{\circ}$

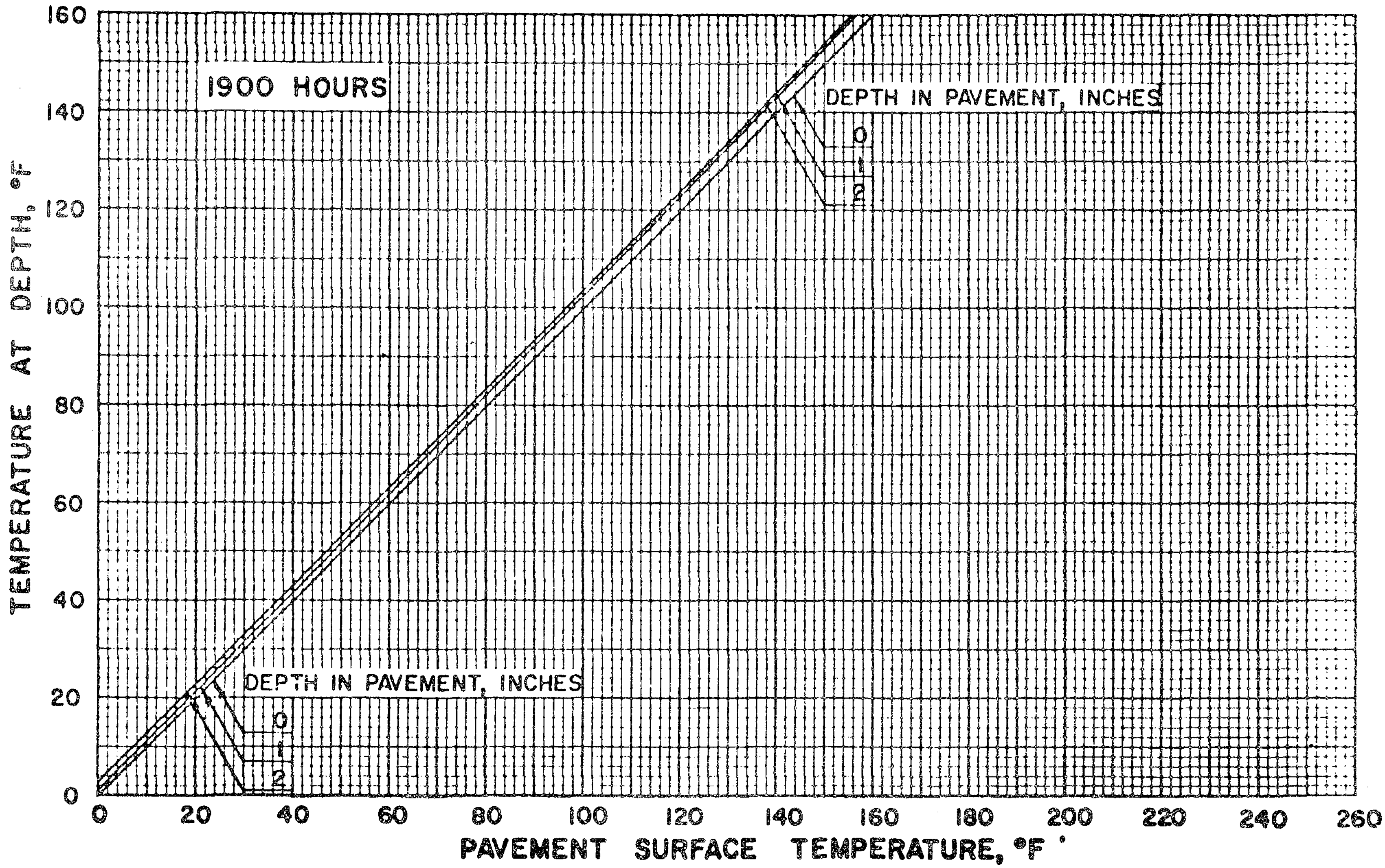

FIGURE 36. **Temperature Prediction Graphs for Pavements Equal To or Less Than 2 Inches Thick**

1 in. = 25.4mm
$1^{o}F = 1.8(^{o}C) + 32^{o}$

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APPENDIX C

A GUIDE FOR SELECTION OF TYPICAL MODULI OF PAVEMENT COMPONENT LAYERS

In this appendix, the typical results of moduli of various pavement component layers such as asphaltic concrete, granular base, granular subbase, cement treated base and subgrade are presented.

The tabulated results reported herein have been gathered from review of various research reports referenced at the end of this appendix and only represent typical values for pavement moduli.

Accompanying tables (Tables 9 through 13) present typical modulus of resilience relationships for various pavement component materials. The relationships have all been determined in the laboratory by repeated load triaxial tests or by a cyclic load triaxial test.

In the first and the second columns, the pertinent properties of the material such as gradation, water content, density, etc., are presented. In column three, the number of the reference from which the data has been obtained, are listed. These references are presented at the end of the Appendix. The type of test, either repeated load triaxial test (TR) or cyclic load triaxial test (MTS) are given in column four. Column five gives the frequency (repetition rate) of the load application in counts per minute and the duration of the load, which is the length of time over which the maximum dynamic load is retained over the sample. Column six gives the number of load applications at which the modulus of resilience values have been computed. As discussed previously, modulus of resilience may be represented by:

$$M_R = K_1(\sigma_i)^{K_2}$$

where

$$i = 3 \text{ or } d, \text{ or}$$

$$M_R = K_3(\theta)^{K_4},$$

depending on the material.

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA

GRANULAR BASE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY &DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3$ or $\sigma_d)$ K_1^+	K_2	$f(\theta)$ K_3^+	K_4	REMARKS
California; well graded and angular crushed stone, 3/4 in. max.; class 2 Aggr. base.	Dry; 3% <#200	1,3, 4,5, 8&23	TR**	30 cpm 0.1 sec.	100	11000 12000	0.53	300- 4000	0.65	v*=0.38
	Dry; 5% <#200			"	"	11400 15000	0.55	3500 5000	0.63	v*=0.31
	Dry; 10% <#200			"	"	14000 15000	0.5	5000	0.57	v*=0.25
	partially saturated; 3% < #200		"	"	"	9000 10000	0.57	2710	0.67	v*=0.27
	partially saturated; 5% < #200		"	"	"	8000 9000	0.58	2300 2700	0.66	v*=0.34
	partially saturated: 10% < #200		"	"	"	9000 10000	0.56	2200 3000	0.66	v*=0.45
California; well graded and subrounded gravel; 3/4 in. max.; class 2 Aggr. base.	Dry; 3% <#200		"	"	"	10000 13000	0.53	2000 4000	0.65	v*=0.47
	Dry; 5% <#200		"	"	"	10200 11000	0.62	2800 3300	0.69	v*=0.38
	Dry; 8% <#200		"	"	"	8000 9000	0.59	"	0.70	v*=0.45

+ = psi

*v = Poisson's Ratio

**TR - triaxial repeated loading

1 in = 25.4mm 1 psi = 6.895 Kpa

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Crushed gravel base	γ_d^*=138.8 W/C=4.4% compactive effort =26400 ft.lbs/cft	10	TR	120 cpm 0.1 sec	10000	5700	0.58			
Gonzales by-pass Agg. base; class 2.	γ_d=131 W/C=5.1 to 7.5%;degree of sat. ∿ 60%	3,5	"	20 cpm 0.1 sec	10000	15200	0.482			
Morro Bay base	degree of sat. ∿ 60%		"	"	"	11000	0.45			
Crushed rock base	γ_d=137.9; W/C=4.4% Compactive effort =12200 ft.lbs/cft	10	"	120 cpm 0.1 sec	"	5600	0.58			
Gravel from McHenry, Ill.	γ_d=126.7 pcf; e=0.31; dry 10% <3/8"	11 12	MTS (triaxial)	50 cpm 0.15 sec	5000			5388	0.59	
	3%<3/8"; γ_d=102.4, e=0.62		"	"	"			8228	0.53	

* γ_d = Dry unit weight in pounds per cubic foot 1 pef = 16.018 kg/m^3 1 ft. lbs/cft = kg m/m^3

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 \text{ or } \sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
California; well graded and angular crushed stone, 3/4 in. max.; class 2 Aggr. base	partially saturated; 3% <#200	1,3, 4,5, 8&23	TR**	"	"	7000 10000	0.55	2000 3500	0.65	v*=0.3
	partially saturated; 3% <#200		"	"	"	"	0.59	2000 3000	0.67	v*=0.41
	partially saturated; 8% <#200		"	"	"	5000 7300	0.63	1600 1900	0.72	v*=0.46
	saturated; 3% <#200		"	"	"	9600 11000	0.54	2700 3700	0.63	v*=0.26
	saturated; 5% <#200		"	"	"	8000 10000	0.54	2400 3200	0.65	v*=0.35
	saturated; 8% <#200		"	"	"	9000 12000	0.5	3000 4000	0.6	v*=0.25
SanDiego Test Road Aggregate Base	Dry; W/C = 2.6 to 2.8%	2	"	"	"			5700	0.5	
	Field W/C = 5.93 to 6.24%		"	"	"			4300	0.5	
	Wet; W/C = 6.21 to 6.52%		"	"	"			3100	0.5	

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Gravel from McHenry, Ill.	3%<3/8"; γ_d=107.5; e=0.54	11, 12	MTS (tri-axial)	50cpm 0.15sec	5000			10431	0.49	
	3%<3/8"; γ_d=112.1; e=0.48		"	"	"			25187	0.38	
	well graded; 20%<#4; γ_d=131.7; e=0.26		"	"	"			7781	0.60	
Crushed gravel from McHenry, Ill.	3%<3/8"; γ_d=100.8; e =0.66		"	"	"			7864	0.56	
Limestone; dolomitic from Kankakee, Ill.	10%<3/8"; γ_d=90.3; e=0.81		"	"	"			11234	0.4	
	10%< 3/8"; γ_d=103.2; e=0.59		"	"	"			5640	0.52	
	10%< 3/8"; γ_d=106.8; e=0.55		"	"	"			7296	0.54	
	3% <3/8"; γ_d=88.9 e=0.84		"	"	"			6513	0.51	

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Limestone; dolomitic from Kankakee, Ill.	3%<3/8"; γ_d=95.9; e=0.71	11, 12	MTS (tri-axial)	50cpm 0.15sec	5000			5883	0.47	
	3%<3/8"; γ_d=99.0; e=0.66		"	"	"			8636	0.46	
	well graded; 20%<#4; γ_d=111.9; e=0.46		"	"	"			5149	0.59	
	well graded; γ_d=112.1; e=0.46		"	"	"			4733	0.61	
	CA-10(Ill.) γ_d=123.8; e=0.32		"	"	"			2598	0.65	
	CA-10(Ill.) γ_d=130.6; e=0.25		"	"	"			4186	0.6	
Granitic Gneiss; from Columbus, GA.	10% <3/8"; γ_d=89.3; e=0.87		"	"	"			34127	0.19	
	3% <3/8"; γ_d=93.0; e=0.76		"	"	"			5128	0.6	

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Granitic Gneiss; from Columbus, GA.	3%<3/8"; γ_d=97.5; e=0.71	11, 12	MTS (triaxial)	50cpm 0.15sec	5000			6819	0.53	
	3%<3/8"; γ_d=102.3; e=0.63		"	"	"			8076	0.52	
	well graded; 20%<#4; γ_d=86.3; e=0.54		"	"	"			7092	0.56	
Basalt from New Jersey	10%<3/8"; γ_d=107.5; e=0.63		"	"	"			8944	0.47	
	3%<3/8"; γ_d=95.3; e=0.82		"	"	"			4725	0.65	
	well graded; 20%<#4; γ_d=115.7; e=0.5		"	"	"			7145	0.6	
Crushed porphyritic Granite Gneiss 3%<#200	γ_d=137.4; W/C=6.5	29	TR	30 cpm 0.1	10000			3746.1	0.532	
	γ_d=130.5; W/C=							2145.8	0.703	
	γ_d=130.5							2857.5	0.632	Soaked

TABLE 9 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3$ or $\sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Crushed porphyritic Granite Gneiss - 11.25% <#200	γ_d=135.0; W/C=6.0	29	TR	30 cpm 0.1sec	10000			1976.9	0.681	
	γ_d=128.25; W/C=	"	"	"	"			3359.2	0.539	
	γ_d=128.25	"	"	"	"			2414.5	0.619	Soaked
Crushed Biotite Granite Gneiss; 3% <#200	γ_d=137.4 W/C=6.5%	"	"	"	"			1986.7	0.682	
11.25% <#200	γ_d=135.0 W/C=6.0%	"	"	"	"			1494.8	0.718	
22% <#200	γ_d=132.9; W/C=6.1%	"	"	"	"			1491.8	0.731	
Dry Gravel		9, 14	"	"				1900	0.61	
Granular Base Colorado standard base ½" max & 8.7% <#200; std. subbase 2½" max & 7.9%<#200	W/C=2.6% W/C=6.3% W/C=8.2%	8	"	120cpm 0.2sec	10000	10618 10019 8687	0.4474 0.465 0.696			
Crushed Stone Base 3%<3/4"	(γ_d)=147pcf; W/C=4.7% 6.2%<#200	21	"	20cpm 0.1sec	10000	7300	1.01			

TABLE 10 MATERIAL CHARACTERISTICS AND MODULI DATA

GRANULAR SUBBASE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1^+	K_2	$f(\theta)$ K_3^+	K_4	REMARKS
Morrow Bay Sub-base	Degree of sat. ∿ 60%	3,5	TR*	20cpm 0.1 sec	10000	7600	0.33			
Blend of 17% Silty sand + 83% Crushed biotite Granite Gneiss	Compacted @ γ_d=143.0 & W/C=4.6%	29	"	30cpm 0.1 sec	"			3835.5	0.534	
								3145.0	0.552	Soaked
Blend of 40% Silty fine sand + 60% no. 467 stone 75%<3/4"; 0%<#10	Compacted @ (γ_d) = 138.0 W/C=4.2%		"	"	"			2507.1	0.624	
								3825.7	0.459	Soaked
	Compacted @ (γ_d) = 138.0 W/C = 6.6%		"	"	"			1791.5	0.802	
								3902.6	0.529	Soaked
Blend of 21% sandy silt + 79% crushed biotite granite Gneiss	Compacted @ γ_d=140.2 & W/C = 6.0%		"	"	"			4982.6	0.45	
								5938.9	0.365	Soaked
Crushed Granite 83% + silty sand 17%	100% T-180;** W/C = 5.1%	8	"	33cpm 0.1 sec	"			3836 3145	0.53 0.55	
Sand	Dry	9, 14	"	20cpm 0.1 sec		12500	0.35	6700	0.36	

TABLE 10 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

GRANULAR BASE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPE-ITION	EQUATION OF STATE $f(\sigma_3 \text{ or } \sigma_d)$ K_1+	K_2	$f(\theta)$ K_3+	K_4	REMARKS
Sand Subbase	γ_d = 133.9 W/C = 4.52%; compactive effort 2500 ft lbs/ft^3	10	TR*	120cpm 0.1 sec	1000	6700	0.55			
Clayey Sandy Silt Blythe Test Section B	$(\sigma_d)_{max}$ = 110 OMC = 15.3%	13	"	20cpm	"	26310	0.022	30134	-0.031	

+ = psi
*TR = triaxial repeated loading
**AASHTO test specification No.
γ_d = Dry unit weight in pounds per cubic foot 1in = 25.4mm 1 psi = 6.895 kPa 1pcf = 16.018 kg/m^3
1ft.1b/cu ft = 4.88 kgm/m^3

TABLE 11 MATERIAL CHARACTERISTICS AND MODULI DATA

SUBGRADE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$ K_1^+	K_2	$f(\theta)$ K_3^+	K_4	REMARKS
Silty sand		18 19	TR**	35 cpm 0.1sec	10000			3126	0.37	
Silty fine sand	100% AASHTO*** T-99; W/C=13.4% 40%<#200	8	"	33 cpm 0.1 sec	10000			1856 3126	0.61 0.37	
Silty fine sand orange tan, slightly clay	Compacted @ (γ_d)=115.4 W/C = 13.0% L.L=22%; PI=6 %	29	"	30 cpm 0.1 sec	"			1855.6 3126.6	0.606 0.371	Dry Soaked
Clayey silty sand Blythe Test Section-A	γ=125; W/C = 4.4%	13	"	20 cpm 0.1sec	10000	19844	0.197	14145	0.194	Subgrade
Clayey sand	Gonzales By-pass Subgrade	3	"	20 cpm 0.1 sec	200 200 60000 60000	9000* 4800* 24500* 6600*	-0.99* 0.09 -0.8* 0.25			$0<\sigma_d<3$psi $3<\sigma_d<10$ $0<\sigma_d<3$ $3<\sigma_d<10$
F-1 type soils	$(\gamma_d)_{max}$=123.9; OMC = 7.8% W/C = 4.5% W/C = 6.0% W/C = 8.0% W/C = 9.7%	17	"			11100 10900 10500 6100	0.46 0.42 0.43 0.54	6000 6000 5690 2640	0.4 0.4 0.41 0.54	

+ = psi
* Functions of σ_d
** TR = Triaxial repeated loading
***AASHTO Test specification No.
γ_d = Dry unit weight in pounds per cubic foot

1 psi = 6.895 kPa 1 pcf = 16.018 kg/m^3

TABLE 11 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$		$f(\theta)$		REMARKS
						K_1	K_2	K_3	K_4	
Silty Clay Subgrade	AASHO Test Rd.; γ_d=119; W/C= 15.3%; Deg. of sat.= 95%	4 8	TR	20cpm 0.25sec	10000	62000*	-1.12*			Kneading Compaction $0< \sigma_d<19$
						1500*	0.21*			$19<\sigma_d<35$
						65000*	-1.0*			Static compaction $0<\sigma_d=32$
						10*	1.11*			$32<\sigma_d<40$
		9	"	"	200	25000*	-0.77*			$0<\sigma_d<18$
						3120*	0.7*			$18<\sigma_d<38$
Silty Clay	PI=25.5	8	"	30cpm 0.1sec	10000	3200*	5.2*			
Highly Plastic Clay	PI=36.5	9	"	"	"	4150*	1.0*			
Silty Clay	A-6; E-5; CL; L.L=28.31% PI=13.7%	22	"	120cpm 0.125sec	"	66000*	-0.38*			
						49000*	-0.38*			
	A-7; E-7; Cl; L.L=41.0% PI=28.3%	"	"	"		24000*	-0.11*			
	A-4; E-6; CL to ML; L.L=26.5% PI=7.6%	"	"	"		46000*	-0.3*			
	A-4; CL L.L=28.8%; PI=10.1%	"	"	"		64000	-0.18			

* Functions of σ_d

TABLE 11 MATERIAL CHARACTERISTICS AND MODULI DATA (cont.)

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3$ or $\sigma_d)$ K_1	K_2	$f(\theta)$ K_3	K_4	REMARKS
Lean Clay	E-8; CL Soils	18	TR	30 cpm 0.1 sec	10000	26800*	-0.495*			$0<\sigma_d<12.5$
Heavy Clay	E-11; CH Soils	18 19	"	"		25000*	-0.77*			$0<\sigma_d<12.5$

TABLE 12 MATERIAL CHARACTERISTICS AND MODULI DATA

CEMENTED TREATED BASE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	EQUATION OF STATE $f(\sigma_3 or \sigma_d)$		$f(\theta)$		REMARKS
						K_1^+	K_2	K_3^+	K_4	
Silty sand stabilized with 60% cement	γ_d = 124.0; W/C = 10%	29	TR*	30 cpm 0.1sec	10000			2.51×10^6	-0.444	
40% Silty sand + 60% #467 stone + 2.73% cement	γ_d = 138.0; W/C = 7.5	29	"	"	100			0.30×10^6	0.399	

+ = psi
*TR = Triaxial repeated loading
γ_d = Dry unit weight in pounds per cubic foot

1 psi = 6.895 kPa
1 pcf = 16.018 kg/m^3

TABLE 13 MATERIAL CHARACTERISTICS AND MODULI DATA

ASPHALTIC CONCRETE

MATERIAL DESCRIPTION	MATERIAL CHARACTERISTICS	REF. NO.	TYPE OF TEST	FREQUENCY & DURATION	LOAD REPETITION	MR (PSI)	REMARKS
California type B, ½ in. max. med. aggr., 85 to 100 pen. asphalt		8	TR*	30 cpm 0.1 sec	100	300000 70000	70°F 90°F
Georgia standard A, 1½" max. aggr., 85 to 100 pen. asphalt		"	"	20 cpm 0.1 sec	10000	220000 100000	72°F 89°F
California Type B; 3/8 inch max. med aggr., 85 to 100 pen asphalt		"	"	30 cpm 0.1 sec	100	2500000 1500000 50000	40°F 55°F 100°F
Asphalt Institute mix IVb, ½ in. max. aggr.; 60 to 70 & 85-100 pen. asphalts		"	CT**	1 to 16 Hz	250 to 300	600000 to 2000000 150000 to 750000 50000 to 150000 1100000 to 3000000 350000 to 1300000 90000 to 450000	40°F; 1Hz 70°F; 1Hz 100°F; 1Hz 40°F; 16Hz 70°F; 16Hz 100°F; 16Hz

*TR = Triaxial repeated loading

**CT = Cyclic Load Triaxial

1 in = 25.4mm 1 psi = 6.895 kPa °F = 1.8°C + 32

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APPENDIX D

TVAL DESCRIPTION AND INPUT GUIDE

The purpose of program TVAL is to calculate Student's t values given a number of overlay values divided into sections. The input to the program includes an alphanumeric title, the number of sections into which overlay project is divided, the number of locations at which overlay thickness is calculated, and the overlay values.

A more detailed description of data input can be found on the attached input guide for TVAL.

TVAL calculates the mean for each section and stores these values in array XMEAN. The program also calculates for each section the following:

$$\sum_{i=1}^{n_x} (x_i - \bar{x})^2 \qquad \text{(D-1)}$$

where:

$\bar{x}$ = mean for the section

x_i = overlay value

n_x = number of locations in section at which overlay thickness is calculated

These values are stored in array SXDIF.

To complete the calculation of the Student's t value, each section is compared once to every other section using the following calculations:

$$S = \left(\frac{\Sigma (x_i - \bar{x})^2 + \Sigma (y_i - \bar{y})^2}{nx-ny-2} \right)^{1/2} \qquad \text{(D-2)}$$

$$S_{\bar{x}-\bar{y}} = (1/nx + 1/ny)^{1/2} \qquad \text{(D-3)}$$

$$T = (\bar{x} - \bar{y}) \;/\; S_{\bar{x}-\bar{y}} \qquad \text{(D-4)}$$

where:

$(x_i = \bar{x})^2$ = SXDIF value for first section

$(y_i - \bar{y})^2$ = SXDIF value for second system

nx = number of locations in first section

ny = number of locations in second system

$\bar{x}$ = mean for first section

$\bar{y}$ = mean for second system

The standard deviation for each section is also calculated. The associated program variable is SDEV, and the equation used is:

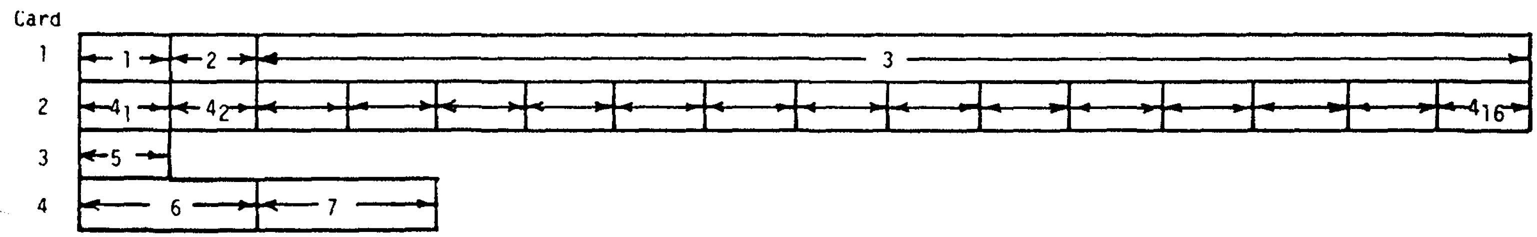
$$SDEV = \left(\frac{(x_i - \bar{x})^2}{nx-1} \right)^{1/2} \qquad (D-5)$$

Following the calculation of t values, a comparison between each calculated t and the table t value for its particular degrees of freedom and selected confidence level is made. (A table of t values has been incorporated into the program and confidence level desired is a data input variable.) If the calculated t value is less than or equal to the table value, the two sections included in the calculation of t are said to be similar or "passing". Otherwise, they are referred to as "failing" or dissimilar.

The output of the program includes an echo print of the overlay values by section, the mean and standard deviation for each section, and t values. The output lists the t value for each pair of sections compared, the degrees of freedom, the selected table value and "PASS" (if the sections compared are similar) or "FAIL" (if the two sections are not similar).

TABLE 14

INPUT GUIDE FOR TVAL



1\. NDEF = Number of locations being submitted (COLUMNS 1-5, INTEGER, RIGHT JUSTIFY)

CARD 1 2. NSEC = Number of sections into which overlay values are divided (Columns 6-10, INTEGER RIGHT JUSTIFY) (Max of 16 sections)

3\. TITLE= Alphanumeric title (COLUMNS 11-80)

4_1. NX_1 = Number of locations in section 1 (Max of 90)(COLUMNS 1-5, INTEGER, RIGHT JUSTIFY)

CARD 2 4_2.** NX_2 = Number of locations in section 2 (Max of 90)(COLUMNS 6-10, INTEGER, RIGHT JUSTIFY)

4_3. NX_{16} = Number of locations in section 16 (Max of 90) (COLUMNS 76-80, INTEGER, RIGHT JUSTIFY)

CARD 3 5. ICL = Confidence level FOR STUDENT'S T ANALYIS (COLUMNS 1-5, INTEGER, RIGHT JUSTIFY)

90 = 90% level
95 = 95% level (Default
99 = 99% level value is 95%)

CARD 4* 6. DIST = Station number for overlay (COLUMNS 1-10, ALPHANUMERIC - CAN BE LEFT BLANK)

TABLE 14

INPUT GUIDE FOR TVAL (cont.)

CARD 4* 7. DEF = Overlay value (F10.0) (COLUMNS 11-20, REAL)

* One type 4 card for each overlay location, max. of 1440 (16 sections at a maximum of 90 locations per section). The overlay values in Section 1 must appear first, followed by the overlay values in Section 2, etc.

** The number of locations for each section is input in I5 format for up to 16 sections.

GPO 882-902

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.