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AIRCRAFT GROUND FLOTATION ANALYSIS PROCEDURES–PAVED AIRFIELDS

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FOREWORD

The research presented herein was accomplished during the time period January 1968 to May 1969. This work supports numerous system programs. It is published to provide standard guidelines for use in determining flotation capabilities of present and future aircraft. The authors served as project engineers.

This report was submitted by the authors in September 1970.

The authors wish to acknowledge the following for significant contributions to the work presented herein:

- US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

- US Army Engineer Ohio River Division Laboratory, Mariemont, Ohio.

- SAE A-5 Committee, particularly to Mr. Joe Jopling, for providing the revision to the rigid pavement evaluation procedures of this report.

This technical report has been reviewed and is approved.

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ABSTRACT

This report describes standardized methods for analyzing ground flotation characteristics for aircraft of various designs based on the type of airfield construction. The method proposed for analyzing flexible pavements is an adaptation of the California Bearing Ratio (CBR) method. The analysis for rigid pavements is based on equations developed by Mr. H. M. Westergaard, Corps of Engineers, Ohio River Division Laboratories, and by the Portland Cement Association.

The methods described have been applied herein with an analysis of the KC-135 aircraft to illustrate the techniques. These methods can be applied to any aircraft to determine its flotation characteristics in relation to a given type runway.

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ILLUSTRATIONS

NOMENCLATURE

Symbols

A	Tire contact area $= \frac{SWL}{p}$
B	Distance between centers of outer main gear tires
C	Tire coverage; value for base pavement factor in overlay calculations
CW	Critical single wheel
D_{CS}	Diagonal spacing of bogie tires
F	Factor
h	Thickness of concrete
h_b	Existing rigid pavement thickness
h_o	Overlay thickness
K	Subgrade modulus
L	Length of single tire contact area
ℓ	Radius of relative stiffness
M	Equivalent single wheel multiplier
N	Number of tires
n	Number of influence chart blocks
P_S	Gear load
P_E	Equivalent pressure
p	Tire inflation pressure
R	Tire footprint radius
S	Aircraft pass
s	Tensile stress in the bottom concrete surface
SWL	Single wheel load
t	Thickness of flexible pavement structure

NOMENCLATURE (CONTD)

W	Width of single tire contact area
X	Main tire tread
Y	Axle base
Z	Nose tire tread

Subscripts

cs	Critical spacing

Terms

Pavement	A permanent runway surface.
Flexible Pavement	An asphaltic concrete or bituminous aggregate mix surface with a thickness normally varying from 1-1/2 to 8 inches (Reference 10).
Rigid Pavement	Portland Cement concrete aggregate mix with a thickness normally varying from 6 to 30 inches (Reference 9).
Overlay Pavement	Flexible or rigid pavement laid over a pavement to increase load-carrying capacity.
Flexible Pavement Structure	Complete depth of prepared flexible pavement, from surface to virgin soil (Reference 10, Figure 3).
California Bearing Ratio (CBR)	The load-bearing capability ratio between the soil and crushed limestone.
Center of Gravity (CG)	That point about which all parts of the aircraft balance; to be used herein to establish landing gear loads.
Gross Weight (GW)	The maximum weight (ramp weight) of the aircraft fully loaded.
Tire Inflation Pressure	Gage pressure of the tire.
Rated Tire Load	Load used in determining the design strength of the tire.

NOMENCLATURE (CONTD)

Tire Contact Area	Tire footprint, determined, unless otherwise specified, by dividing the load by the tire inflation pressure.
Single Wheel Load (SWL)	Calculated static load on each tire; normally computed by dividing the assembly load by the number of tires on the assembly.
Equivalent Single Wheel Load (ESWL)	Calculated load which, if applied to a single tire, would produce the same effect on the airfield as does the multiple wheel assembly.
Tread Distance	Distance between the center lines of two adjacent tires.
Axle Base	Distance between the center lines of the fore and aft axles of the main gear.
Wheel Base	The distance between center lines of the nose axle and the main gear bogie pivot.
Strut Spacing Distance	Distance between center lines of main landing gear struts.
Assembly Load	Load on the landing gear assembly used in calculating ground flotation, equal to ground reaction load calculated from the specified aircraft gross weight and CG condition.
Critical Single Wheel (Main Gear)	For a multiwheeled bogie, an equally loaded or the most heavily loaded wheel of the geometric arrangement (see Appendix I for designation of critical single wheels).
Aircraft Pass	An aircraft passing a given taxiway station; a takeoff and a landing constitute one pass.
Coverage	When applied to a point, a tire moving over that point; when applied to an area, movement of a tire over every point in that area.

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SECTION I

INTRODUCTION

During the past 25 years, numerous attempts have been made to develop a simple standard method for determining whether or not a proposed aircraft can operate satisfactorily from an existing airfield, as evidenced by the literature (References 2, 3, 4, 5, 6, 7, and 8). Many methods are being used today for rating airfield bearing capabilities, but all of the methods are not appropriate for our purposes and all do not provide identical results. Moreover, the literature containing the theories is so voluminous that the aircraft designer very easily reaches an impasse in determining the appropriate method to use for the existing situation and cannot establish a common base for determining flotation capabilities.

Methods for determining airfield flotation capabilities have generally been adapted from airfield design theory and construction factors. The Unit Construction Index (Reference 3), for example, which was based on a construction factor, was a very useful tool, but it did not define flotation capability in terms compatible with airfield construction.

The CBR method described in Reference 8, which the Air Force recently modified and adopted for determining flotation capability, is basically a flexible pavement analysis. Reference 8 does not provide a method of determining the flotation capabilities for rigid pavement, however. It merely categorizes rigid pavements as to their capabilities for supporting heavy, medium, or light loads.

This report presents a method for determining the ground flotation characteristics of an air vehicle and evaluating these characteristics in relation to flexible, rigid, or overlay pavements. By use of these methods, airfields from which a proposed aircraft can operate can be determined in advance, or the design of the aircraft can be modified to permit it to be operated from existing facilities.

SECTION II

PROCEDURES FOR DETERMINING FLEXIBLE PAVEMENT STRUCTURAL REQUIREMENTS FOR AIRCRAFT

Procedures for evaluating the ground flotation characteristics of an aircraft to determine whether or not it can be operated from flexible pavement are based on (but are not identical to) the CBR techniques described in References 1, 7, and 8. (The background for this analysis is not included here, since that information is available in the literature.) Flexible pavement is defined as a surface constructed of an asphaltic concrete or bituminous aggregate mix, with a surface thickness varying from 1-1/2 to 8 inches, as described in Reference 10. The flexible pavement structure consists of the complete depth of the prepared flexible pavement, including the surface and subsurfaces down to the virgin soil, as shown in Figure 3 of Reference 10.

The technique described herein involves constructing a curve of CBR values versus airfield surface thickness, which indicates whether that surface can support that particular aircraft. For this analysis, we will first present the theory and then calculate the values for the KC-135 aircraft for each of the steps in the procedure.

Procedures are given for calculating only the main landing gear values. Calculations should be made for the nose wheels also, to determine which landing gear assembly is the more critical.

1. AIRCRAFT DATA

The first step in the analysis is to determine the landing gear configuration and the load characteristics of the aircraft. Information needed includes loads on landing gear, single wheel loads (SWL), and tire pressure for the gross weight of the aircraft being considered, using the most forward CG for the nose gear and the most aft CG for the main gear. The gear assembly load is divided by the number of tires to determine the SWL.

For this analysis, we will use the values for the KC-135 aircraft as an example. The landing gear configuration for the KC-135 aircraft is shown in Figure 1. Values for the required aircraft parameters are as follows:

Nose Gear

Total Load	22,000 lbs
SWL	11,000 lbs
Tire Pressure	95 psi

Main Gear

Individual Gear Load	144,000 lbs
SWL	36,000 lbs
Tire Pressure	155 psi

2. TIRE FOOTPRINT RADIUS

The tire contact area, A, can be determined from

$$A = \frac{SWL}{\text{Tire Pressure}} \qquad (1)$$

The contact area, A, can be converted to footprint radius, R, by

$$R = \sqrt{\frac{A}{\pi}} \qquad (2)$$

For our example, the tire contact area would be:

$$\frac{36{,}000}{155} = 232.3 \text{ Square Inches}$$

And the footprint radius would be

$$R = \sqrt{\frac{232.3}{3.14}} = 8.6 \text{ Inches}$$

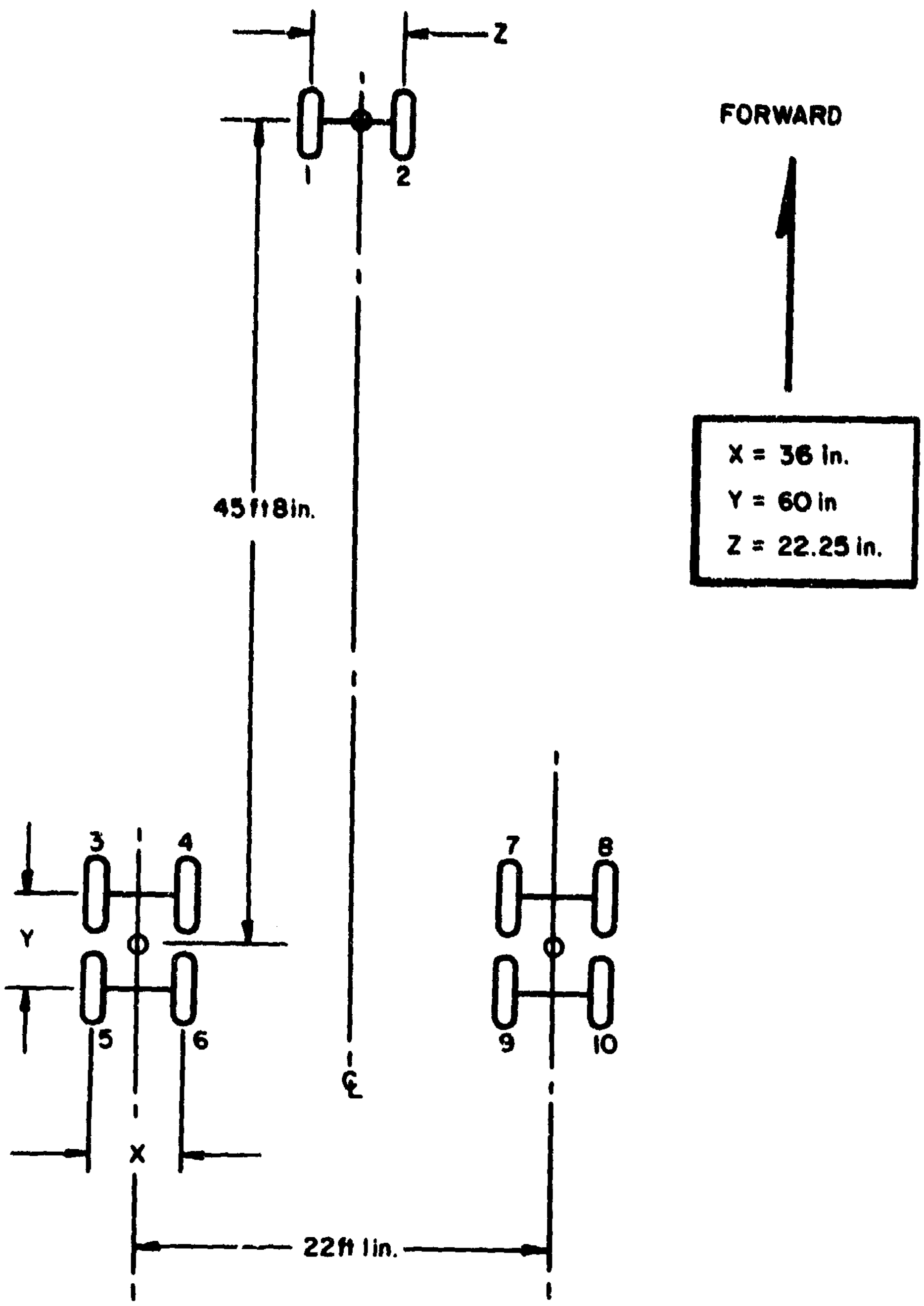


Figure 1. Landing Gear Configuration for KC-135 (Twin-Tandem Gear)

3. CRITICAL WHEEL DEFLECTION FACTORS

a. Offset Dimensions

Next, we must determine from the critical wheel the offset dimensions for all other wheels. (The critical wheel is indicated by an X on the configuration layouts given in Appendix I). The critical spacing is measured in radii and is determined by the following equations:

Critical spacing, width

$$W_{cs} = \frac{X}{R} \tag{3}$$

Critical spacing, length

$$L_{cs} = \frac{Y}{R} \tag{4}$$

Critical spacing, diagonal

$$D_{cs} = \sqrt{W_{cs}^2 + L_{cs}^2} \tag{5}$$

The critical wheel on the twin-tandem configuration of the KC-135 is Wheel No. 6. For our example, therefore,

$$W_{cs} = \frac{X}{R} = \frac{36}{8.6} = 4.18$$

$$L_{cs} = \frac{Y}{R} = \frac{60}{8.6} = 6.98$$

$$D_{cs} = \sqrt{4.18^2 + 6.98^2} = 8.14$$

Offset factors obtained from Equations 3, 4, and 5 are used to determine deflection factor values from Figure 2. (Deflection Factor Values are tabulated in Appendix III.) Values for deflection factor vs depth in radii should then be tabulated. We recommend tabulating values to at least 8 radii of depth; large aircraft may require greater depths. Values for the KC-135 aircraft are listed in Table I.

b. Critical Main Gear Assembly Load

The next step is to determine the offset of the wheels from the geometrical center of the main gear. For our example, the landing gear assembly for the KC-135 is symmetrical, as shown in Figure 1, and therefore the

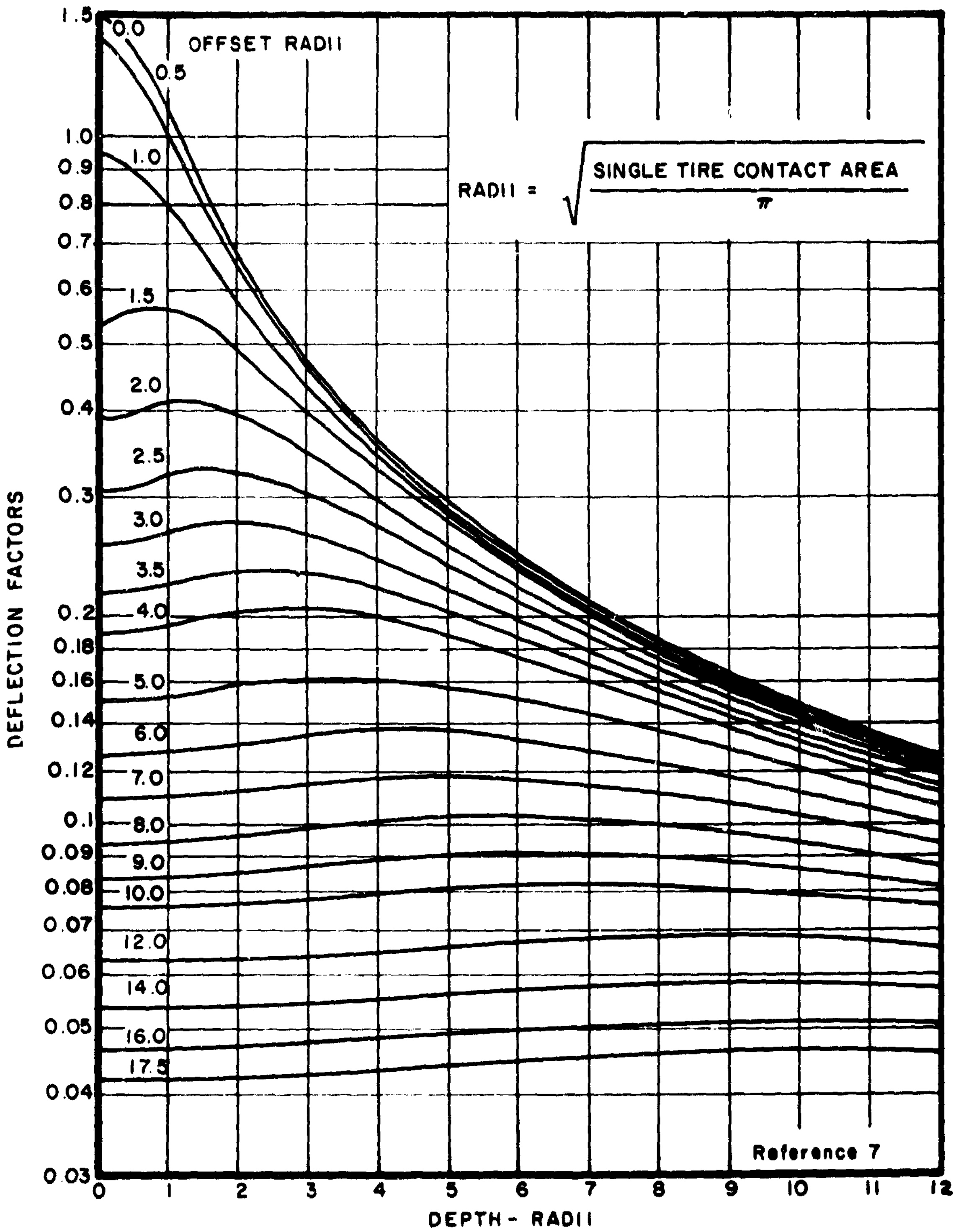


Figure 2. Deflection Factors Versus Depth in Radius for Given Offset Values (More accurate tabulated values are presented in Appendix III)

TABLE I

WHEEL DEFLECTION FACTORS FOR KC-135 AIRCRAFT

	Deflection Factor for Wheel No.				
	3	4	5	6	Total Deflection
Offset	8.14	6.98	4.18	0	
Depth In Radii					
0	0.092	0.109	0.182	1.5	1.883
0.5	0.0925	0.110	0.185	1.342	1.730
1	0.093	0.111	0.187	1.060	1.451
2	0.0945	0.112	0.197	0.670	1.074
3	0.097	0.115	0.200	0.474	0.886
4	0.099	0.117	0.192	0.364	0.772
5	0.100	0.118	0.183	0.294	0.695
6	0.100	0.116	0.170	0.247	0.633
7	0.099	0.115	0.157	0.212	0.583
8	0.0985	0.112	0.147	0.186	0.544

geometrical center is in the center of the main gear. Since the diagonal dimension, D_{cs}, calculated in Equation 5, is 8.14, the offset distance from all four wheels would be

$$\text{Offset Distance} = \frac{8.14}{2} = 4.07$$

Deflection factors should be determined for each wheel at each depth and offset, and the information tabulated. Deflection factors for our example, the KC-135 aircraft, are tabulated to 8 radii of depth in Table II.

c. Maximum Deflection Factor Curve

The critical deflection factors for the critical wheel and the entire assembly should now be plotted versus depth in radii. (It may be necessary to plot these factors in half radii to form smooth curves.) The critical wheel curve is valid at shallow depths and the assembly curve at deep depths. At intermediate depths, however, the curves for wheel and assembly may cross over; in this case, values must be estimated and a transition curve drawn in. This transition curve should originate at the deeper depths, closely follow but stay to the right of the assembly deflection factor curve, and fair into the single wheel deflection factor curve as it progresses upward. This transition curve indicates the maximum deflection factor at the given depth.

For our example, deflection factors from Tables I and II have been plotted in Figure 3. The faired portion of the curve is shown to extend from a depth of 5.3 to 1.8 radii. The lower portion of this curve is conservative.

d. Equivalent Single Wheel Multiplier Curve

A multiplier, M, to determine the equivalent SWL is developed by dividing the values on the limiting curve by the critical single wheel deflection factors for a given depth. These values should be plotted in a curve of M versus depth in radii.

For our example, the limiting value of the deflection factor at each depth was divided by the critical wheel deflection factor to produce M. These values are tabulated in Table III and are plotted in Figure 4.

TABLE II

ASSEMBLY DEFLECTION FACTORS FOR KC-135 AIRCRAFT
(OFFSET = 4.07)

Depth (In Radii)	Deflection Factor Per Wheel*	Total Deflection Factor for 4 Wheels
0	0.185	0.740
1	0.192	0.768
2	0.200	0.800
3	0.201	0.804
4	0.196	0.784
5	0.185	0.740
6	0.172	0.688
7	0.159	0.636
8	0.148	0.592

* If the bogie is not symmetrical, each wheel may have a different deflection factor. In that case, they would have to be listed separately, as in Table I.

TABLE III

MULTIPLIERS FOR EQUIVALENT SINGLE WHEEL LOAD OF KC-135 AIRCRAFT

Depth (In Radii)	Total Deflection Factor	Critical Wheel Deflection Factor	M
0	1.883	1.5	1.255
0.5	1.730	1.342	1.289
1	1.451	1.050	1.369
2	1.100	0.670	1.642
3	0.940	0.474	1.983
4	0.830	0.364	2.280
5	0.755	0.294	2.568
6	0.688	0.247	2.785
7	0.636	0.212	3.000
8	0.592	0.186	3.183

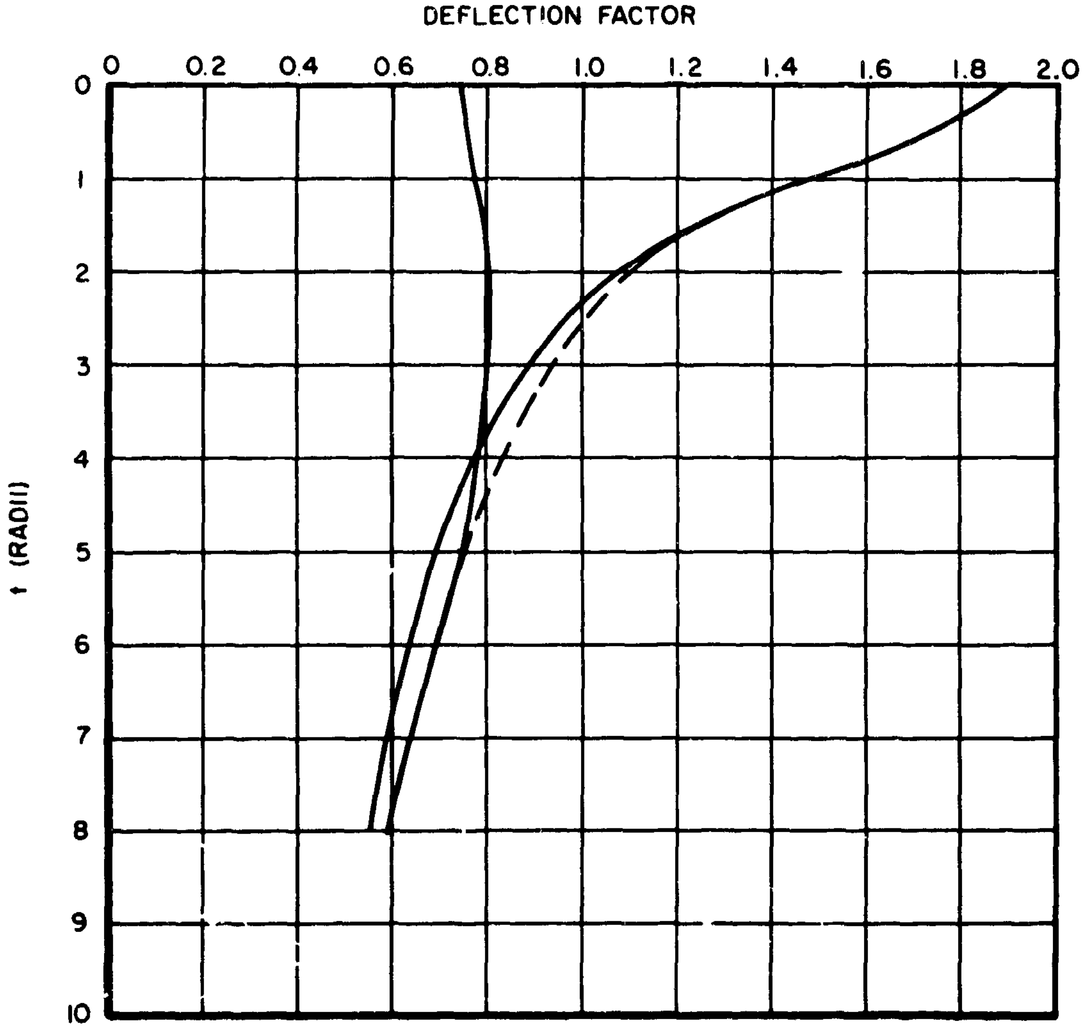


Figure 3. Deflection Factors for Various Depths

For convenience, a plot of M versus depth in inches should be provided instead of depth in radii, since airfield structures are measured in inches. To determine the multiplier for a given depth in inches, divide the number of inches by the number of inches in 1 radius; the quotient will be the value for converting the multiplier from R to an equivalent value in inches. These values should then be plotted in a curve of M vs. depth in inches.

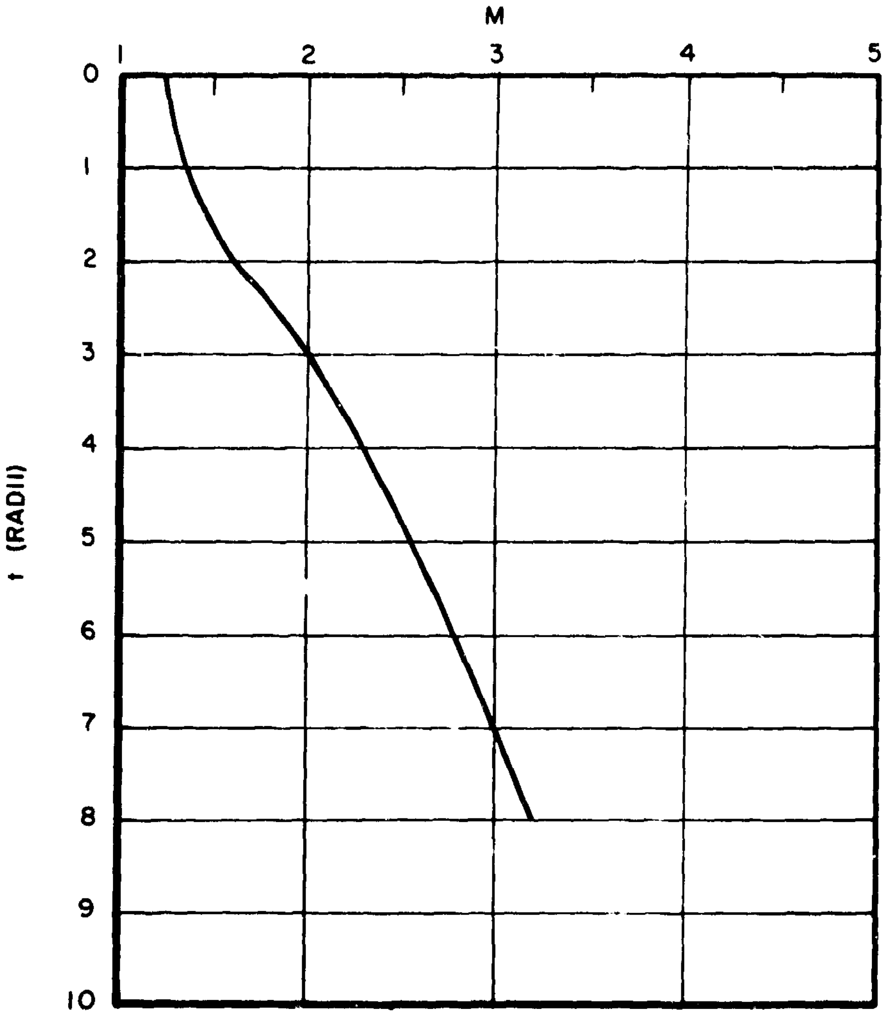


Figure 4. Equivalent Single Wheel Multiplier (M) Versus Depth in Radii

For our example, the conversion values are developed as follows:

Depth (In Inches)	Divide	Quotient	M
0			1.255
10	10/8.6	1.16	1.40
20	20/8.6	2.325	1.76
30	30/8.6	3.49	2.15
40	40/8.6	4.66	2.48
50	50/8.6	5.82	2.76
60	60/8.6	6.98	2.99

These values have been plotted in Figure 5.

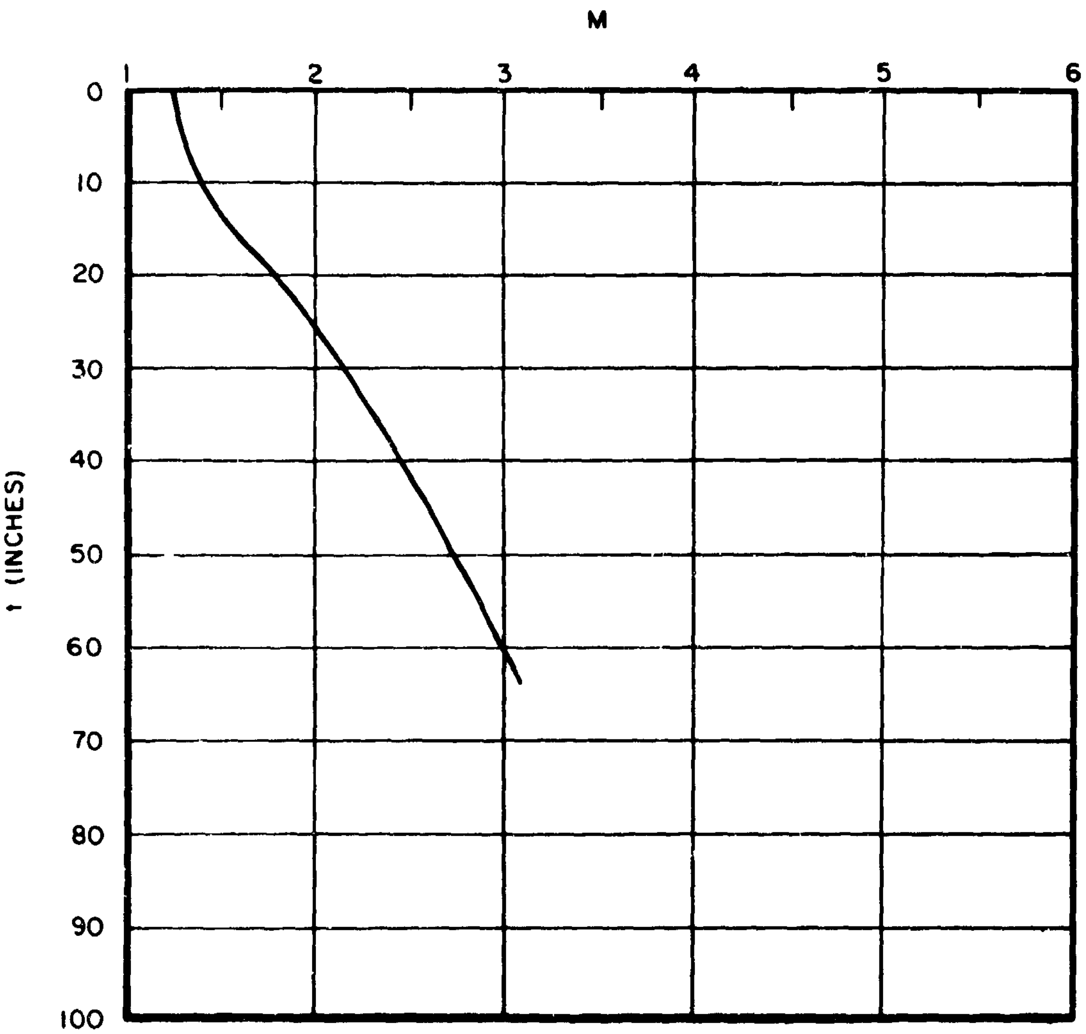


Figure 5. Equivalent Single Wheel Multiplier Versus Depth in Inches

4. CORRECTION OF COMBINED CBR CURVE AT SHALLOW DEPTHS

Basic CBR theory does not provide valid strength values for the shallow depths because it does not consider the surface deformations resulting from variations in wheel loads. A correction must be computed, therefore, to determine the proper surface thickness for the wheel loads of a given aircraft. This correction factor is determined as follows:

a. Surface thickness has been determined for varying wheel loads and tire inflation pressures. These values are plotted in Figure 6. Determine from Figure 6 the required surface thickness for the SWL and tire inflation pressure for the given aircraft. Our example, the KC-135, uses a tire pressure of 155 psi and has a single wheel load of 36,000 lbs. Figure 6 shows the minimum surface thickness for such an aircraft to be 2.1 inches.

For a multiwheeled landing gear, determine the equivalent tire pressure, P_E, by multiplying the M value for the indicated surface thickness by the tire inflation pressure.

$$P_E = M \times \text{tire inflation pressure} \qquad (6)$$

For our example, where Figure 6 indicated a thickness of 2.1 inches of asphalt, the M value would be 1.28. Therefore,

$$P_E = 1.28 \times 155 = 199 \text{ psi}$$

To correct the CBR curve at the indicated surface depth, two ratios must be established: CBR to P_E; and t (surface depth) to $\sqrt{A}$. For our example, where the CBR is 100 and P_E is 199, this ratio would be

$$\frac{CBR}{P_E} = \frac{100}{199} = 0.502$$

And for a surface depth of 2.1 inches and a contact area of 232.3 sq in, the second ratio would be

$$\frac{t}{\sqrt{A}} = \frac{2.1}{15.2} = 0.138$$

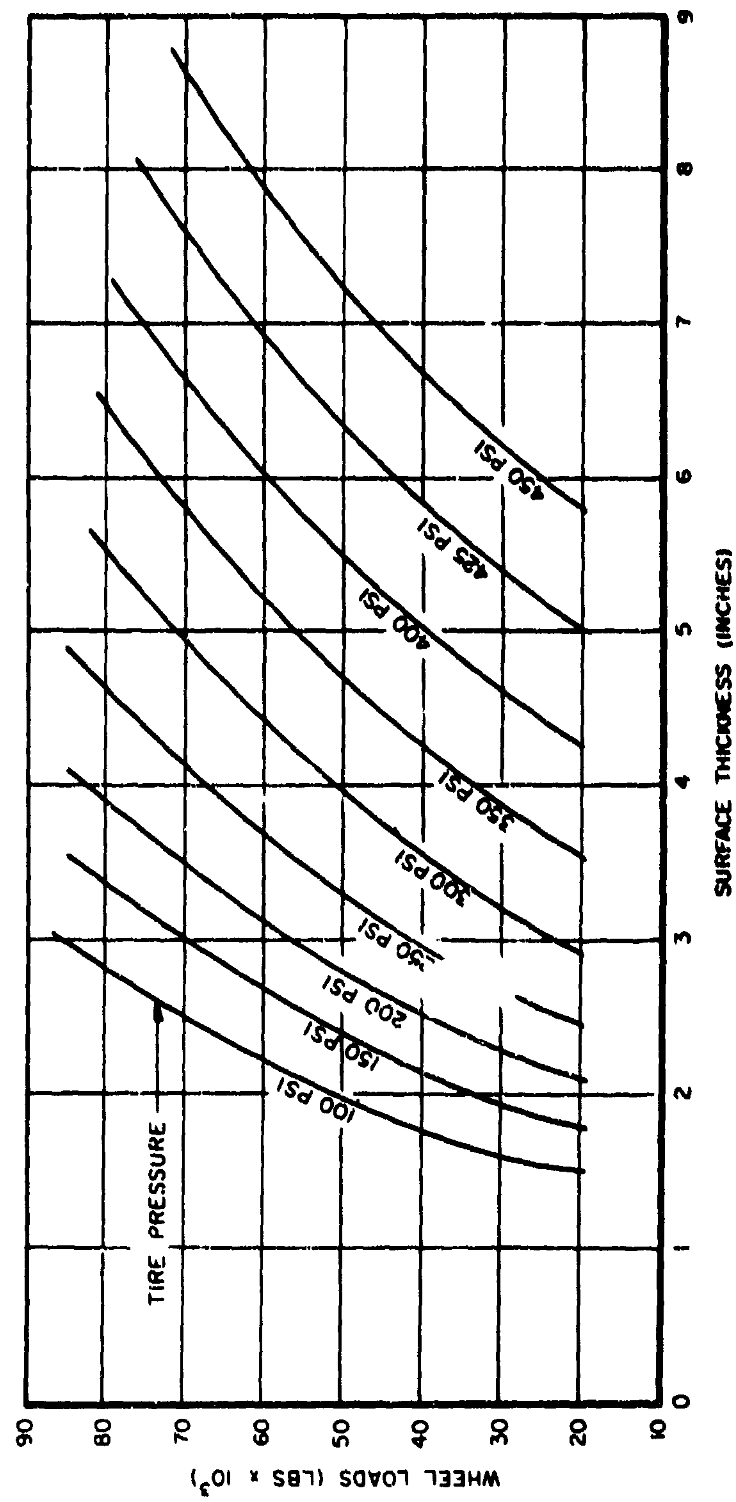


Figure 6. Wheel Load Versus Surface Thickness (CBR = 100) for Various Tire Inflation Pressures

The corrected values for CBR/P_E and $t/\sqrt{A}$ are used to establish a point for plotting a corrected CBR curve, beginning at a CBR/P_E value o[illegible] pproximately 0.25. This curve should be faired in, as shown in Figure 7.

5. CONSTRUCTING THE CBR CURVE

a. Determining CBR for 5000 Coverages

Data for $t/\sqrt{A}$, CBR/P_E, and P_E are used to construct a CBR curve for 5000 aircraft coverages. The CBR value for 5000 coverages is obtained from the equation

$$CBR = \left(\frac{CBR}{P_E}\right) P_E \qquad (7)$$

Table IV presents CBR data for 5000 coverages of the KC-135 aircraft.

TABLE IV

CBR DATA FOR 5000 COVERAGES

t (Inches)	$\frac{t}{\sqrt{A}}$	$\frac{CBR}{P_E}$ (a)	P_E (b)	CBR (c)
Surface	0.138	0.502	199	100 (e)
5 (d)	0.328	0.31	200	62.0
10	0.656	0.165	217	35.8
15	0.984	0.088	238	20.9
20	1.310	0.057	273	15.5
25	1.64	0.040	306	12.2
30	1.97	0.029	333	9.7
35	2.30	0.022	364	8.0
40	2.63	0.018	384	6.9

(a) From Corrected Combined CBR Curve (Figure 7)
(b) From Equation 6
(c) From Equation 7
(d) If surface thickness is 5 inches or more, omit this line
(e) CBR value at a depth of 2.1 inches.

b. Converting Passes to Coverages

Since the number of passes rather than the number of coverages is the value usually specified, the next step is to convert the passes to coverages by means of the following equation:

$$C = \frac{S}{P/C} \tag{8}$$

where

S = the number of passes

C = the number of coverages

P/C = the number of passes per load repetition factor, as determined in Figure 9

and the equivalent thickness of runway surface, t_E, can be determined by dividing the depth by a conversion factor

$$t_E = \frac{t}{0.15 + 0.23 \log C} \tag{9}$$

We now determine the number of coverages that would be equivalent to 300 passes for our example, the KC-135 aircraft. From Figure 9, we find that the value for P/C is 3.24. Therefore

$$C = \frac{300}{3.24} = 92.6$$

The equivalent thickness, t_E, therefore, would be

$$t_E = \frac{t}{0.15 + 0.23 \log 92.6} = \frac{t}{0.6023}$$

Data for 300 passes of the KC-135 aircraft are tabulated in Table V and are plotted in Figure 8 together with the values for 5000 coverages. Values can be computed from Equations 8 and 9 for any desired number of passes.

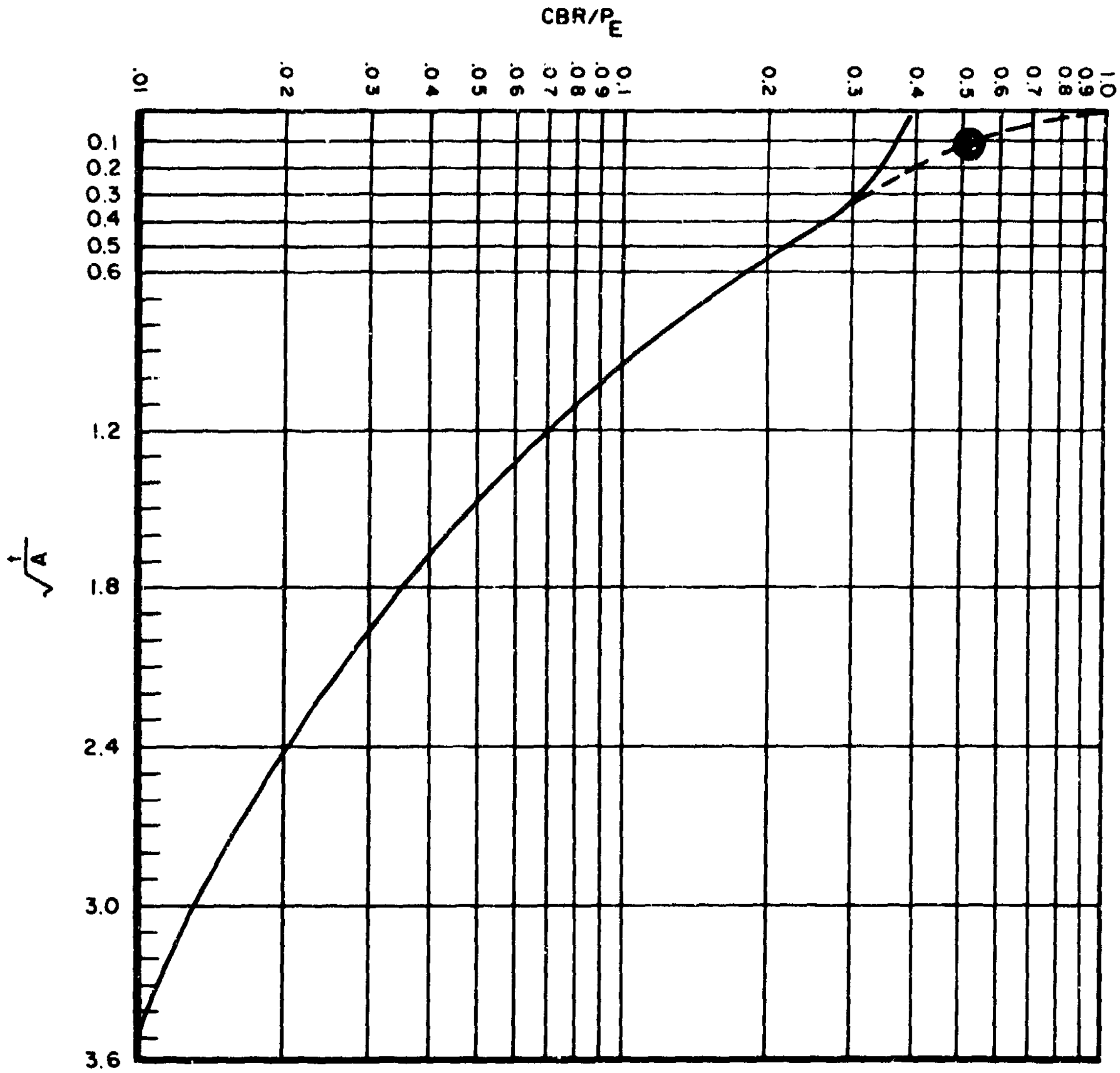


Figure 7. Corrected CBR Curve

6. EVALUATION OF AIRCRAFT VS. RUNWAY CAPABILITY

a. The use of a specific runway by a specific aircraft can be evaluated by first determining the runway construction. A typical flexible type runway is constructed as follows:

Depth (Inches)	Structure	Material	CBR
0 - 4	Surface	Asphaltic Concrete	100
4 - 10	Base	Sand, Gravel, and Limestone	60
10 - 20	Subbase 1	Crushed Limestone	45
20 - 30	Subbase 2	Stabilized Silty Sand	40
30 - 34	Subbase 3	Subbase Material No. 1	30
34 -	Subgrade	Virgin Soil	7

These values for runway CBR have been plotted as the heavy solid black line in Figure 8 with the CBR curves for 300 passes and 5000 coverages of the KC-135 aircraft. If all the CBR values for the runway are below the CBR curves for the aircraft, the runway is capable of supporting the aircraft; if not, it is not considered safe. For our example, the runway is not adequate for 5000 coverages, but it would be adequate for 300 passes.

TABLE V

CBR CURVE FOR 300 PASSES OF KC-135 AIRCRAFT

t (a) (inches)	t_E (inches)	$\frac{t_E}{\sqrt{A}}$	$\frac{CBR}{P_E}$ (b)	P_E (c)	CBR (d)
Surface		0.138	0.515	194	100 (e)
5	8.3	0.542	0.200	200	40
10	16.6	1.09	0.083	217	18
15	24.9	1.63	0.041	238	9.8
20	33.2	2.18	0.0255	273	6.9

(a) Use these thicknesses vs CBR values for plotting on Figure 8.

(b) From Corrected Combined CBR curve (Figure 7) using values of $\frac{t_E}{\sqrt{A}}$.

(c) From Equation 6.

(d) From Equation 7.

(e) CBR at a depth of 2.1 inches.

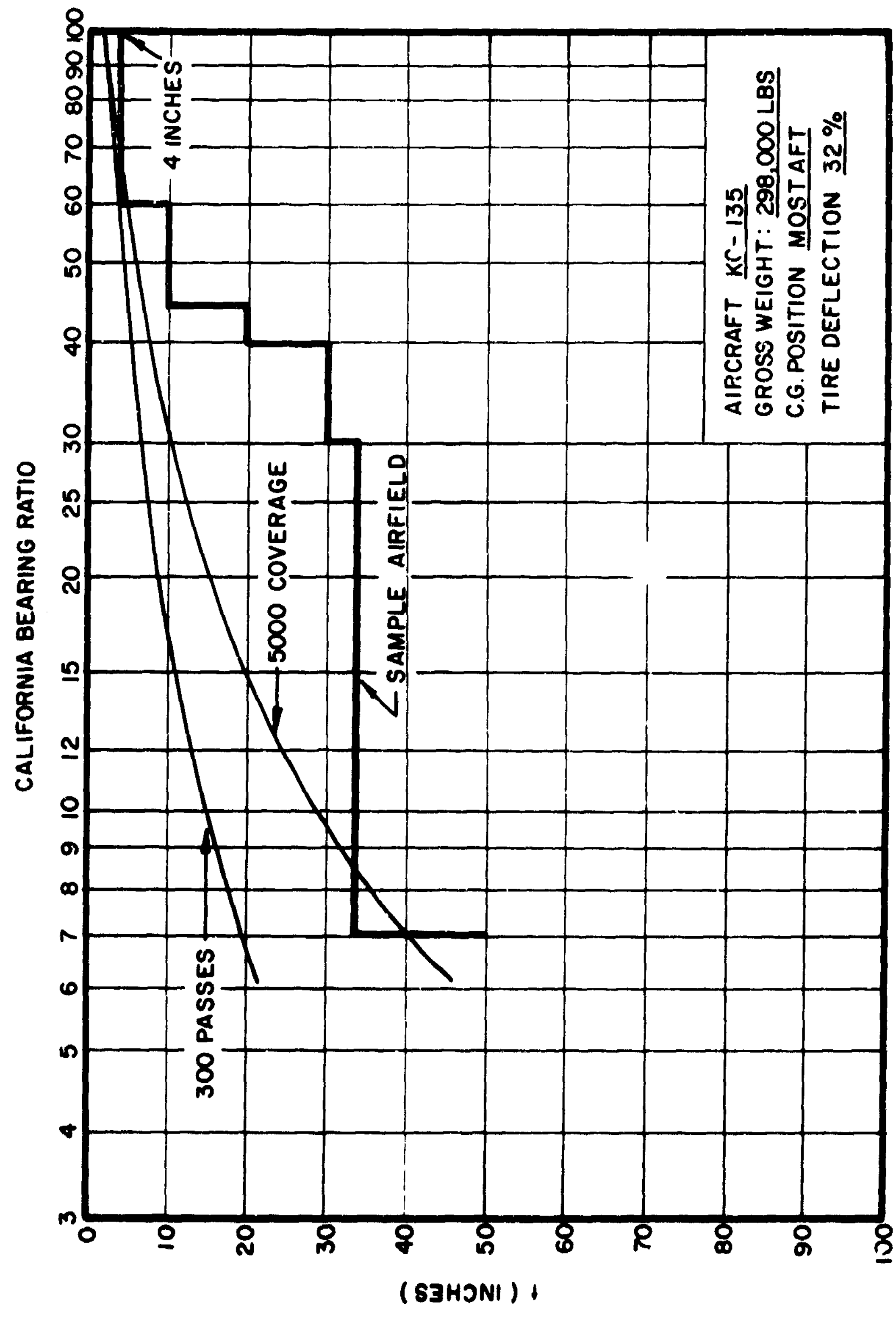
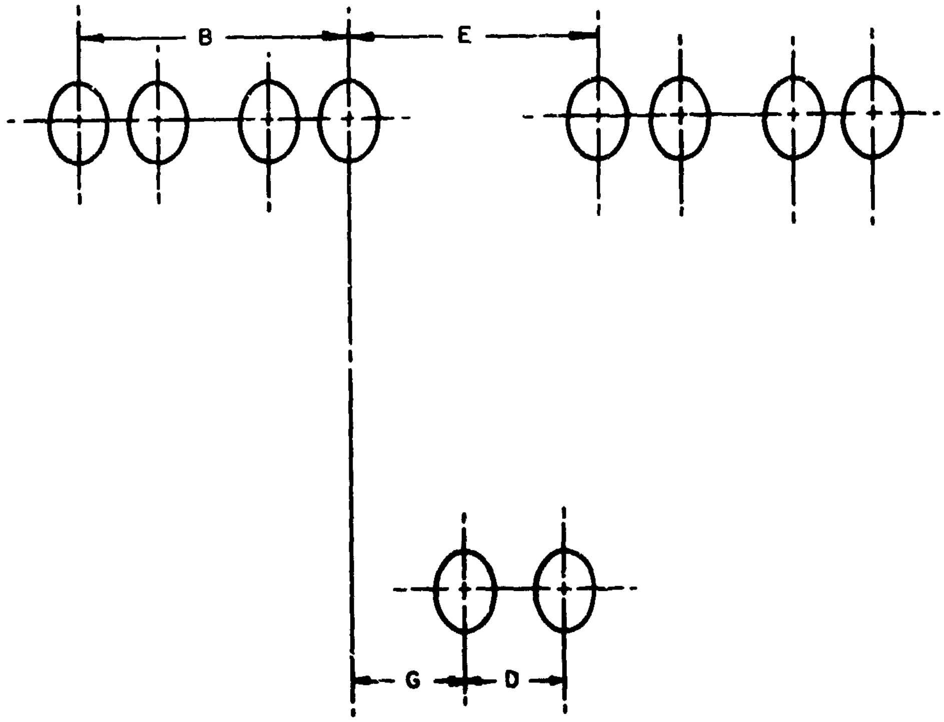


Figure 8. CBR Curves for 5000 Coverages and 300 Passes of KC-135 Aircraft



PROCEDURE

Main Assembly: $P/C = \dfrac{B + 80 + W_M}{(0.75)(N_M)(W_M)}$

Nose Assembly: $P/C = \dfrac{D + 80 + W_N}{(0.75)(N_N)(W_N)}$

P/C Passes per load repetition factor

N_M Number of tires per main gear

N_N Number of tires per nose gear assembly

W_M Width of main single tire contact area $W_M = 0.874\sqrt{A_M}$

W_N Width of nose single tire contact area $W_N = 0.874\sqrt{A_N}$

A_M Single tire contact area of main tires

A_N Single tire contact area of nose tires

Figure 9. Procedure for Finding P/C Value

SECTION III

PROCEDURES FOR DETERMINING RIGID PAVEMENT STRUCTURAL REQUIREMENTS FOR AIRCRAFT

1. METHODOLOGY

Procedures for evaluating the ground flotation characteristics of an aircraft to determine whether it can be operated from a specific rigid pavement runway are based on the interior-loaded-slab, concrete-stress techniques described in References 2, 4, 5, and 6. The term "rigid pavement," as used herein, is defined as a surface of Portland cement aggregate mix, with a thickness varying from 6 to 30 inches, constructed on a prepared subgrade, the strength of which is defined by the subgrade modulus, K, in psi/in (Reference 9). The technique described herein for making this evaluation involves constructing a curve for concrete thickness versus K values to define the pavement characteristics required to support the aircraft for the required volume of traffic.

A chart showing the functional flow for the technique is given in Figure 10. The notation in parenthesis following each step in the procedure refers to the paragraph which explains that step. An alternate input in the computation permits using stress rather than coverages or passes as the input, which provides data consistent with that used by civilian agencies.

2. PROCEDURE

The evaluation procedure includes four major steps described as follows:

a. Develop n vs ℓ relationship, which indicates the basic stress characteristics of a gear on rigid pavement, where

n = number of blocks on the influence chart (Figure 11) covered by the gear footprint, and

ℓ = radius of relative stiffness of the pavement.

Values of n must be determined for the full range of applicable ℓ values. Usually, computations for ℓ values from 20 to 90 should be made in the following increments: 1 from 20 to 30; 5 from 30 to 50; and 10 above 50. For single-wheel gears, n can be determined from Figure 12; for multiple-wheel

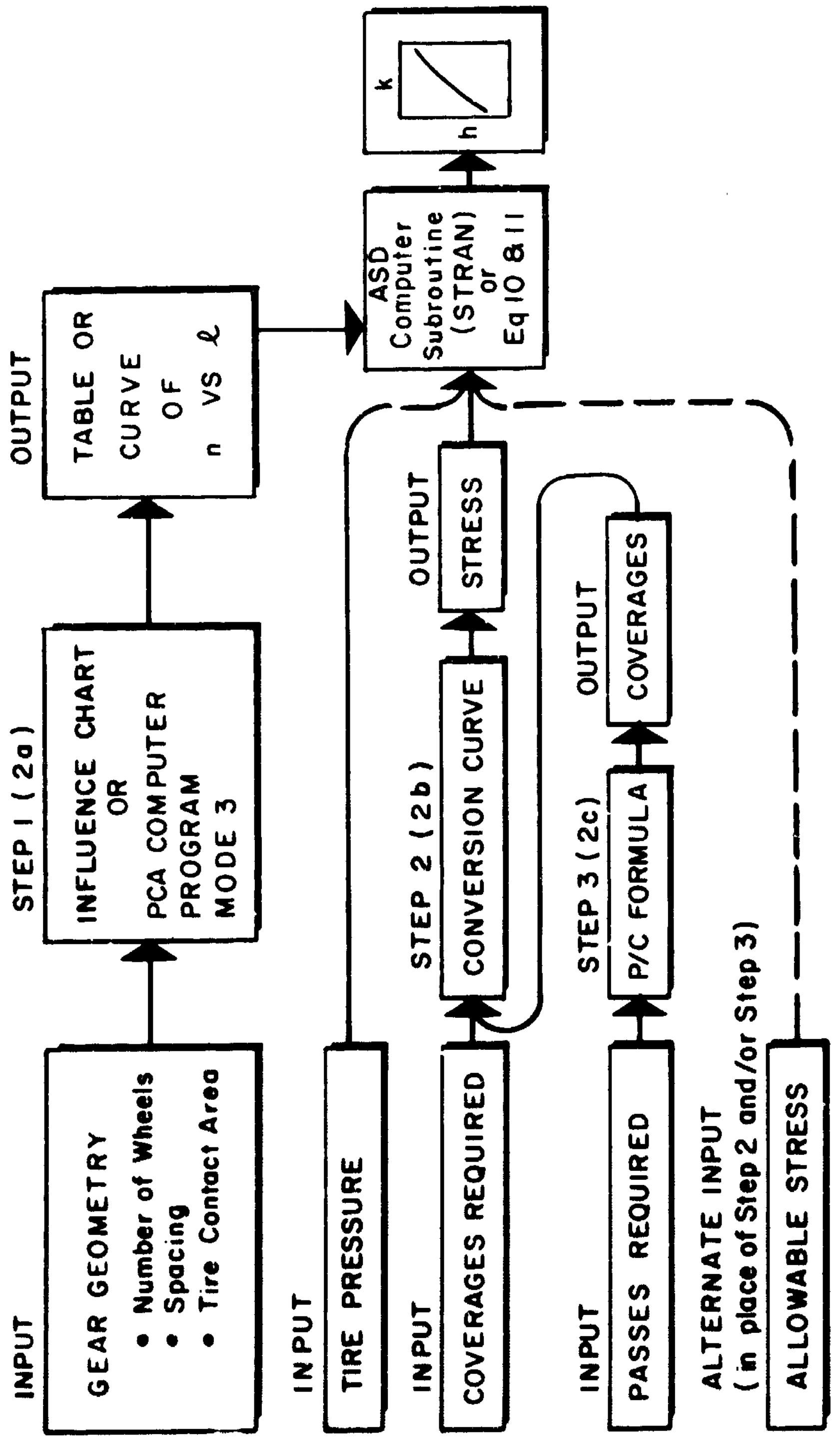


Figure 10. Functional Flow Methodology

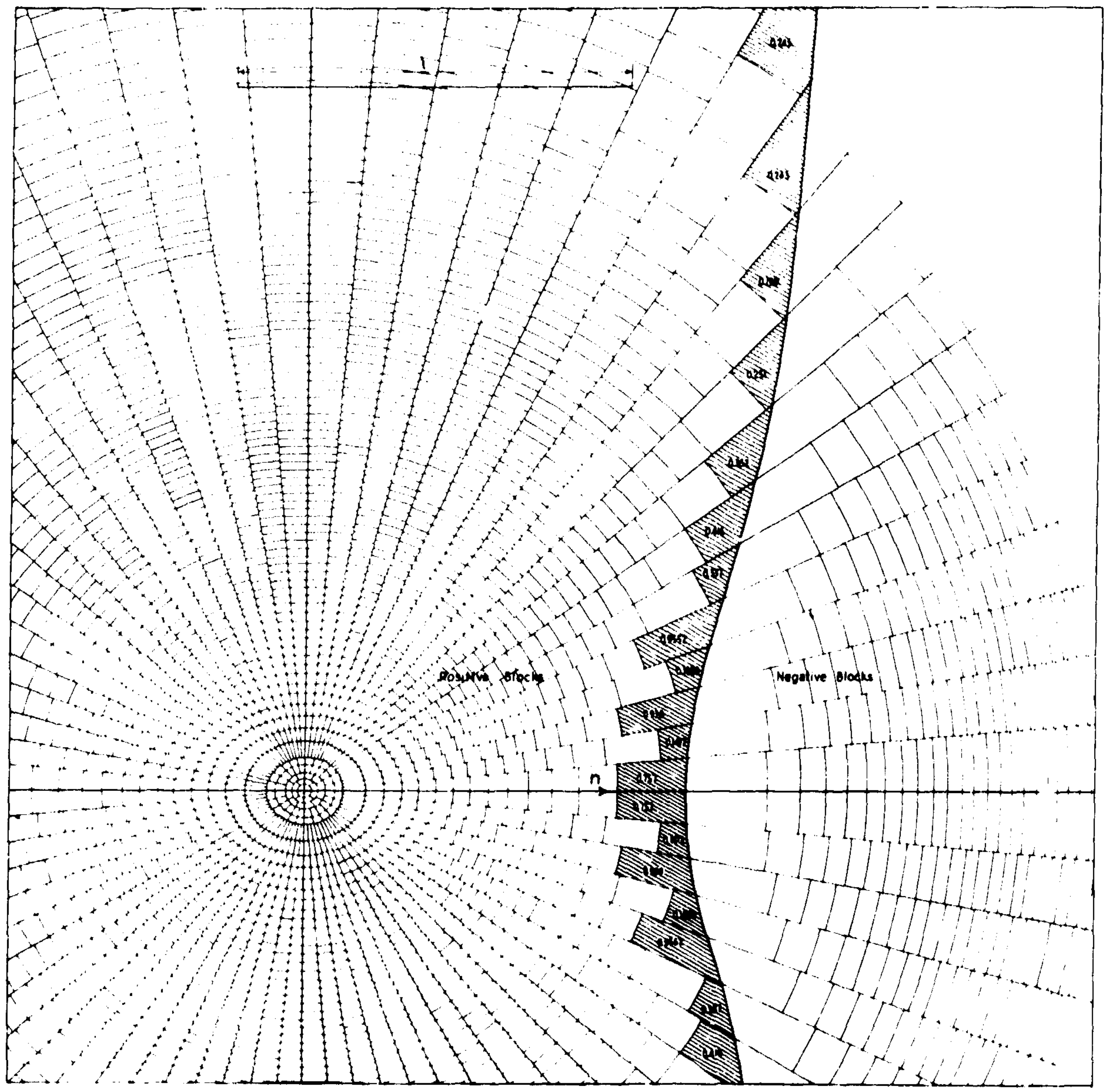


Figure 11. Influence Chart for Interior-Loaded Slab

(Large-Scale charts are available from the Portland Cement Association and should be used when a manual solution is necessary.)

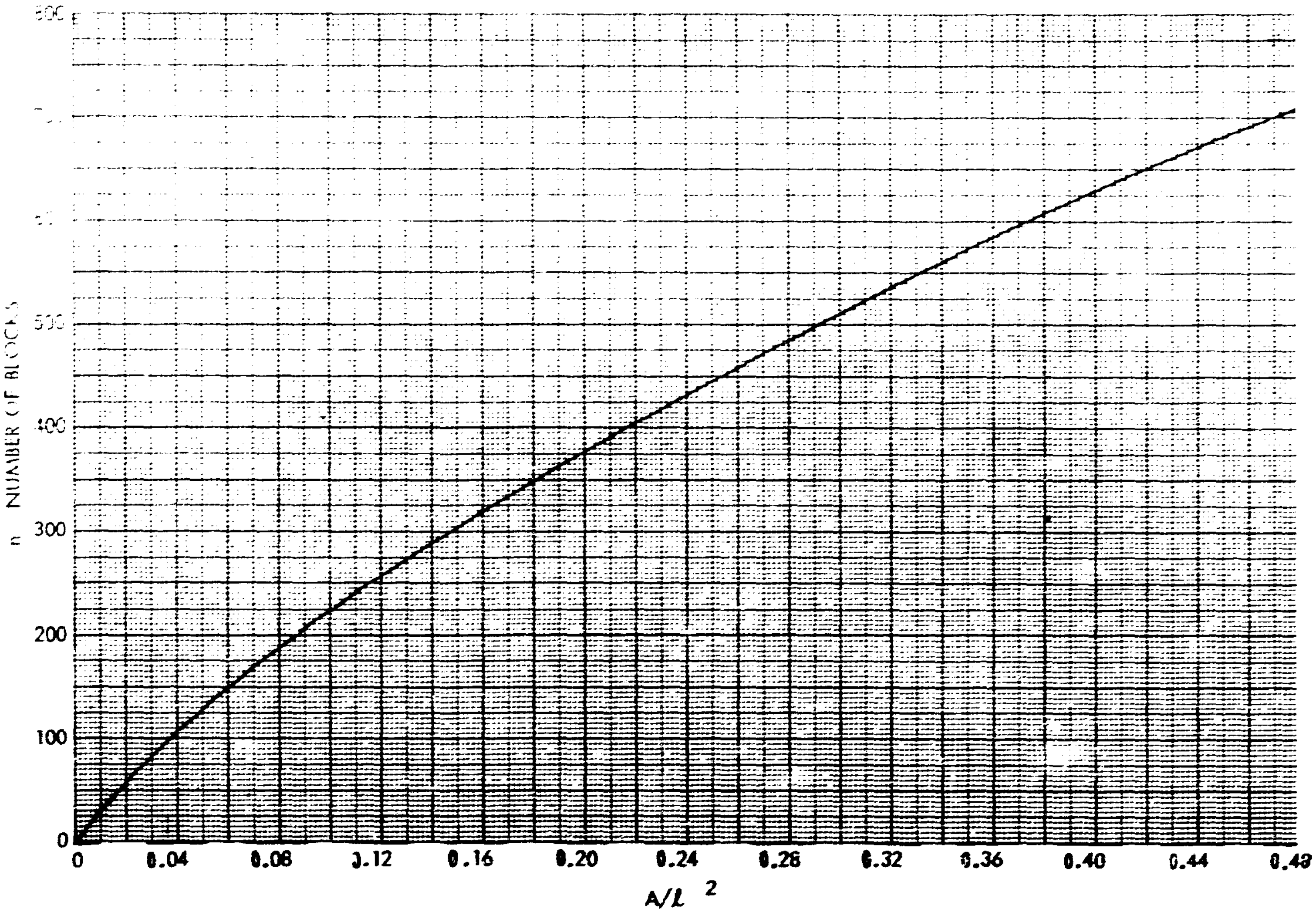


Figure 12. Determination of n for Single Wheel Gears

gears, the PCA computer program (Reference 13) can be used. If computer facilities are not available, n can be determined manually by using a large-scale version of the influence chart and proceeding as follows:

(1) Draw the gear footprint pattern on transparent paper to the following scale:

$$\text{Drawing Dimension} = \text{Actual Dimension} \times \frac{\ell \text{ on Chart}}{\text{Actual } \ell}$$

Tire contact areas are assumed to be rectangles with rounded ends, having a length, $L = \sqrt{\frac{A}{0.5227}}$, and a width $W = 0.6L$.

(2) Place the drawing on the chart with the center of the critical wheel on the origin, oriented approximately as shown in Appendix I.

(3) Count the number of blocks enclosed by the tire footprints; estimate fractional blocks. Deduct negative blocks from the positive total.

(4) Rotate the footprint about the origin and repeat Step (3) until the maximum block count is obtained.

(5) Repeat Steps (1) through (4) for all ℓ values and tabulate.

b. If a coverage level is specified, determine the allowable pavement stress from Figure 13.

c. If a pass level is specified, use Figure 9 to convert passes to the corresponding number of coverages and then determine the allowable pavement stress level from Figure 13.

d. Use the n/ℓ curve derived in Step a, the allowable stress from Steps b and c, and the tire inflation pressure to determine the required pavement thickness (h) and subgrade strength (K) by using the following equations (developed in Appendix II):

$$h = 0.0245\,\ell \sqrt{\frac{pnF}{s}} \qquad (10)$$

$$K = \frac{3.41 \times 10^{5} \times h^{3}}{\ell^{4}} \qquad (11)$$

where F = 0.75 for runway centers (Type C traffic area) and 1.00 for runway ends, taxiways, etc. (Type A and B traffic areas). If the aircraft in question does not have a positive lift force during takeoff run prior to rotation, however, use 1.00 for the runway center also.

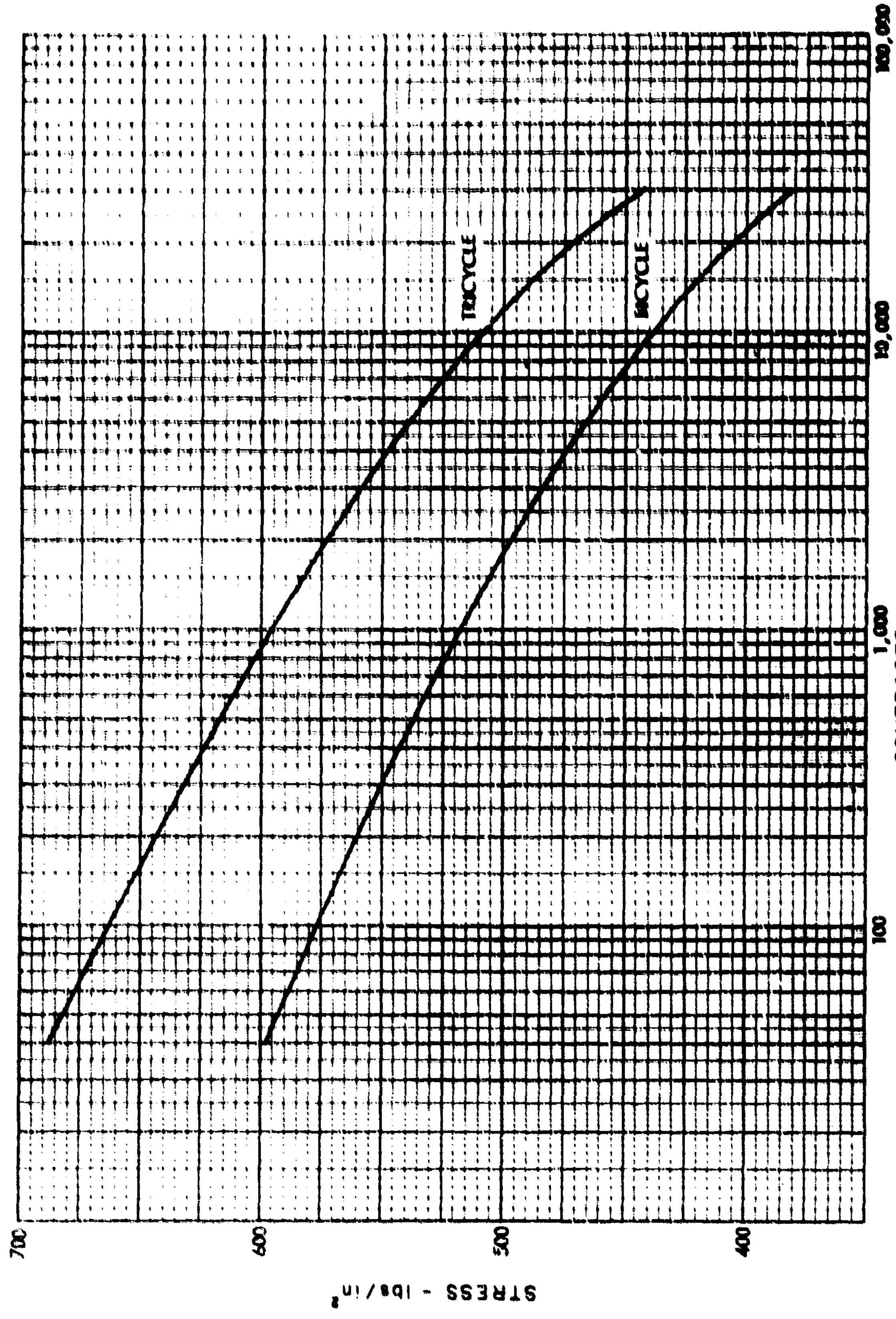


Figure 13. Stress Coverage Conversion

3. EXAMPLE

The KC-135 aircraft, as described in Section II, is used as the example. (Dimensions, tire contact area, and tire inflation pressure are given on pages 2, 3, and 4.) We have assumed requirements for 10,000 coverages and 300 passes on a Type C traffic area.

a. Develop n vs ℓ *

(1) Footprint Construction: **

$$X = 36 \times \frac{2.28}{60} = 1.37 \quad (\ell = 60 \text{ for this computation})$$

$$Y = 60 \times \frac{2.28}{60} = 2.28$$

$$L = \sqrt{\frac{232.3}{0.5227}} \times \frac{2.28}{60} = 0.83$$

$$W = 0.6 \times 0.83 = 0.498$$

Draw footprint to these dimensions.

(2) Locate footprint drawing on chart (Figure 14) using Appendix I as a guide.

(3) Count the blocks - 238.

(4) Rotate footprint and repeat count until the position providing the maximum count is found (the maximum count position has already been determined in this case).

(5) Repeat Steps (1) through (4) for ℓ values of 20, 30, 40, 50, 60. Results are given in Table VI, Item 1.

---

* A small-scale chart (Figure 14) with ℓ = 2.28 inches is used for this example. In actual computations, a large-scale chart (ℓ = 10 inches) should be used.

** CAUTION: The PCA computer program uses gear dimensions of X and Y rotated 90 degrees to those shown in Figure 1.

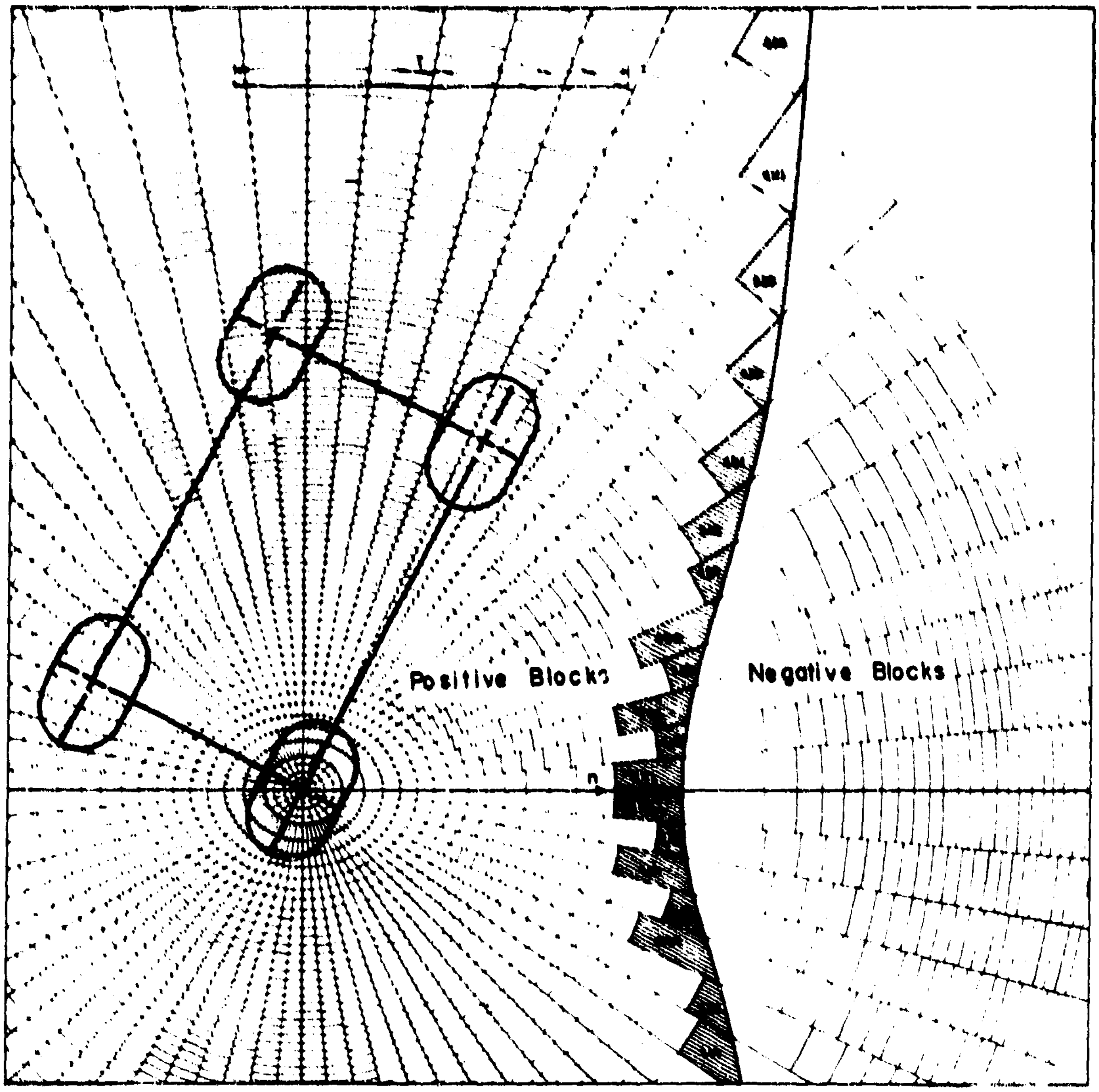


Figure 14. KC-135 Gear Footprint on Influence Chart

TABLE VI

DATA SUMMARY FOR KC-135

ℓ Values

Item		20	22	25	30	40	50	60*
1	n	801	694	584	491	371	294	239
2	h	6.65	6.80	7.09	7.80	9.05	10.1	10.9
3	K	626	459	311	200	98.6	55.5	34.0
4	h	5.8	6.0	6.2	6.8	7.9	8.8	9.5
5	K	418	307	208	134	65.9	37.1	22.7

*Note: ℓ values used in the example

b. The allowable stress level for 10,000 coverages determined from Figure 13 is 505 psi.

c. The coverage equivalent for 300 passes is 92.6 (See II, para 5,b). The allowable stress from Figure 13 is 662 psi.

d. Calculate h for 10,000 coverages (505 psi).

$$h = 0.0245 \times 60 \times \sqrt{\frac{155 \times 239 \times 0.75}{505}} = 10.89$$

Repeat for other ℓ values (results indicated in Table VI, item 2).

e. Calculate K for corresponding h values.

$$K = \frac{3.41 \times 10^5 \times 10.89^3}{60^4} = 33.98$$

Repeat for other h values (Table VI, Item 3).

f. Plot h versus K (Figure 15).

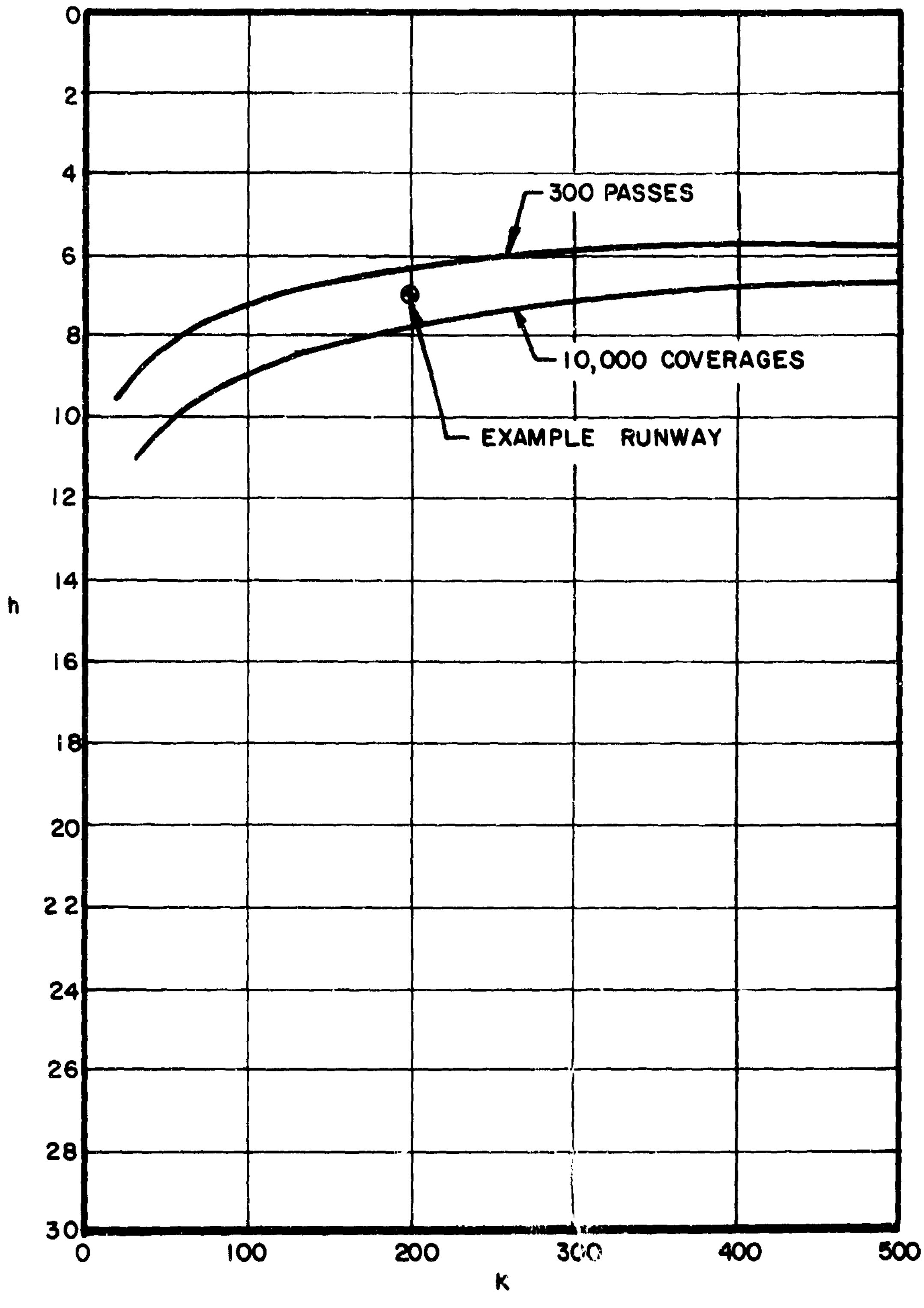


Figure 15. Air Vehicle Rigid Pavement Requirements -- KC-135 Main Gear

g. Calculate h for 300 passes.

$$h = 0.0245 \times 60 \sqrt{\frac{155 \times 239 \times 0.75}{662}} = 9.52 \quad (\text{Table VI, Item 4})$$

h. Calculate K for corresponding h values

$$K = \frac{3.41 \times 10^5 \times 9.52^3}{(60)^4} = 22.72 \quad (\text{Table VI, Item 5})$$

i. Plot h versus K values (Figure 15).

4. FLOTATION CAPABILITY OF RIGID PAVEMENT

To determine whether an aircraft can operate from a specific runway, find the K and h values for that runway and plot them on the h vs. K curve for the aircraft. If the runway curve falls below the aircraft curve, the field can be used by that aircraft for that number of operations. For example, a runway 7 inches thick, constructed on a K of 200, is adequate for 300 passes of the KC-135 aircraft, but is not adequate for 10,000 coverages (Figure 15).

SECTION IV

OVERLAY PAVEMENT CONSIDERATIONS

This section provides standard procedures for determining ground flotation characteristics of proposed aircraft in relation to overlay pavements, including the following:

- Rigid overlay over rigid pavement
- Flexible overlay over rigid pavement
- Rigid overlay over flexible pavement
- Flexible overlay over flexible pavement
- Sandwich construction, consisting of rigid-flexible-rigid pavement

These procedures provide the equivalent strength of the overlay pavement. When the equivalent strength is determined, these values must be applied to the equations for flexible or rigid pavement, as applicable.

1. RIGID OVERLAY OVER RIGID PAVEMENT

The equivalent strength for this case (from Reference 9) depends on whether or not a bonding process has been used between the base pavement and the overlay. If no bonding process is used, the equation is

$$h_E = \sqrt[1.4]{(h_o^{1.4}) + C(h_b^{1.4})} \qquad (12)$$

If a bonding process is used between the base pavement and the overlay, then the applicable equation is

$$h_E = \sqrt{(h_o^{2}) + C(h_b^{2})} \qquad (13)$$

where

h_E = equivalent thickness of rigid pavement

h_b = thickness of existing rigid pavement

h_o = overlay thickness

and C is a factor with a value of 1.00 if the base pavement is in good condition, 0.75 if it has initial but nonprogressive cracks, and 0.35 if it is badly cracked, with continuity interrupted.

The h_E and the K values can then be used to plot the pavement capability vs ground flotation capability of the aircraft (see Figure 15).

2. FLEXIBLE OVERLAY OVER RIGID PAVEMENT

The equation for determining the equivalent strength of a flexible pavement overlay over a rigid base pavement (based on Reference 9) is

$$h_E = \frac{1}{F}(0.4t + h_b) \qquad (14)$$

where

h_E = equivalent thickness of combined overlay and base

F = factor determined from Figure 16

t = thickness of flexible overlay

h_b = thickness of rigid base pavement

The h_E value can be used as total rigid pavement thickness together with the K value to plot pavement capability vs ground flotation capability (Figure 15).

3. RIGID OVERLAY OVER FLEXIBLE PAVEMENT

The equivalent strength of a rigid pavement overlay over a flexible pavement can be determined by equating the strength of the flexible pavement to a K value (Figure 16) and solving as for rigid pavement.

4. FLEXIBLE OVERLAY OVER FLEXIBLE PAVEMENT

The equivalent strength of a flexible pavement overlay over a flexible pavement is evaluated by determining the thickness of the thinnest section of the base pavement and adding this value to the thickness of the overlay. Then solve as for flexible pavement.

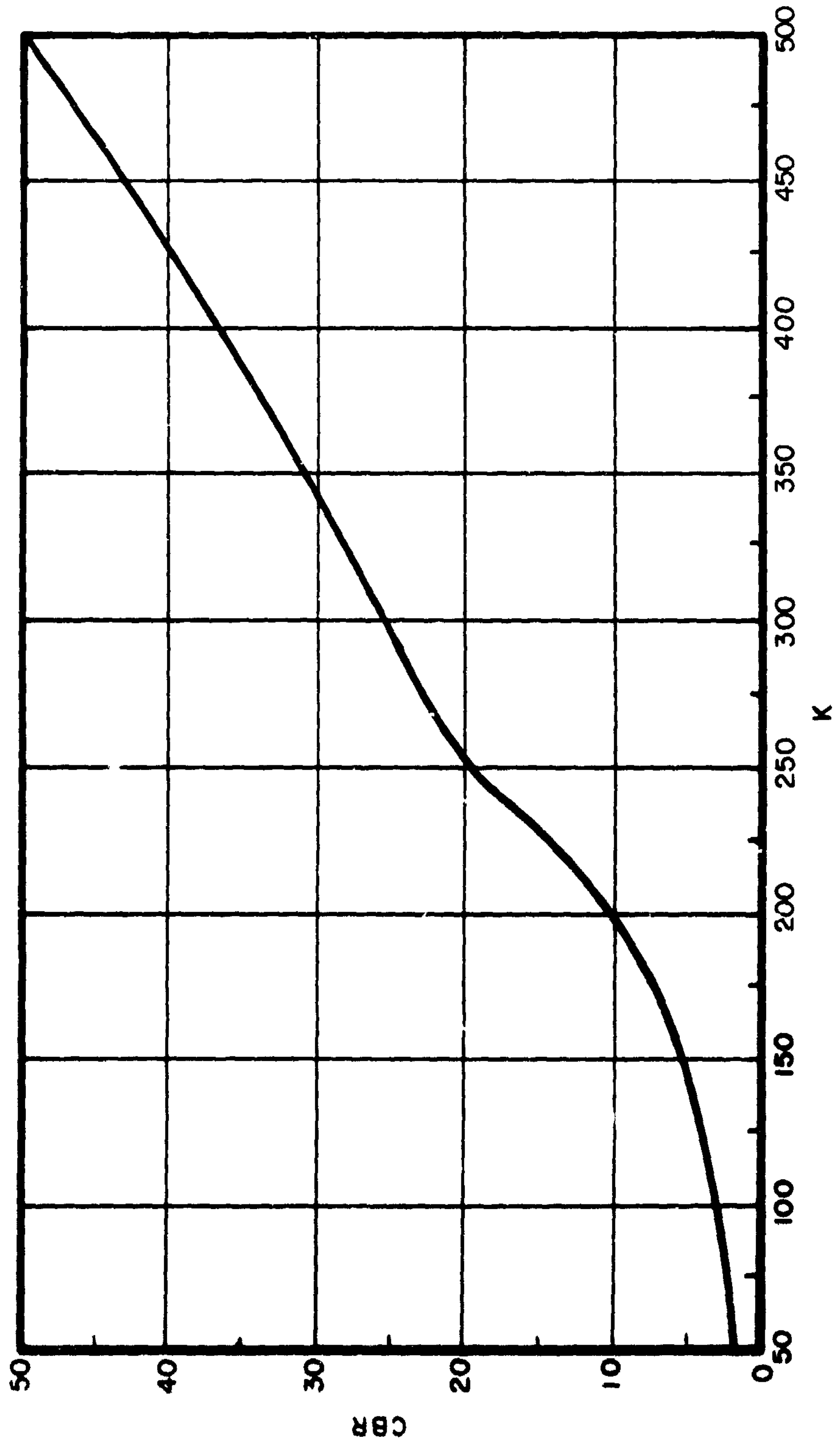


Figure 16. Conversion of K to CBR

5. SANDWICH CONSTRUCTION

For a rigid overlay over a flexible overlay over a rigid base pavement, use the following assumptions in making the determination.

a. If the flexible overlay is less than 4 inches thick, consider the structure to be a rigid overlay over a rigid pavement with a bonding agent.

b. If the flexible overlay is 4 inches or greater, consider the structure to be a rigid overlay over a flexible pavement, using the rigid base pavement and flexible overlay as a base course with a given K value.

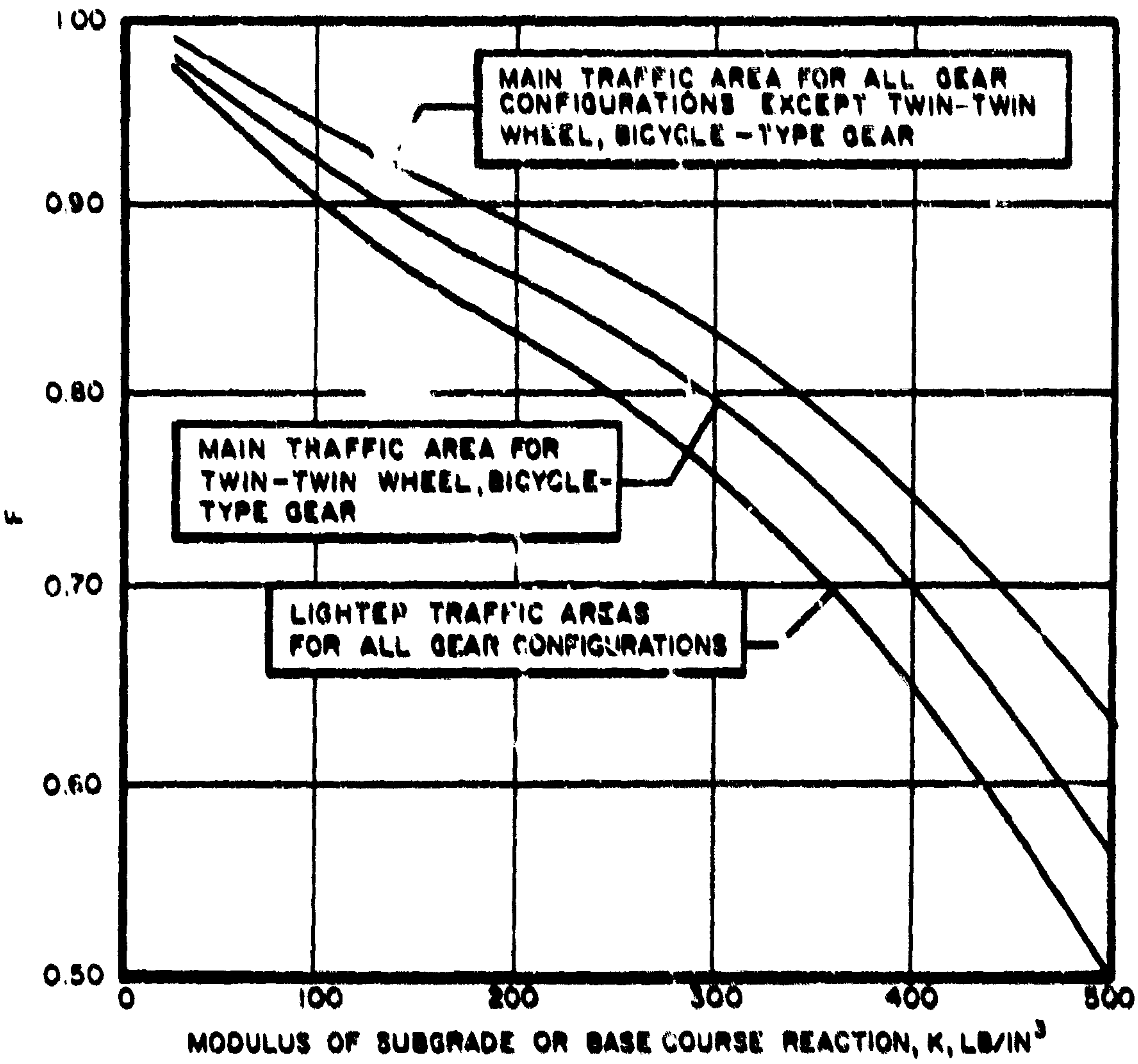


Figure 17. Criteria for Evaluating Overlay Pavements

APPENDIX I

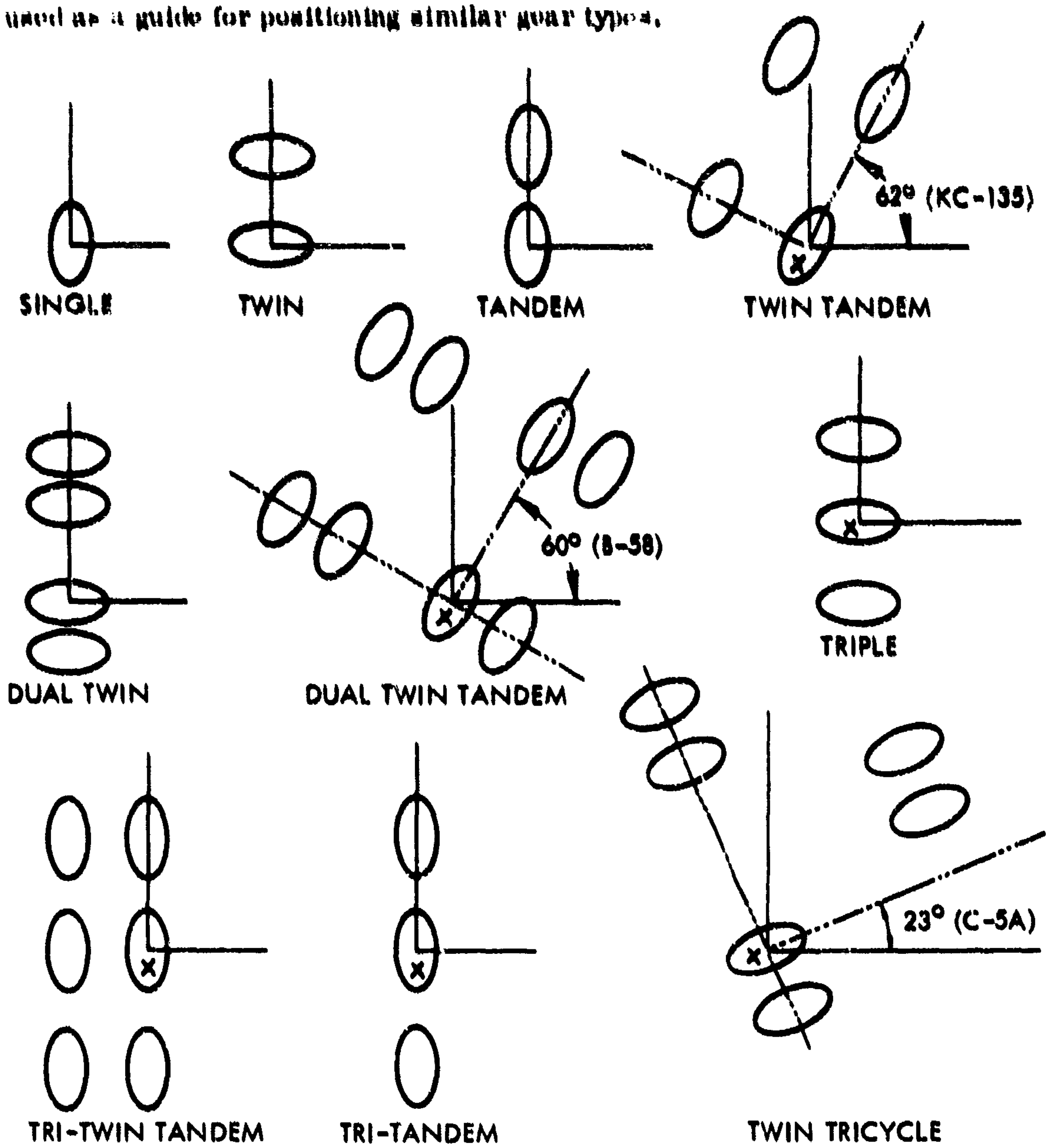
LANDING GEAR CONFIGURATIONS

LANDING GEAR CONFIGURATIONS

Ten landing gear concepts are depicted.

For flexible pavements, the X marked on a wheel indicates the critical wheel, which is the wheel used in the summation of principal movements.

For rigid pavements, the angular orientation is that required for maximum block count for the parenthetically noted aircraft (at ℓ = 50) and can be used as a guide for positioning similar gear types.



APPENDIX II

FORMULA DERIVATIONS

FORMULA DERIVATIONS

Equation 10

$$h = 0.0245 \sqrt{\frac{pnF}{s}}$$

is derived from formulas presented in Reference 6.

$$\text{Stress} = M_n \div \frac{h^2}{6}$$

where

$$M_n = \text{Moment at center of chart}$$

$$= \frac{p\ell^2 nF}{10{,}000}$$

(In Reference 6, q is used instead of p and N instead of n. The F has been added to account for the different types of traffic areas. See Reference 14.)

Substituting:

$$s = \frac{6p\ell^2 nF}{10{,}000\, h^2}$$

and

$$h = \sqrt{\frac{6p\ell^2 F}{10{,}000 s}} = 0.0245\ell \sqrt{\frac{pnF}{s}}$$

Equation 11

$$K = \frac{3.41 \times 10^5 \times h^3}{\ell^4}$$

is a transposition of the formula in Reference 6:

$$\ell = 24.1652 \sqrt[4]{\frac{h^3}{K}}$$

APPENDIX III

TABULATED DEFLECTION FACTOR VALUES

DEFLECTION FACTOR VALUES

Offset-Radii	Depth-Radii														
	0.	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.	11.	12.
0.	1.5000	1.3420	1.0600	0.8300	0.6700	0.4740	0.3640	0.2940	0.2470	0.2120	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.5	1.4000	1.2330	0.9830	0.7870	0.6440	0.4650	0.3580	0.2920	0.2440	0.2110	0.1860	[illegible]	[illegible]	[illegible]	[illegible]
1.0	0.9500	0.8860	0.7750	[illegible]	0.5750	0.4360	0.3440	0.2860	0.2400	[illegible]	[illegible]	0.1640	[illegible]	[illegible]	[illegible]
1.5	0.5330	0.5600	0.5620	[illegible]	0.4830	0.3940	0.3340	0.2730	0.2330	0.2040	0.1790	[illegible]	[illegible]	[illegible]	[illegible]
2.0	0.3900	0.3990	0.4150	0.4130	0.3970	0.3490	0.3000	0.2550	0.2230	0.1970	0.1750	[illegible]	[illegible]	[illegible]	[illegible]
2.5	0.3080	0.3100	0.3230	0.3300	0.3260	0.3020	0.2730	0.2390	0.2110	0.1890	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3.0	0.2540	0.2580	0.2670	0.2730	0.2730	0.2650	0.2450	0.2200	0.1990	0.1800	0.1630	[illegible]	[illegible]	[illegible]	[illegible]
3.5	0.2170	0.2200	0.2240	0.2310	0.2360	0.2330	0.2210	0.2050	0.1870	0.1720	0.1560	0.1440	[illegible]	[illegible]	[illegible]
4.0	0.1880	0.1910	0.1950	0.2000	0.2050	0.2070	0.2000	0.1890	0.1750	0.1620	0.1500	[illegible]	[illegible]	[illegible]	[illegible]
5.0	0.1510	0.1520	0.1540	0.1570	0.1590	0.1630	0.1630	0.1590	0.1530	0.1460	0.1370	[illegible]	[illegible]	[illegible]	[illegible]
6.0	0.1260	0.1270	0.1280	0.1290	0.1310	0.1350	0.1370	0.1360	0.1330	0.1290	0.1230	[illegible]	0.1110	[illegible]	[illegible]
7.0	0.1080	0.1090	0.1100	0.1110	0.1120	0.1150	0.1170	0.1170	0.1160	0.1140	0.1110	[illegible]	[illegible]	[illegible]	[illegible]
8.0	0.0930	0.0935	0.0940	0.0950	0.0960	0.0990	0.1010	0.1030	0.1030	0.1020	0.1000	[illegible]	0.0940	0.0920	[illegible]
9.0	0.0830	0.0830	0.0830	0.0840	0.0850	0.0870	0.0890	0.0910	0.0910	0.0910	0.0900	[illegible]	0.0870	0.0840	0.0820
10.0	0.0750	0.0750	0.0750	0.0756	0.0766	0.0774	0.0788	0.0802	[illegible]	0.0818	0.0816	0.0807	0.0794	0.0780	0.0765
12.0	0.0625	0.0626	0.0628	0.0631	0.0635	0.0644	0.0650	0.0663	0.0674	0.0681	0.0684	0.0685	0.0683	0.0676	0.0667
14.0	0.0535	0.0537	0.0538	0.0540	0.0543	0.0550	0.0558	0.0568	0.0576	0.0580	0.0584	0.0586	0.0586	0.0586	0.0582
16.0	0.0463	0.0464	0.0467	0.0470	0.0473	0.0477	0.0485	0.0490	[illegible]	0.0502	0.0507	0.0510	0.0512	[illegible]	0.0510
17.5	0.0418	0.0419	0.0421	0.0423	0.0426	0.0432	0.0438	0.0445	0.0452	0.0456	0.0460	0.0466	0.0469	0.0472	0.0475
18.0	0.0403	0.0404	0.0407	0.0409	0.0412	0.0417	0.0424	0.0431	0.0436	0.0440	0.0444	0.0451	0.0455	0.0459	0.0463
18.5	0.0388	0.0389	0.0396	0.0394	0.0397	0.0402	0.0409	0.0416	0.0421	0.0425	0.0429	0.0435	0.0441	0.0446	0.0451
19.0	0.0373	0.0374	0.0377	0.0379	0.0382	0.0387	0.0394	0.0401	0.0406	0.0410	0.0414	0.0421	0.0427	0.0433	0.0439
19.5	0.0358	0.0359	0.0362	0.0364	0.0367	0.0372	0.0379	0.0386	0.0391	0.0395	0.0399	0.0406	0.0413	0.0420	0.0427
20.0	0.0343	0.0344	0.0347	0.0349	0.0352	0.0357	0.0364	0.0371	0.0376	0.0380	0.0384	0.0391	0.0399	0.0407	0.0415

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13. ABSTRACT

This report describes standardized methods for analyzing ground flotation characteristics for aircraft of various designs based on the type of airfield construction. The method proposed for analyzing flexible pavements is an adaptation of the California Bearing Ratio (CBR) method. The analysis for rigid pavements is based on equations developed by Mr. H. M. Westergaard, Corps of Engineers, Ohio River Div Lab., and by the Portland Cement Association.

The methods described have been applied herein in an analysis of the KC-135 aircraft to illustrate the techniques. These methods can be applied to any aircraft to determine its flotation characteristics in relation to a given type runway.

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