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RIGID PAVEMENT DESIGN CHART CONSTRUCTION WITH LOCKHEED MODIFIED PCA PDILB COMPUTER PROGRAM

C. W. Foster

Lockheed-California Company
Burbank, California

1 September 1973

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TITLE

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PUBLICATION NO. LR 26049

DATE SEPT. 1, 1973

L-1011 TriStar

DOCUMENT SIGNATURE PAGE

AD 766915

PREPARED BY: C. W. Foster

C. W. FOSTER
DESIGN SPECIALIST

APPROVED BY: W. P. Ericksen

W. P. ERICKSEN
GROUP ENGINEER AIRPORT COMPATIBILITY

PRODUCT EVALUATION: Charles H Stoll

LEGAL: CAB for L. G. TURNER

20

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REVISIONS

REV NO.	DATE	REV. BY	PAGES AFFECTED	REMARKS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

RIGID PAVEMENT DESIGN CHART
CONSTRUCTION WITH LOCKHEED MODIFIED PCA
PDILB COMPUTER PROGRAM

There has been a need for a more descriptive explanation of concrete rigid pavement design charts as used in the Airplane Characteristics for Airport Planning document. Lockheed has made certain modifications to the published Portland Cement Association (PCA) computer program which assists us in preparation of the charts. This explanation will permit others to better understand the development and use of the charts for the design and evaluation of airfield pavements as well as of the use of the program for landing gear design.

Most systems of rigid pavement analysis used throughout the world are based on the Westergaard analysis and these procedures make the most use of computer technology to provide accurate and reliable tools for pavements/landing gear design and evaluation. The charts provided in the L-1011 Airplane Characteristics for Airport Planning (CER 12013) conform to the National Aerospace Standard (NAS 3601) format. This information will enhance the use of these pavement charts and should encourage a more wide-spread use and acceptance of these methods.

LOCKHEED MODIFIED COMPUTER PROGRAM AND DESIGN CHART CONSTRUCTION FOR RIGID PAVEMENTS

MODIFIED COMPUTER PROGRAM - PDILB

The Portland Cement Association (PCA) has developed the basic computer program. It is based on Westergaard's analysis for loads at the interior of a concrete slab supported by a dense liquid subgrade. The program has the same basis and applications as Pickett and Ray's Influence Chart No. 2. The PCA Special Report, "Computer Program for Airport Pavement Design", by Robert G. Packard provides details for this program including examples of both "input" and "output" for the following four operating modes:

Mode 1. Thickness Design. With given aircraft data, maximum stresses are tabulated for various pavement thicknesses within the proper design range. From this data, the designer may select the design thickness for the load and safety factors he has chosen.

Mode 2. Pavement Evaluation. For an existing pavement with known thickness and subgrade strength, the program gives the maximum stress for the specified aircraft load and landing gear configuration.

Mode 3. Data for Design Charts. This mode generates F (moment factor) values corresponding to a series of ℓ-values (radius of relative stiffness). These data are used to construct design charts for specific aircraft. Lockheed has extended Mode 3 to minimize the additional calculations required to construct the design charts. Details of this modification will be explained later.

Mode 4. General Analysis. This is a basic mode that does not maximize the moment with respect to the position of the landing gear. It is used for studies of the properties of the moment function as selected parameters are varied including the angle of rotation.

Lockheed has modified the Mode 3 portion of the program to provide data points for direct plotting of the curved subgrade K-lines as a function of a pavement parameter. The airplane weight lines are also plotted as a function of the same pavement parameter values. Since the computer program has the same basis as the Pickett and Ray's Influence Chart No. 2, the influence chart equations are used to derive the pavement parameter and stress coefficient relationship as follows:

No.	Equation	
(1)	$M_n = \text{MOMENT} = \frac{q\ell^2 N}{10,000}$	(Ref. 1 Equation 5A)
(2)	$S = \text{STRESS} = \frac{M_n}{h^2/6}$	(Ref. 1 Equation 6A)

Where: q = contact pressure, assumed equal to tire pressure p (psi)

ℓ = radius of relative stiffness (inches)

N = number of blocks, algebraic sum of all tires on one gear

h = concrete slab thickness (inches)

(3)	$F = \frac{\text{Bending moment}}{\text{Contact pressure}} = \frac{M_n}{q}$	(Reference 2)
(4)	Stress Coeff. $\frac{S}{q} = \frac{6F}{h^2} = \frac{6F}{D^2}$ = pavement parameter	

Where: D = h (D is computer symbol for slab thickness)

Equation (4) provides the parameters for the design chart abscissa scale.

The Lockheed modified rigid pavement computer program (PDILB 3196) uses the same inputs as the basic PCA program. The computations have been extended to include the pavement thickness D and pavement parameter $6F/D^2$. Pavement thickness is computed from the equation:

$$\ell = 24.1652 \sqrt[4]{D^3/K}$$ (Ref. 1 page 45)

The program uses selected values of ℓ and K, where K is the subgrade modulus in pounds per cubic inch (pci).

DESIGN CHART CONSTRUCTION

Two types of design charts used for design and evaluation of rigid pavement for a specific airplane are:

Constant Area Design Chart

This chart is based on varying the tire pressure as a function of airplane weight so that the tire deflection is equal to the tire rated deflection; therefore, the contact area remains constant for all operating weights. This chart permits maximum aircraft weight when limited by the allowable stress on an existing pavement. It also minimizes tire wear, but requires additional aircraft servicing to maintain the correct tire pressure.

To construct a "constant area" chart for a given airplane, a Mode 3 computer run is made. The inputs include the number of wheels and wheel coordinates for one landing gear, plus the single tire contact area. This contact area is computed by dividing the tire rated load by the rated pressure. An example of calculations for input data is provided in Appendix A. Table 1 shows a portion of the output data which is the same as the original basic PCA program. Table 2 shows a portion of the output data for the extended Mode 3 program. All examples are for the Lockheed L-1011-1 airplane so that each step of the procedure may be followed.

The "constant area" design chart is constructed with pavement thickness scale at the left side and concrete stress scale at the right side as the ordinates. The pavement parameter $6F/D^2$ and stress coefficient S/q are equal to each other and are used as a common scale for the abscissa shown in Figure 1. This figure shows the K 300 subgrade line only and is plotted from data points from Table 2 as a function of D versus $6F/D^2$.

Data points for the airplane load lines are computed as a function of the tire pressure required to maintain the contact area used for computing the pavement parameter $6F/D^2$. The calculations for the two load lines shown in Figure 2, for a contact area of 283 sq. inches, are provided below.

Load on MLG's L_M	Tire Pressure $p = L_M \div 8(283)$	Stress $S = p(S/q)$	
		$S/q = 2.0$	$S/q = 3.4$
(lbs)	(psi)	(psi)	(psi)
408,000	180.0	360.0	612.0
350,000	154.6	309.2	525.6

The stresses computed are then plotted as S versus S/q and establishes the load line.

Figure 2 shows a complete constant area design chart for the L-1011-1 as provided in Reference 3. The abscissa scale has been omitted since it is not required for normal use as indicated by the arrows for two examples. This is normally used for pavement evaluation where the airplane operating weight is limited by an existing pavement. The procedure and results of these two examples are as follows:

Example 1. Determine the stress level for maximum weight (408,000 lbs on MLG's) for 12 inches of pavement on a K 300 subgrade:

Enter thickness scale at 12 inches, proceed horizontally to K 300 curve, vertically to 408,000 lbs load line, then horizontally to stress scale and read 416 psi.

Example 2. Determine the maximum load on the main landing gears when limited by a 12.5 inch pavement on a K 200 subgrade and 400 psi stress:

A. Enter the thickness scale at 12.5 inches, proceed horizontally to the K 200 curve and draw a line vertically across the airplane load lines.

B. Enter the stress scale at 400 psi, and draw a line horizontally until it intersects the vertical line drawn in Step A.

C. Read the maximum gear load intersection of the lines drawn in Steps A and B (interpolating if necessary). Answer, 370,000 lbs.

Constant Pressure Design Chart

This chart is based on inflating the tires for maximum airplane weight and allowing the tire area to vary proportional to the weight on the main landing gears. This chart is usually used for pavement design since it considers the worst condition for any selected airplane weight. It may also be used for evaluation where the pavement strength is adequate for the operating weight required.

To construct the "constant pressure" chart for a given airplane, a Mode 3 computer run is made for each load line to be plotted. The contact area for each line is determined by dividing the single wheel load (SWL) by the tire pressure. Appendix A shows these calculations for the L-1011-1 airplane using 180 psi tire pressure for two selected weights. All other inputs to the computer are identical to those used for "constant area". Output for 242 sq. inch area is shown in Table 3.

The format and scales for the constant pressure chart are the same as for constant area, except that the stress coefficient S/q only applies to the contact area used to determine and plot the subgrade modulus K lines, therefore, the abscissa scale is identified as a pavement parameter only. It is customary to plot the K lines for the area corresponding to the maximum weight line. At this weight the area for the L-1011-1 is 283 sq. inches, so Table 2 is applicable for constructing the K lines. Figure 3 shows how the "constant pressure" chart is constructed. The single K 300 line is the same as for the "constant area".

The data points for plotting the airplane load lines are calculated for two selected values of ℓ, as a function of tire area and pressure. The calculations for the two load lines shown in Figure 4 for a constant pressure of 180 psi are provided below.

Load on MLG's L_M	Tire Area $A = L_M \div 8(180)$	Pav. Parameter $6F/D^2$ @ K 300		Stress $S = 180(6F/D^2)$	
		$\ell = 30$	$\ell = 40$	$\ell = 30$	$\ell = 40$
(lbs)	(sq. in.)			(psi)	(psi)
408,000	283 (Table 2)	3.3559	2.0697	604.1	372.5
350,000	242 (Table 3)	2.9963	1.8289	539.3	329.2

To plot the load lines, vertical lines are drawn through the points on the K 300 line corresponding to the selected ℓ values. The two points for each load line are then located on these vertical lines opposite the corresponding computed stress values.

Figure 4 shows a complete constant pressure design chart for the L-1011-1 as provided in Reference 3. The abscissa scale has been omitted since it is not required for normal use as indicated by the examples. Since all load lines are constructed from the K 300 line, all values are accurate for K 300 but deviate slightly for other values of K. The values obtained using the maximum load line are exact for all values of K since the K lines were plotted for the pavement parameter computed for the same tire contact area as the maximum load line.

The examples shown in Figure 4 and procedures are the same as described for Figure 2. The results of these examples are shown in Table 4. This shows that for example 2, the A.U.W. is increased 10,500 pounds by tire inflation to 164 psi to maintain a constant area.

LR 26049

RIGID PAVEMENT DESIGN

TABLE 1

UNITS POUNDS INCHES DEGREES

AIRCRAFT	GEAR	NO. OF WHLS.	CONTACT AREA
L-1011	MAIN	4	283.00

COORDINATES OF WHLS.

NO.	X	Y
1	0.0	0.0
2	0.0	52.00
3	70.00	0.0
4	70.00	52.00

MODE
3

RAD. REL. STIFF. 20.00

WHL. NO.	1	F	33.4352	CODE	0	COUNT	835.9
WHL. NO.	2	F	1.5678	CODE	0	COUNT	39.2
WHL. NO.	3	F	0.0	CODE	2	COUNT	0.0
WHL. NO.	4	F	0.0	CODE	2	COUNT	0.0
	TOTAL	F	35.0030		TOTAL	COUNT	875.1

XMAX 0.0 YMAX -0.7 MAX. ANGLE 0.0

RAD. REL. STIFF. 25.00

WHL. NO.	1	F	38.7481	CODE	0	COUNT	620.0
WHL. NO.	2	F	3.6369	CODE	0	COUNT	58.2
WHL. NO.	3	F	-3.4575	CODE	1	COUNT	-55.3
WHL. NO.	4	F	0.0	CODE	2	COUNT	0.0
	TOTAL	F	38.9275		TOTAL	COUNT	622.8

XMAX 1.0 YMAX -1.2 MAX. ANGLE 0.0

RAD. REL. STIFF. 30.00

WHL. NO.	1	F	46.2570	CODE	0	COUNT	514.0
WHL. NO.	2	F	-2.3175	CODE	0	COUNT	-25.8
WHL. NO.	3	F	0.0179	CODE	0	COUNT	0.2
WHL. NO.	4	F	0.6652	CODE	1	COUNT	7.4
	TOTAL	F	44.6225		TOTAL	COUNT	495.8

XMAX 0.2 YMAX -0.2 MAX. ANGLE 57.2

RAD. REL. STIFF. 35.00

WHL. NO.	1	F	50.1535	CODE	0	COUNT	409.4
WHL. NO.	2	F	-0.9941	CODE	0	COUNT	-8.1
WHL. NO.	3	F	0.9551	CODE	0	COUNT	7.8
WHL. NO.	4	F	1.8358	CODE	0	COUNT	15.0
	TOTAL	F	51.9504		TOTAL	COUNT	424.1

XMAX 0.1 YMAX -0.3 MAX. ANGLE 56.9

LR 26049

CONTACT AREA
283.00

TABLE 2

K	THICKNESS D	RADIUS L	F	6F/D**2
50.0	2.86	20.0	35.0030	25.6274
	3.85	25.0	38.9275	15.7191
	4.92	30.0	44.6225	11.0810
	6.04	35.0	51.9504	8.5524
	7.21	40.0	59.2688	6.8341
	8.44	45.0	66.5721	5.6071
	9.71	50.0	73.7321	4.6890
	11.03	55.0	80.6760	3.9792
	12.39	60.0	87.3656	3.4168
	13.78	65.0	93.7881	2.9630
	15.21	70.0	99.9407	2.5912
	16.68	75.0	105.8307	2.2828
	18.18	80.0	111.4694	2.0242
	19.71	85.0	116.8672	1.8055
	21.27	90.0	122.0393	1.6188
100.0	3.61	20.0	35.0030	16.1442
	4.86	25.0	38.9275	9.9024
	6.19	30.0	44.6225	6.9806
	7.61	35.0	51.9504	5.3877
	9.09	40.0	59.2688	4.3052
	10.63	45.0	66.5721	3.5322
	12.24	50.0	73.7321	2.9539
	13.90	55.0	80.6760	2.5067
	15.61	60.0	87.3656	2.1524
	17.36	65.0	93.7881	1.8665
	19.17	70.0	99.9407	1.6323
	21.01	75.0	105.8307	1.4381
	22.90	80.0	111.4694	1.2752
	24.83	85.0	116.8672	1.1374
	26.80	90.0	122.0393	1.0198
200.0	4.54	20.0	35.0030	10.1702
	6.12	25.0	38.9275	6.2381
	7.80	30.0	44.6225	4.3975
	9.58	35.0	51.9504	3.3940
	11.45	40.0	59.2688	2.7121
	13.40	45.0	66.5721	2.2252
	15.42	50.0	73.7321	1.8608
	17.51	55.0	80.6760	1.5791
	19.66	60.0	87.3656	1.3560
	21.88	65.0	93.7881	1.1759
	24.15	70.0	99.9407	1.0283
	26.48	75.0	105.8307	0.9059
	28.85	80.0	111.4694	0.8033
	31.28	85.0	116.8672	0.7165
	33.76	90.0	122.0393	0.6424
300.0	5.20	20.0	35.0030	7.7613
	7.00	25.0	38.9275	4.7606
POINTS USED IN FIG. 1 & 3	8.93	30.0	44.6225	3.3559
	10.97	35.0	51.9504	2.5901
	13.11	40.0	59.2688	2.0697
	15.34	45.0	66.5721	1.6981

CONTACT AREA
242.00

TABLE 3

	K	THICKNESS D	RADIUS L	F	6F/D**2
	50.0	2.86	20.0	31.5838	23.1240
		3.85	25.0	34.8900	14.0888
		4.92	30.0	39.8392	9.8931
		6.04	35.0	46.1104	7.5910
		7.21	40.0	52.3722	6.0388
		8.44	45.0	58.6183	4.9372
		9.71	50.0	64.7404	4.1172
		11.03	55.0	70.6761	3.4859
		12.39	60.0	76.3951	2.9877
		13.78	65.0	81.8845	2.5869
		15.21	70.0	87.1447	2.2594
		16.68	75.0	92.1797	1.9883
		18.18	80.0	96.9982	1.7615
		19.71	85.0	101.6127	1.5698
		21.27	90.0	106.0342	1.4065
	100.0	3.61	20.0	31.5838	14.5672
		4.86	25.0	34.8900	8.8754
		6.19	30.0	39.8392	6.2323
		7.61	35.0	46.1104	4.7820
		9.09	40.0	52.3722	3.8042
		10.63	45.0	58.6183	3.1102
		12.24	50.0	64.7404	2.5937
		13.90	55.0	70.6761	2.1960
		15.61	60.0	76.3951	1.8822
		17.36	65.0	81.8845	1.6296
		19.17	70.0	87.1447	1.4233
		21.01	75.0	92.1797	1.2526
		22.90	80.0	96.9982	1.1096
		24.83	85.0	101.6127	0.9889
		26.80	90.0	106.0342	0.8861
	200.0	4.54	20.0	31.5838	9.1768
		6.12	25.0	34.8900	5.5911
		7.80	30.0	39.8392	3.9261
		9.58	35.0	46.1104	3.0125
		11.45	40.0	52.3722	2.3955
		13.40	45.0	58.6183	1.9593
		15.42	50.0	64.7404	1.6339
		17.51	55.0	70.6761	1.3834
		19.66	60.0	76.3951	1.1857
		21.88	65.0	81.8845	1.0266
		24.15	70.0	87.1447	0.8966
		26.48	75.0	92.1797	0.7891
		28.85	80.0	96.9982	0.6990
		31.28	85.0	101.6127	0.6230
		33.76	90.0	106.0342	0.5582
	300.0	5.20	20.0	31.5838	7.0032
		7.00	25.0	34.8900	4.2668
DATA USED →		8.93	30.0	39.8392	2.9962
FOR 350,000		10.97	35.0	46.1104	2.2999
LB LOAD LINE →		13.11	40.0	52.3722	1.8289
		15.34	45.0	58.6183	1.4952

TABLE 4

	Example 1		Example 2	
Figure No.	2	4	2	4
Constant	Area	Press.	Area	Press.
Tire pressure, psi	180	180	164	180
Contact area, sq. in.	283	283	283	250
Pavement thickness, in.	12	12	12.5	12.5
Subgrade modulus K. pci	300	300	200	200
Concrete stress, psi	416	416	400	400
Wt. on MLG's, lbs	408,000	408,000	370,000	360,000
A.U.W.*, lbs	432,000	432,000	391,500	381,000

*Based on 94.5% carried on MLG's. Typical operation applies only 92.5% A.U.W. on MLG's, and would permit an A.U.W. of 400,000 lbs for example 2, constant area.

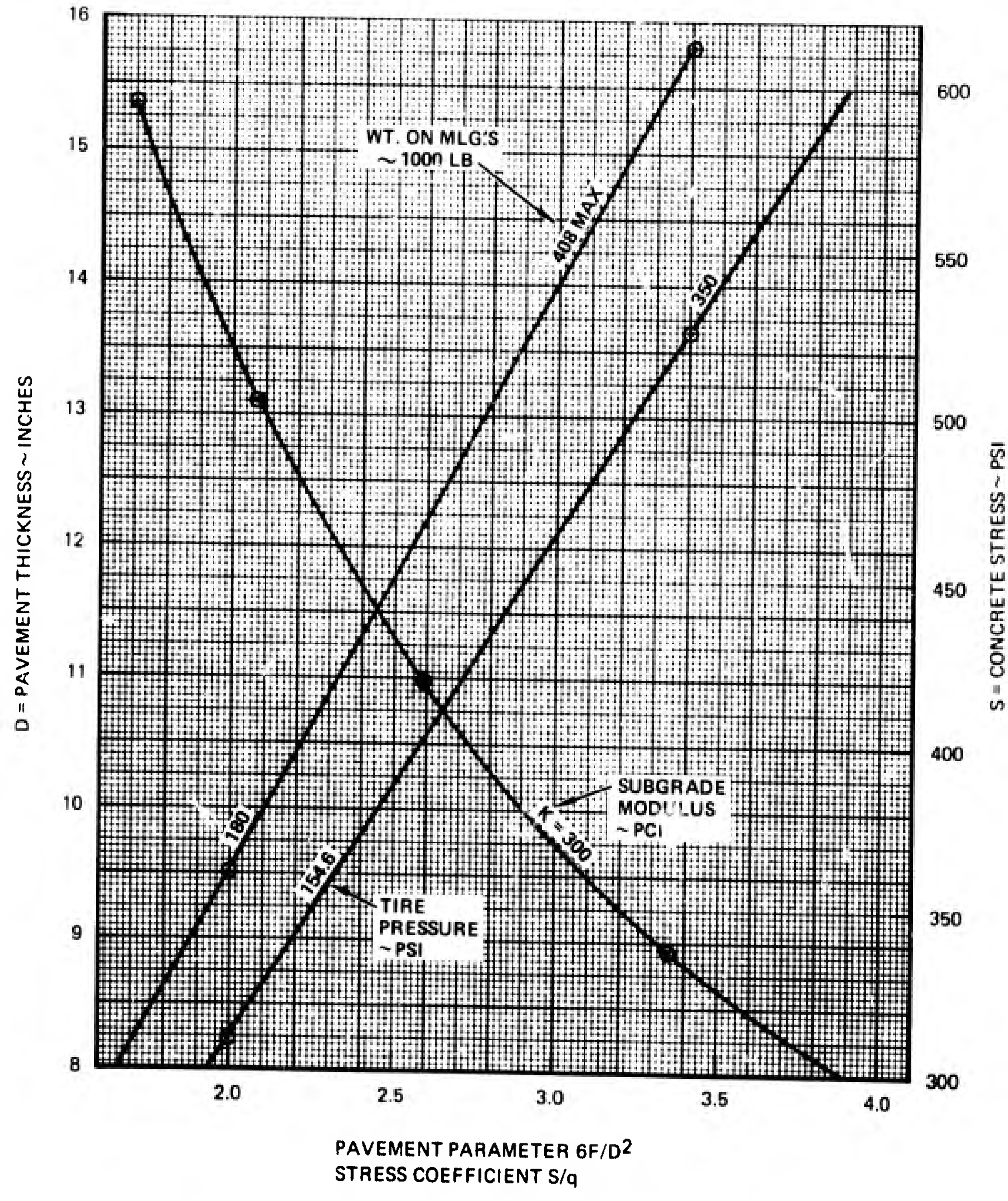
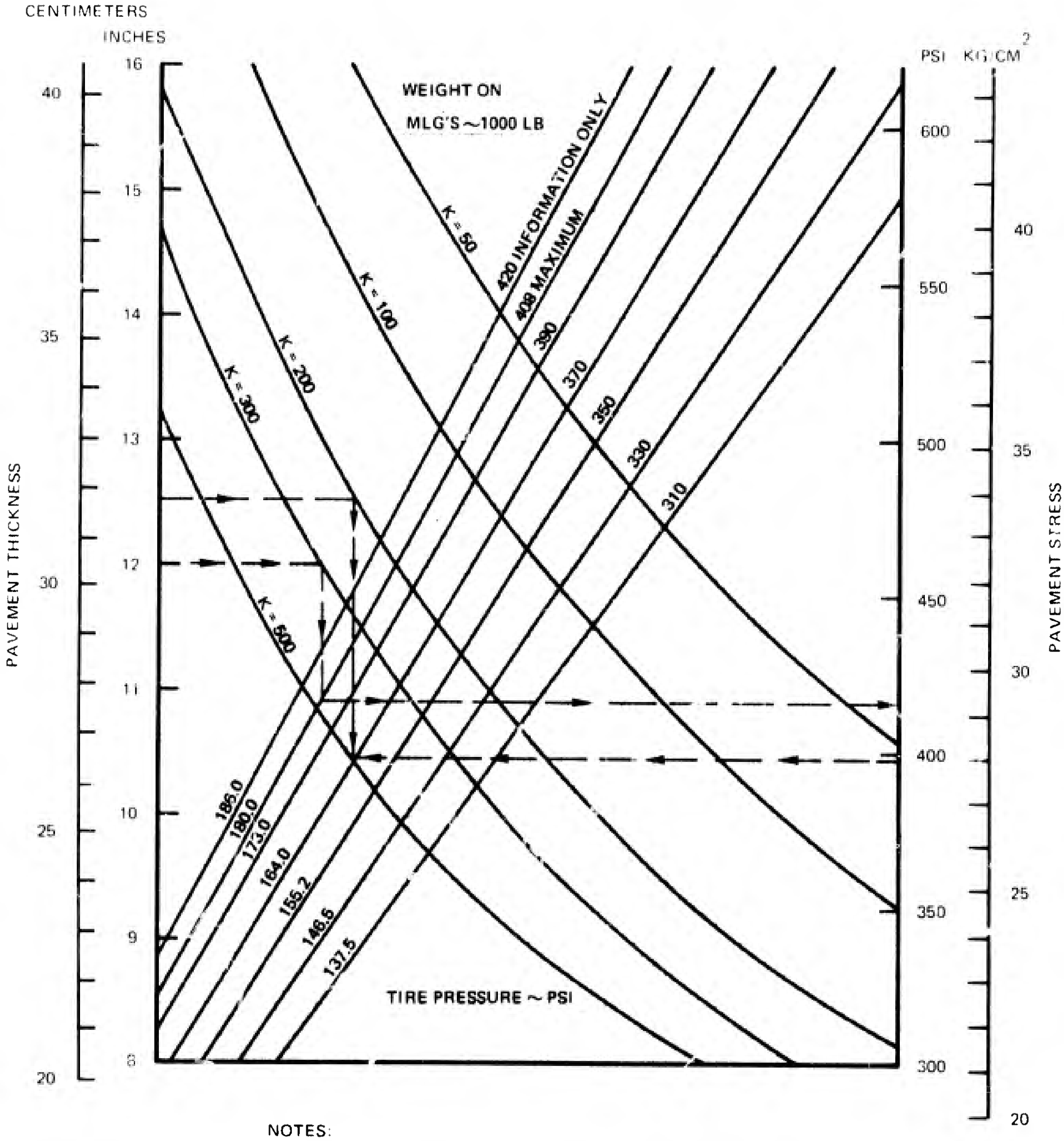


FIGURE 1. L-1011-1 CONSTANT AREA DESIGN CHART CONTACT AREA = 283 IN^2

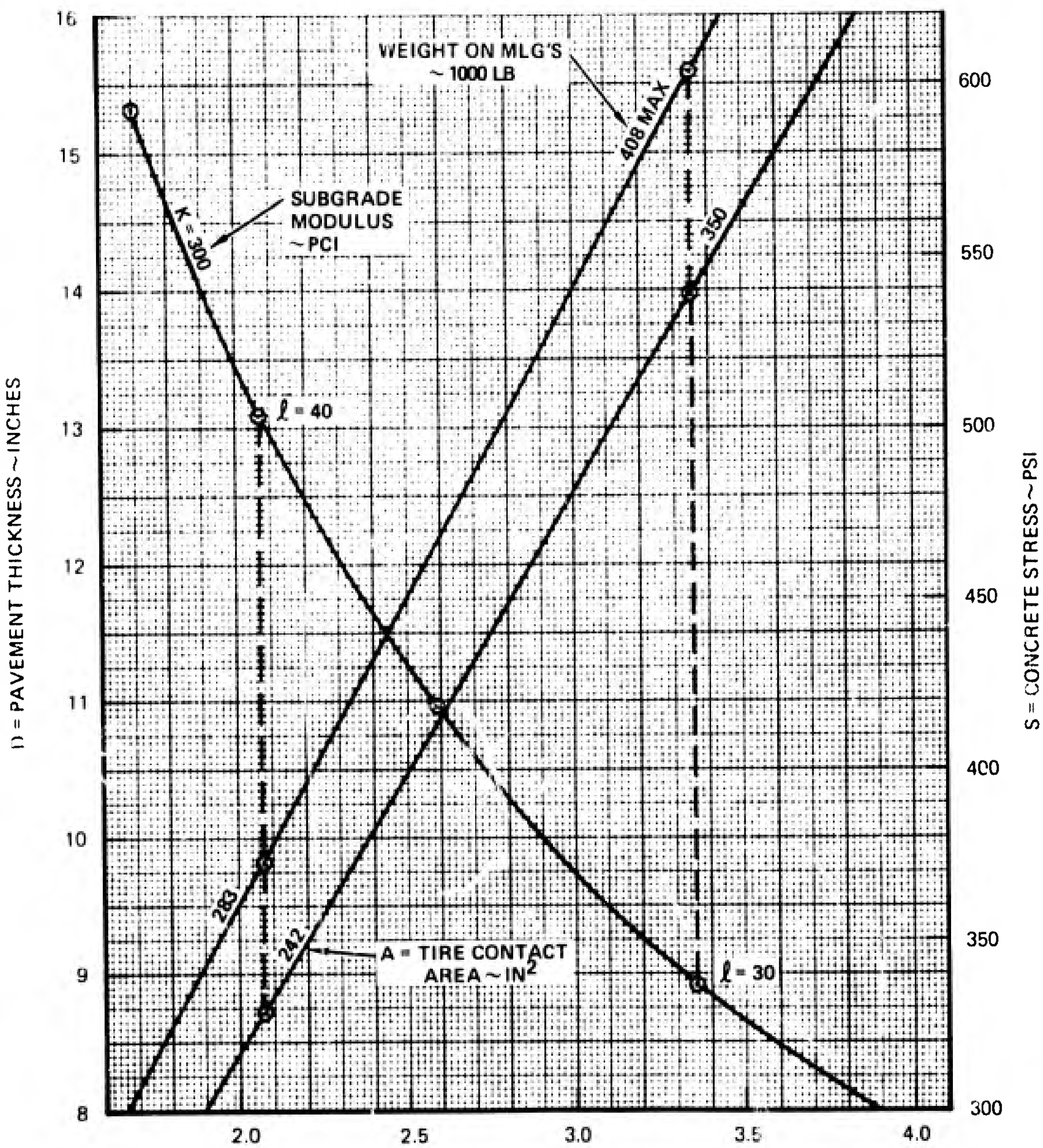


NOTES:

1. TIRE AREA CONSTANT, **283 SQ.** IN., 50 X 20.0 - 20
2. PCA COMPUTER PROGRAM PDILB
3. VALUES OBTAINED USING ANY LOAD LINE AND ANY K LINE ARE EXACT.

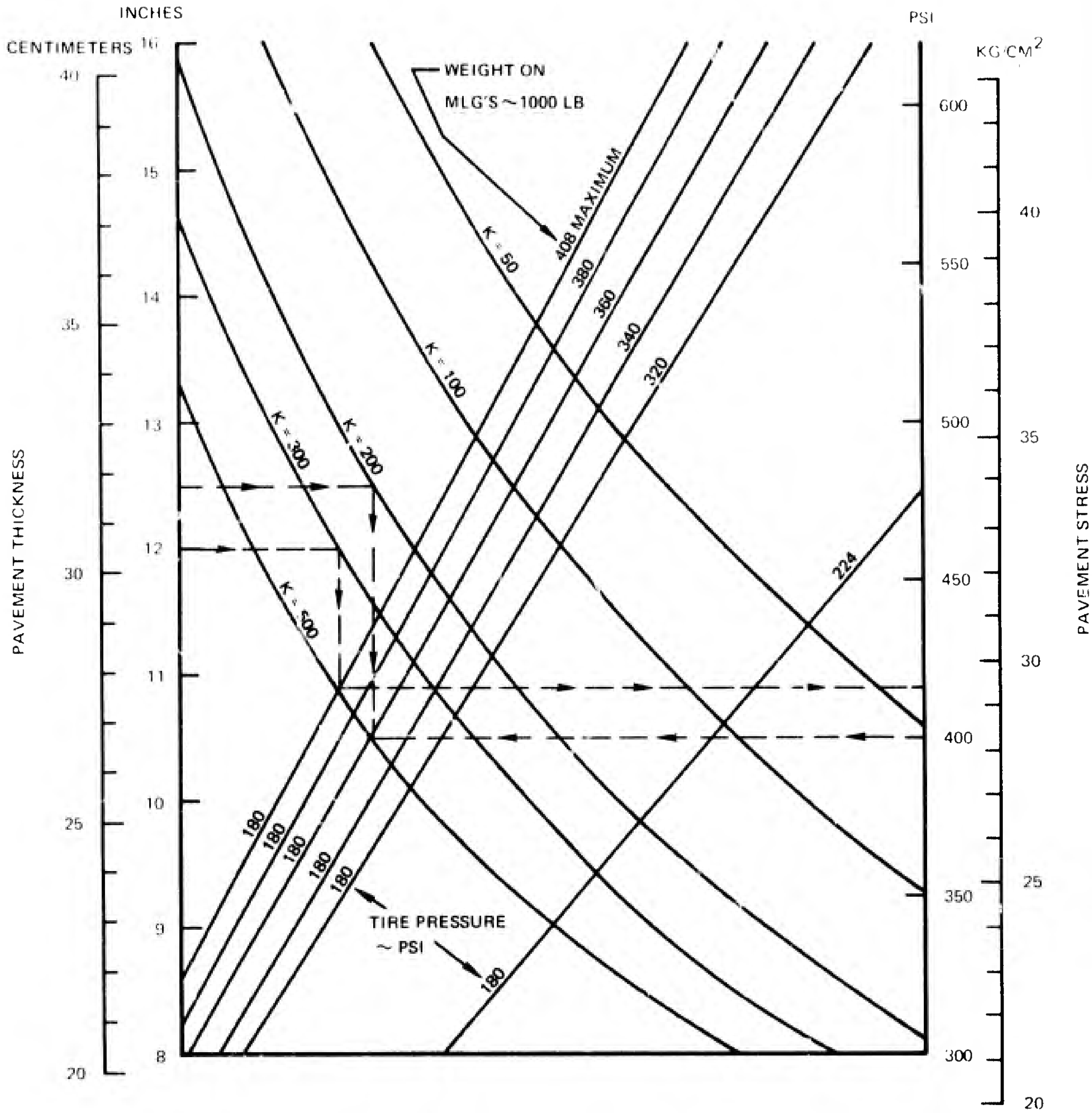
REF: "DESIGN OF CONCRETE AIRPORT PAVEMENTS" PORTLAND CEMENT ASSOCIATION (PCA)

FIGURE 2 RIGID PAVEMENT REQUIREMENTS, PCA METHOD, CONSTANT TIRE AREA MODEL L-1011-385-1



PAVEMENT PARAMETER = $6F/D^2$ @ A = 283

FIGURE 3 L-1011-1 CONSTANT PRESSURE CHART
TIRE PRESSURE = 180 PSI



NOTES

1. TIRE PRESSURE CONSTANT 180 PSI
2. PCA COMPUTER PROGRAM PDILB
3. VALUES OBTAINED BY USING THE MAXIMUM LOAD LINE AND ANY VALUE OF K ARE EXACT. FOR LOADS LESS THAN MAX, RESULTS ARE ACCURATE FOR K300 BUT DEVIATE SLIGHTLY FOR OTHER VALUES OF K.

REF. "DESIGN OF CONCRETE AIRPORT PAVEMENTS" PORTLAND CEMENT ASSOCIATION (PCA)

FIGURE 4 RIGID PAVEMENT REQUIREMENTS, PCA METHOD, CONSTANT TIRE PRESSURE MODEL L-1011-385-1

REFERENCES

1. Design of Concrete Pavement, Portland Cement Association, 1955.

2. Operating Instructions - Computer Program for Concrete Airport Pavement Design, Program PD1LB (July 1968), Portland Cement Association, Skokie Illinois

3. L-1011-1 Airplane Characteristics, CER 12013 (Rev. April 1972) Lockheed California Company Burbank, California

APPENDIX A

L-1011-1 LANDING GEAR DATA

MAXIMUM RAMP WEIGHT = W = 432,000 lb

L_M = Load on MLG's (Aft cg) = 0.945W = 408,000 lb max.

Tire Data: 50 x 20 - 20 32 ply rating

L_R = rated tire load = 53,800 lb

P_R = rated tire pressure = 190 psi

$A = \frac{L_R}{P_R}$ = Indicated contact area at rated deflection (32%) = 283 sq. in.

Wheel Arrangement: Twin tandem, spaced 52 x 70

n = Number of wheels on one main gear = 4

SWL = Single Wheel Load = $L_M/2n$ = 51,000 lb max.

P_{max} = Maximum Tire Pressure = $\frac{SWL}{A}$ = 180 psi

REDUCED OPERATING WEIGHT = W_O

W_O = 380,000 lbs. (selected for example)

L_M = Load on MLG's (Mid cg) = 0.92 W_O = 350,000 lb

SWL = Single Wheel Load = $L_M/2n$ = 43,750 lb

P = Tire Pressure = $\frac{SWL}{A}$ = 154.6 psi (minimum)

P_{max} = Maximum Tire Pressure = 180 psi

A = Tire contact area at P_{max} = $\frac{SWL}{P_{max}}$ = 242 sq. in.