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ECONOMIC IMPLICATIONS OF A UNITED STATES SUPERSONIC TRANSPORT AIRCRAFT UPON AIRPORTS AND ENROUTE SUPPORT SERVICES

Volume IV

Airport Pavement Requirements for Large Commercial Aircraft

PRC R-890

31 December 1966

Prepared for

Economics Staff
Office of Supersonic Transport Development
Federal Aviation Agency

PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIFORNIA WASHINGTON, D.C.

[redacted]

ECONOMIC IMPLICATIONS OF A UNITED STATES SUPERSONIC TRANSPORT AIRCRAFT UPON AIRPORTS AND ENROUTE SUPPORT SERVICES

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AIRPORT PAVEMENT REQUIREMENTS FOR LARGE COMMERCIAL AIRCRAFT

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ABSTRACT

Complementing the three-volume analysis of the potential economic impact of a United States SST upon airports and enroute support services, Volume IV examines airport pavement requirements for large commercial aircraft: Boeing models 707-320, 747, 2707; Lockheed models L-500 and L-2000; Douglas models DC-8-55 and DC-8-63; and the Anglo-French SST, Concorde.

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The rapid growth of commercial aviation has brought about many technological changes in transport aircraft. These changes have included large increases in range, speed, and aircraft size. However, since ranges have become adequate for most operations and speed capability has surpassed the speed of sound, the outlook for future technological changes to a great extent concerns increases in aircraft size. Even in the case of the supersonic transport in which a three-fold speed increase is planned, the increase in size is also very important. The weights predicted for transport aircraft about 1980 are in some cases as much as three times that of today's heaviest commercial airplanes. The technological feasibility of such forecasts has brought about realization of the need for studies concerning the stress capabilities of pavements at major airports in relation to the exceptional loads which may be imposed upon them. The necessity for extensive research concerning landing gear flotation characteristics has been recognized and the majority of aircraft manufacturers have already performed some research in this area.

Investigation of the methods used to compare pavement strength and the potential load to be imposed by specific aircraft reveals considerable confusion. Therefore, before a recommendation for the use of a specific methodology can be made, it is necessary to summarize and compare the several accepted methods for performing these calculations.

1. Survey of Pavement Analysis Methodologies

The various methodologies for calculating pavement stress and thickness requirements can be divided into two areas, according to the two main groupings of pavement types. These types are: flexible pavement, which is defined as a mixture of bituminous material and aggregate overlaid on one or more base and subbase courses of high-quality granular material, and rigid pavement or concrete, which may or may not include an underlying subbase course. In the discussion of flexible pavement which follows, the method of determining stress and required pavement thickness which is endorsed by the Federal Aviation Agency will be treated first. An approach developed by the U.S. Army Corps of Engineers will then be summarized, and the U.S. Air Force (SEFL) method which was used for flotation analyses of the military C-5A will be described. The pioneer work of Dr. H.M. Westergaard and Dr. Gerald Pickett on rigid pavement analysis will be summarized and an explanation of the adaptations of their work by the FAA and by the Portland Cement Association will be presented. The Load Classification Number (LCN) method which is used in the British Isles will also be mentioned.

a. Flexible Pavement Analysis

(1) FAA Method of Calculating Pavement Stress

The Federal Aviation Agency advisory circular AC150/5320-6 entitled Airport Paving, which was published in June 1964, sets forth the basic concepts involved in the FAA method of calculating pavement stress and required thickness. The determination of soil characteristics and their evaluation and classification are central to this method. Exhibit 1 presents the classification of soils recommended by the FAA. It is noted that this classification not only includes an indication of the relative coarseness of the samples, but also includes the liquidity and plasticity factors. The total of these three factors is represented by an E number which ranges from E-1 through E-13. When combined with factors for drainage and frost as shown in Exhibit 2, the E numbers can be translated into F numbers (or R numbers for rigid pavement). It is evident that a sample of a particular soil group may fall in one of several subgrade classes. For example, soils of the E-5 group may be classed as F-1 subgrade

EXHIBIT 1 - CLASSIFICATION OF SOILS FOR AIRPORT PAVEMENT CONSTRUCTION

Soil Group	Mechanical Analysis				Liquid Limit	Plasticity Index
	Material Retained on No. 10 Sieve (percent)[1]	Material Finer Than No. 10 Sieve (percent)				
		Coarse Sand, Passing No. 10; Retained on No. 60	Fine Sand, Passing No. 60; Retained on No. 270	Combined Silt and Clay; Passing No. 270		
Granular						
E-1	0-45	40+	60-	15-	25-	6-
E-2	0-45	15+	85-	25-	25-	6-
E-3	0-45	--	--	25-	25-	6-
E-4	0-45	--	--	35-	35-	10-
E-5	0-45	--	--	45-	40-	15-
Fine-Grained						
E-6	0-55	--	--	45+	40-	10-
E-7	0-55	--	--	45+	50-	10-30
E-8	0-55	--	--	45+	60-	15-40
E-9	0-55	--	--	45+	40+	30-
E-10	0-55	--	--	45+	70-	20-50
E-11	0-55	--	--	45+	80-	30+
E-12	0-55	--	--	45+	80+	--
E-13		Muck and peat--field examination				

Note: (1) If percentage of material retained on the No. 10 sieve exceeds that shown, the classification may be raised, provided such material is sound and fairly well graded.

Source: (a) Federal Aviation Agency, Advisory Circular AC 150/5320-6, Airport Paving, 10 June 1964, p. 10

for good drainage and no frost, F-2 for good drainage and severe frost, F-3 for poor drainage and no frost, and F-4 for poor drainage and severe frost.

After the subgrade classification has been determined, other factors such as the magnitude and character of the aircraft loads to be supported, the volume of traffic, the concentration of traffic in certain areas, and the landing gear geometry and dimensions must be considered. Determination of pavement thickness requirements is not an exact science. Solutions must be based on theory, analytical experiments, and performance of pavements under actual service. The FAA method has been developed from a correlation of the data obtained from all three sources.

The FAA assumes that 5 percent of the gross weight of the aircraft is supported by the nose wheel and the remaining 95 percent is distributed equally between two main undercarriage assemblies. These assemblies may take the form of single-wheel, dual-wheel, and dual-tandem arrangements. For each of these configurations, the FAA has developed design curves, a sample of which (for the dual-tandem configuration) is shown in Exhibit 3. The F curves on the chart are taken as given, and the landing gear characteristics and load are superimposed over them. Exhibit 4 indicates the two major measurements used in superimposing these characteristics. They are d, defined as the distance between the inner faces of two dual tires, and S (or S_D in the case of dual-tandem gear), which represents the distance between the center lines of dual tires. (This is the diagonal distance between one front tire and the opposite rear tire for dual-tandem gear.) The depth $d/2$ and the single-wheel load (gear loading divided by the number of tires) for three representative aircraft of 50,000, 100,000, and 200,000 pounds are used to establish line a in Exhibit 3 and the depth $2S_D$ and total gear load are used to establish line b. Exhibit 5 presents the result of the conversion of data in Exhibit 3 from the single-wheel load concept to gross aircraft weight in thousands of pounds, which is used on the vertical axis. This is made possible by the gear dimension assumptions used in preparing the design chart.

EXHIBIT 2 - AIRPORT PAVING SUBGRADE CLASSIFICATION

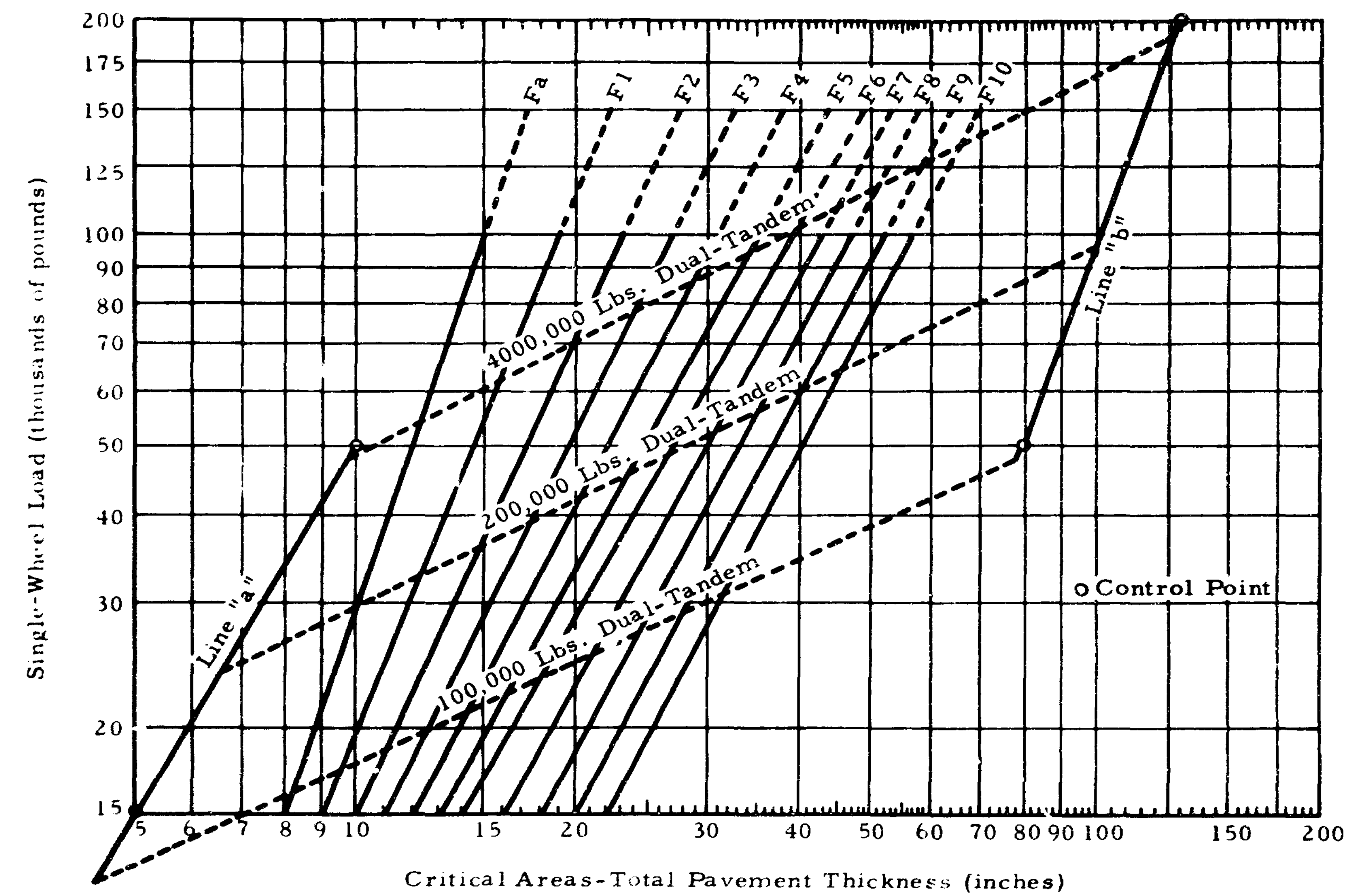
Soil Group	Subgrade Class			
	Good Drainage		Poor Drainage	
	No Frost	Severe Frost	No Frost	Severe Frost
E-1	Fa or Ra	Fa or Ra	Fa or Ra	Fa or Ra
E-2	Fa or Ra	Fa or Ra	F1 or Ra	F2 or Ra
E-3	F1 or Ra	F1 or Ra	F2 or Ra	F2 or Ra
E-4	F1 or Ra	F1 or Ra	F2 or Rb	F3 or Rb
E-5	F1 or Ra	F2 or Rb	F3 or Rb	F4 or Rb
E-6	F2 or Rb	F3 or Rb	F4 or Rb	F5 or Rc
E-7	F3 or Rb	F4 or Rb	F5 or Rb	F6 or Rc
E-8	F4 or Rb	F5 or Rc	F6 or Rc	F7 or Rd
E-9	F5 or Rc	F6 or Rc	F7 or Rc	F8 or Rd
E-10	F5 or Rc	F6 or Rc	F7 or Rc	F8 or Rd
E-11	F6 or Rd	F7 or Rd	F8 or Rd	F9 or Re
E-12	F7 or Rd	F8 or Re	F9 or Re	F10 or Re
E-13	Not suitable for subgrade			

Source (a): Federal Aviation Agency, Advisory Circular AC 150/5320-6, Airport Paving, 10 June 1964, p. 15

As an example of the use of these charts, assume a soil classification of E-8, good drainage and severe frost. From the table above, the subgrade classification would be F-5. The pavement thickness requirement in critical areas[1] is determined by the following procedures.

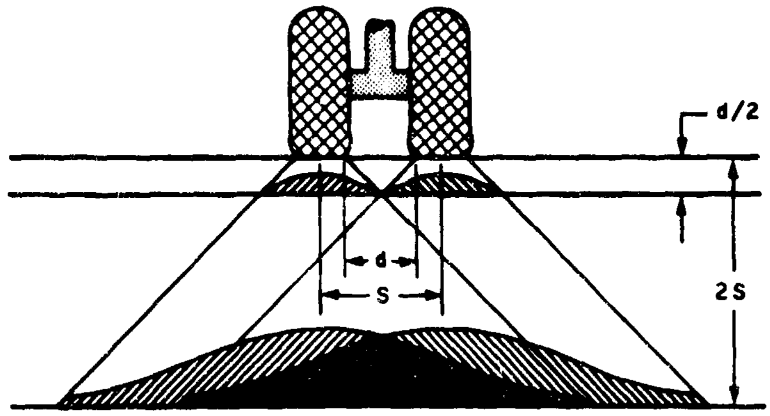
Assume that the aircraft for which the pavement is being designed has a maximum gross weight of 320,000 lbs. Entering Exhibit 3 from the vertical axis, proceed horizontally to the intersection with the subgrade classification F-5, and then vertically to the critical pavement thickness scale. The conclusion is that such an aircraft would require approximately 30 inches of flexible pavement.

[1] Center portions of runways on which aircraft are usually in varying stages of liftoff are not considered critical.

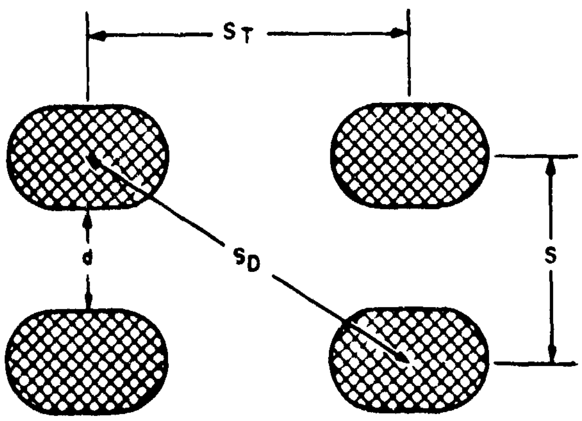


Source: (a) Federal Aviation Agency, Advisory Circular, AC 150/5320-6, Airport Paving, 10 June 1964, Appendix 1, p. 8

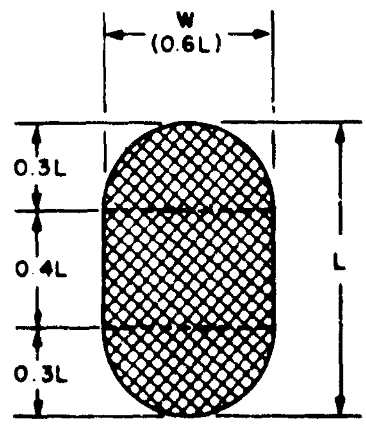
EXHIBIT 3 - DEVELOPMENT OF FLEXIBLE PAVEMENT CURVES, DUAL-TANDEM GEAR



DISTRIBUTION OF WHEEL LOADS THROUGH FLEXIBLE PAVEMENTS



DUAL TANDEM GEAR TIRE IMPRINT

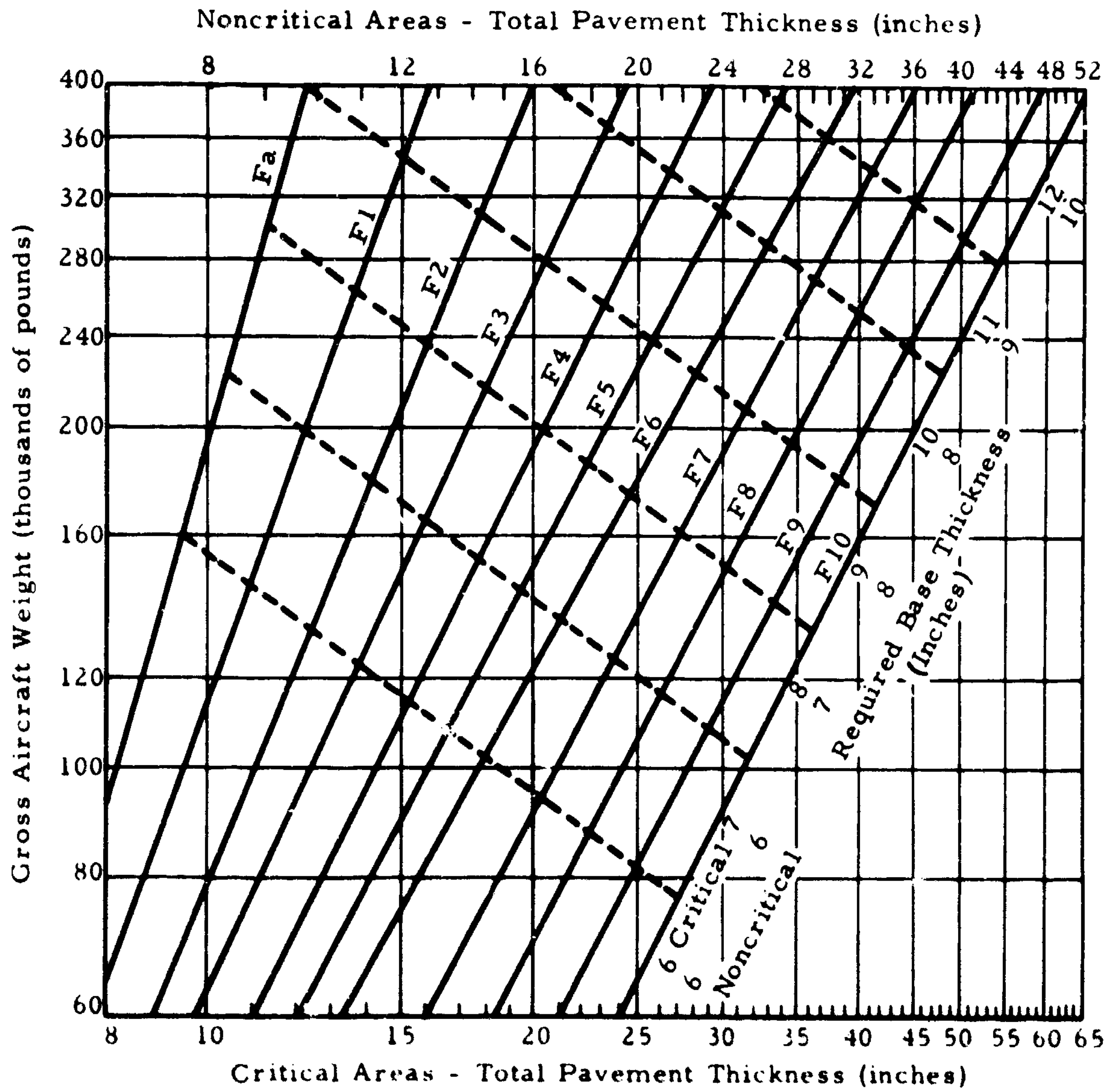


SINGLE TIRE IMPRINT

Source: (a) Federal Aviation Agency, Advisory Circular AC 150/5320-6, <u>Airport Paving</u>, 10 June 1964, Appendix 1, p. 3

EXHIBIT 4 - LOAD DISTRIBUTION AND TIRE IMPRINT DATA

Thickness - Bituminous Surface
3" Critical Areas
2" Noncritical Areas



Source (a) Federal Aviation Agency Advisory Circular AC 150/5320-6, Airport Paving, 10 June 1964, p.29

EXHIBIT 5 - DESIGN CURVES, FLEXIBLE PAVEMENT, DUAL-TANDEM GEAR

Going back to the intersection of F-5 and the 320,000-lb. line, proceed downward and to the right, parallel with the dotted lines. It is seen that this particular aircraft requires a base course thickness of 11 inches for critical areas.

If the area being examined had been noncritical rather than critical, the total pavement thickness would have varied downward by a factor of 20 percent. Total pavement thickness in noncritical areas would have been 24 inches, 9 of which would be for the base course.

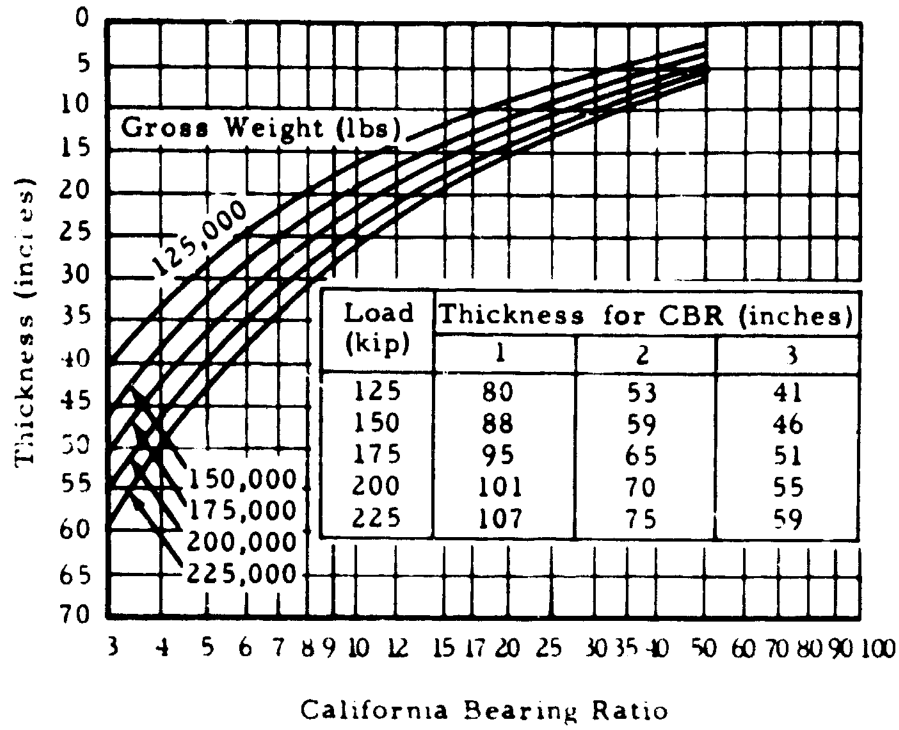
Since a surface course thickness of 3 inches is recommended, and the base course thickness is determined by the chart, the required thickness of the subbase is determined by subtraction.

(2) Corps of Engineers Method

The California Bearing Ratio (CBR) pavement evaluation method was developed by the California Division of Highways in 1928. The method was adopted in 1942 by the U.S. Army Corps of Engineers for military airport use. It is now used by many civilian engineers to determine soil characteristics and in the calculation of the required thickness of flexible airport pavements.

The CBR test expresses an index of the shearing strength of soil. Essentially, the test consists of compacting and soaking a soil sample, then penetrating the sample with a steel piston at a specified load. The soil's resistance, expressed as a percentage of the resistance for a standard crushed stone, is the CBR level. An empirical relationship was developed between the test value and adequate pavement thickness under various loads. Load data for aircraft was at first extrapolated from truck experience curves and later verified empirically. In this method, aircraft load characteristics are usually expressed as a curve, the axes of which are the CBR value and pavement thickness, as in Exhibit 6.

Two methods of determining appropriate pavement thickness for loads resting on multiple wheels have been used by the Corps of Engineers.



Load (kip)	Thickness for CBR (inches)		
	1	2	3
125	80	53	41
150	88	59	46
175	95	65	51
200	101	70	55
225	107	75	59

EXHIBIT 6 - FLEXIBLE PAVEMENT DESIGN CURVE FOR CONVAIR 880

Initially, a straight line superimposed over given CBR value curves was used (much like the present FAA method with its F value curves), with the plot points for the straight line determined by the thickness at which each tire stresses the subgrade as an independent unit along with the gear load divided by the number of tires in the gear assembly, and the thickness at which the total number of tires stresses the subgrade as one single unit along with the load imposed by the entire assembly. The coordinates of the first point are expressed as d/2 and P, and of the second, $2S_D$ and 4P (for dual-tandem gear), as in the FAA method. A sample is shown in Exhibit 7.

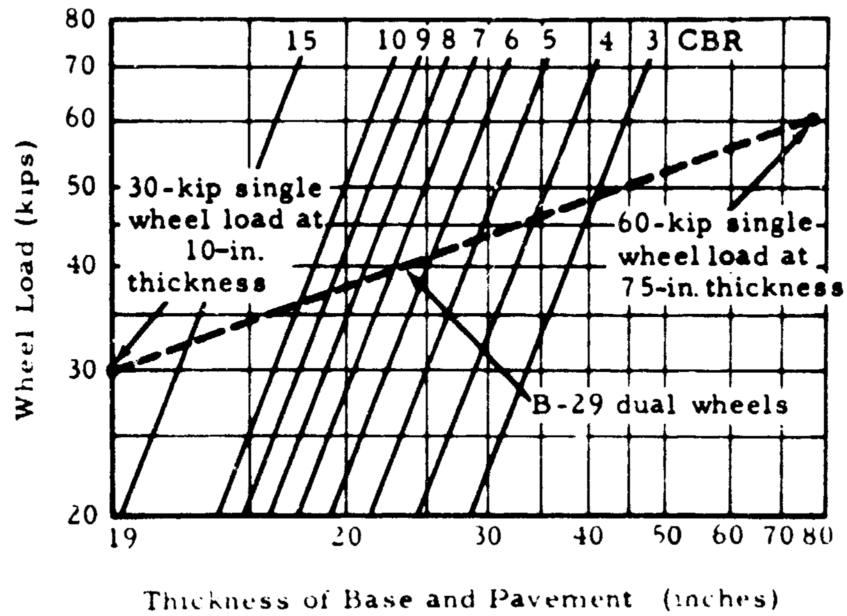


EXHIBIT 7 - DEVELOPMENT OF DESIGN CURVES FOR A 60-KIP LOAD ON B-29 DUAL WHEELS

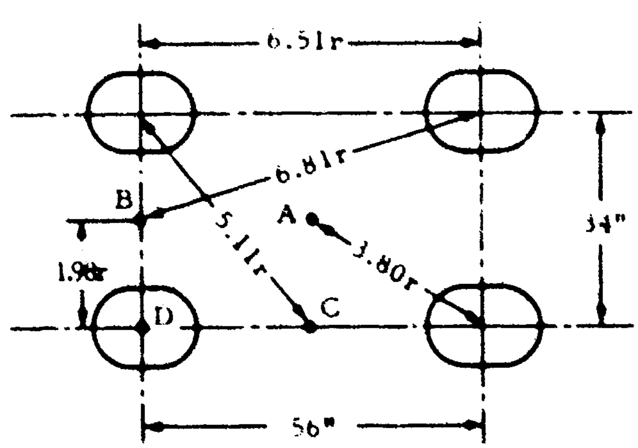
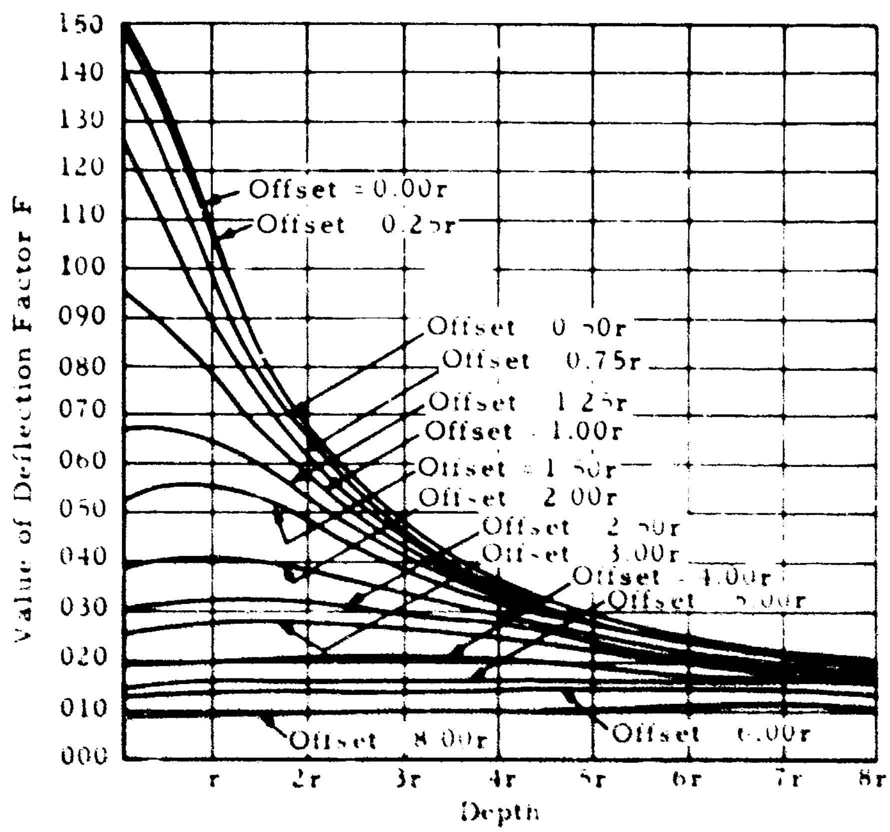


EXHIBIT 8 - DUAL-IN-TANDEM EXAMPLE REANALYSIS

In 1954, the procedure for measuring pavement stress imposed by multiple wheel assemblies was re-examined by the Corps of Engineers, and a new system based on deflection factors in the pavement was adopted. From an analysis of deflection at equal depths from single and multiple wheels, it was found that a single-wheel load which yields the same maximum deflection as a multiple-wheel load would produce equal or more severe strains on pavements in comparison with the multiple-wheel load.

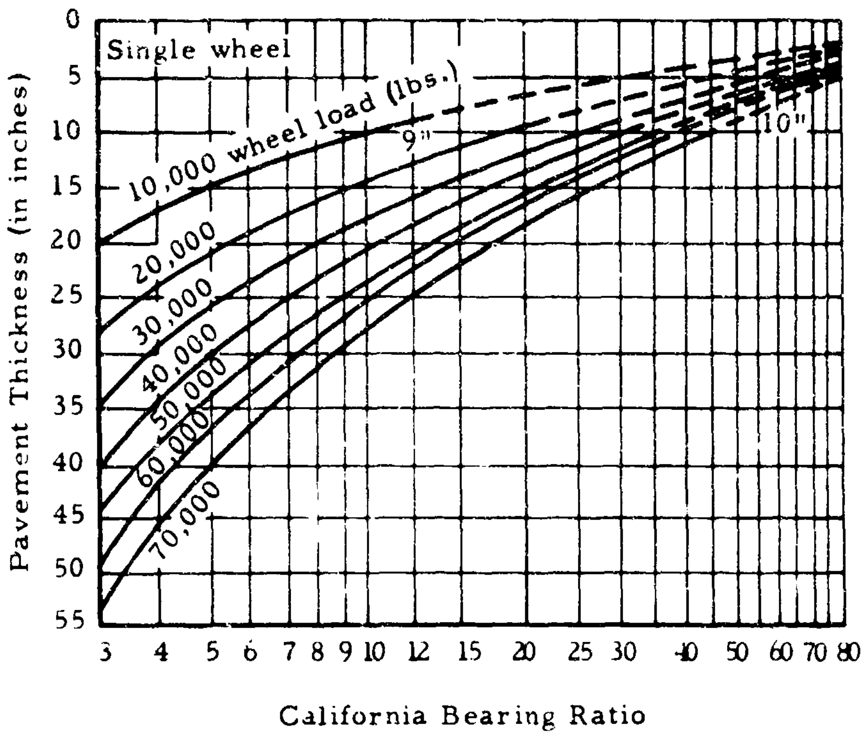
Thus the problem became one of finding the location of an imaginary single wheel, or the point and corresponding depth at which maximum deflection takes place as illustrated in Exhibit 8. In determining this point, the unit of measurement for distance from the actual wheel locations is the radius of the circle which is assumed to be the shape of the equivalent single-wheel imprint. The area of this circle is equal to the area of the actual imprint of a single tire.

After determination of the point and depth of maximum deflection, its value is found from Exhibit 9 and compared to the deflection caused by one wheel of the assembly. This ratio is then divided by the number of wheels in the assembly and the result is the percentage of the total gear load represented by the equivalent single-wheel load. The three necessary parameters are now known, and a chart showing equivalent single-wheel load as a function of pavement thickness and CBR can be constructed, as shown in Exhibit 10. If desired, the curves can be translated to gross aircraft weight for use with readily available data. For noncritical areas, required thickness is reduced by 10 percent.



Note: (1) Poisson's ratio 0.5

EXHIBIT 9 - DEFLECTION FACTOR F FOR UNIFORM LOAD OF RADIUS r AT POINTS BENEATH x AXIS



200-psi tire pressure (1)

Note: (1) Thickness should be reduced 10 percent for central portion of runways (area between 1,000-ft. section at each end.)

EXHIBIT 10 - FLEXIBLE PAVEMENT DESIGN CURVES FOR TAXIWAYS

(3) U.S. Air Force SEFL Method

In designing the landing gear for the giant C-5A aircraft, the Air Force recommended that the design competitors (Boeing, Douglas, and Lockheed) employ the Corps of Engineers method, utilizing the California Bearing Ratio method. However, some modifications were suggested which are worthy of note.

Slight changes were made in the deflection factor - offset value chart (Exhibit 9) through theoretical analysis. In the range of offset values from 0 to 20 radii, a value equal to .0019 (radii of offset) is subtracted from the theoretical value. Further, at offset distances greater than 20 radii, the deflection factor is assumed to be zero.

Upward adjustments of indicated thicknesses in the high CBR value range is made through a simplified curve extension method.

The CBR procedures as originally developed assumed a surface designed to withstand a load repetition factor or coverage level of 5,000. This would represent unlimited operation of the aircraft for a period of approximately 10 years. In the case of the C-5A, it was considered desirable to investigate lower coverage levels. This was accomplished by adjusting the thickness requirement by a factor equal to (.15 + .231 log C) where C is the coverage level desired.

b. Rigid Pavement Analysis

In contrast to the various methods used in flexible pavement calculations, rigid pavement analysis is generally accomplished through the use of a uniform method. The method was developed by Dr. H.M. Westergaard and utilizes a factor for soil strength called the "modulus of subgrade reaction" or the "k" factor. Dr. Gerald Pickett has performed further studies, and has developed a set of influence charts as a means of determining concrete thickness requirements without the exhaustive mathematics required by the Westergaard method alone.

(1) The Westergaard Analysis

Dr. H.M. Westergaard was dean of the Graduate School of Engineering at Harvard for several years. His analysis is for computing critical stresses developed in a concrete slab in the interior of the slab, and near the edge or near an unsupported joint. The formula which is more common in usage is that for the interior of the slab, which is as follows:

$$\sigma_i = \frac{P}{h^2}\left[.0275\,(1+\mu)\,\log_{10}\frac{Eh^3}{k\left(\frac{a+b}{2}\right)^4} + 0.239\,(1-\mu)\left(\frac{a-b}{a+b}\right)\right]$$

where σ_i = maximum tensile stress at the slab bottom under the center of the load

P = load in pounds

a, b = semiaxes of an ellipse which represents the footprint of the tire

h = slab thickness in inches

E = modulus of concrete elasticity in psi per inch

k = modulus of subgrade reaction in psi per inch

μ = Poisson's ratio

The modulus of subgrade reaction is determined by a procedure of applying loads to a steel plate 30 inches in diameter by means of hydraulic jacking at representative areas of the foundation material. By definition,

$$k = \frac{\text{pressure in psi to cause a deformation of 0.05 inches}}{\text{0.05 inches}}$$

While other factors (such as moisture content) certainly affect this test, it is noted that stress is also sensitive to k value. In theory, k is related to other soil classifications through estimates of a soil value as a foundation material, as seen in Exhibit 11.

(2) Influence Chart

The basic Westergaard equations can be used for stress induced by gear configuration, but the procedure is tedious.

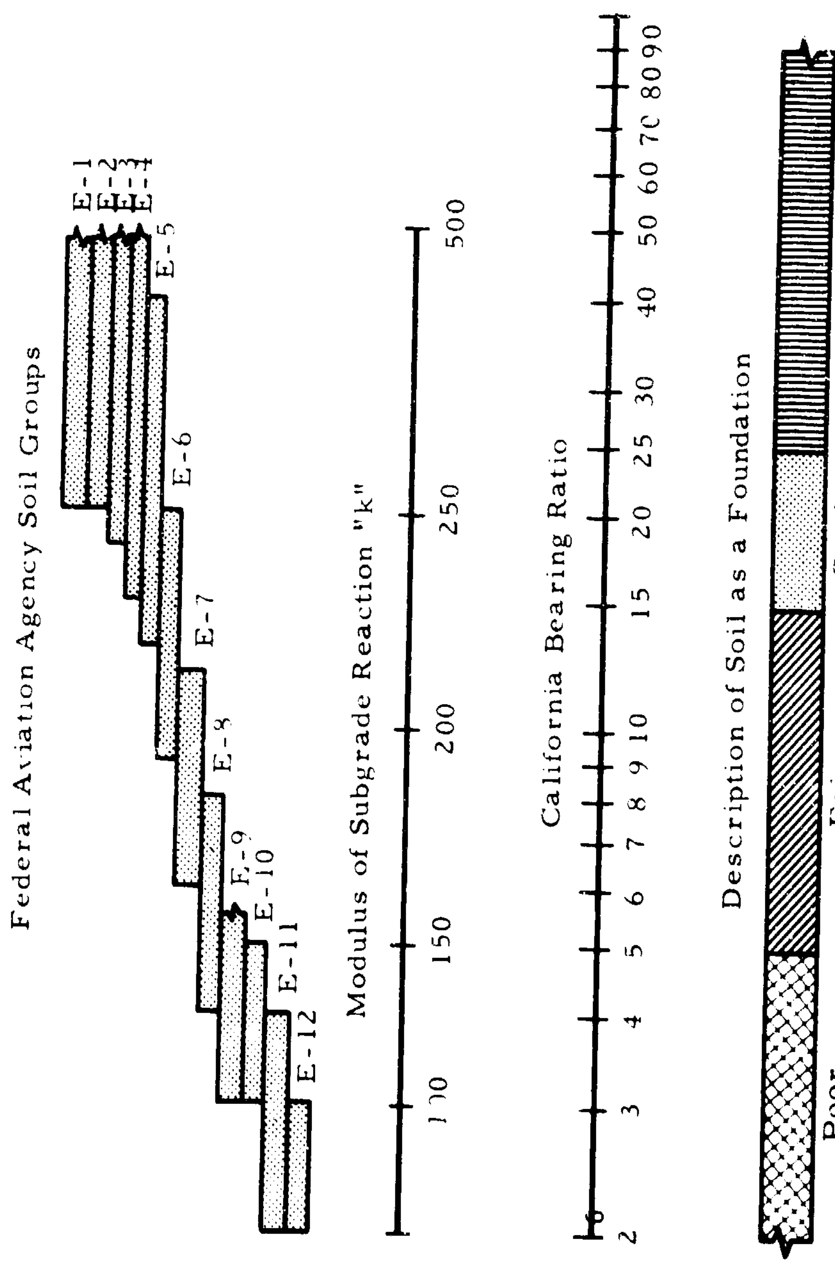


EXHIBIT 11 - APPROXIMATE INTERRELATIONSHIPS OF SOIL CLASSIFICATION SYSTEMS

To save time, Dr. Gerald Pickett developed influence charts from the Westergaard equations. A sample chart is shown as Exhibit 12.

The essential data for using the influence charts are the gear load, tire spacing, tire pressure, the modulus of elasticity of the concrete (assumed at 4,000 pounds per square inch), Poisson's ratio (assumed at 0.15), k or the modulus of subgrade reaction, and concrete thickness. The value ℓ , the radius of relative stiffness, is then computed by the equation

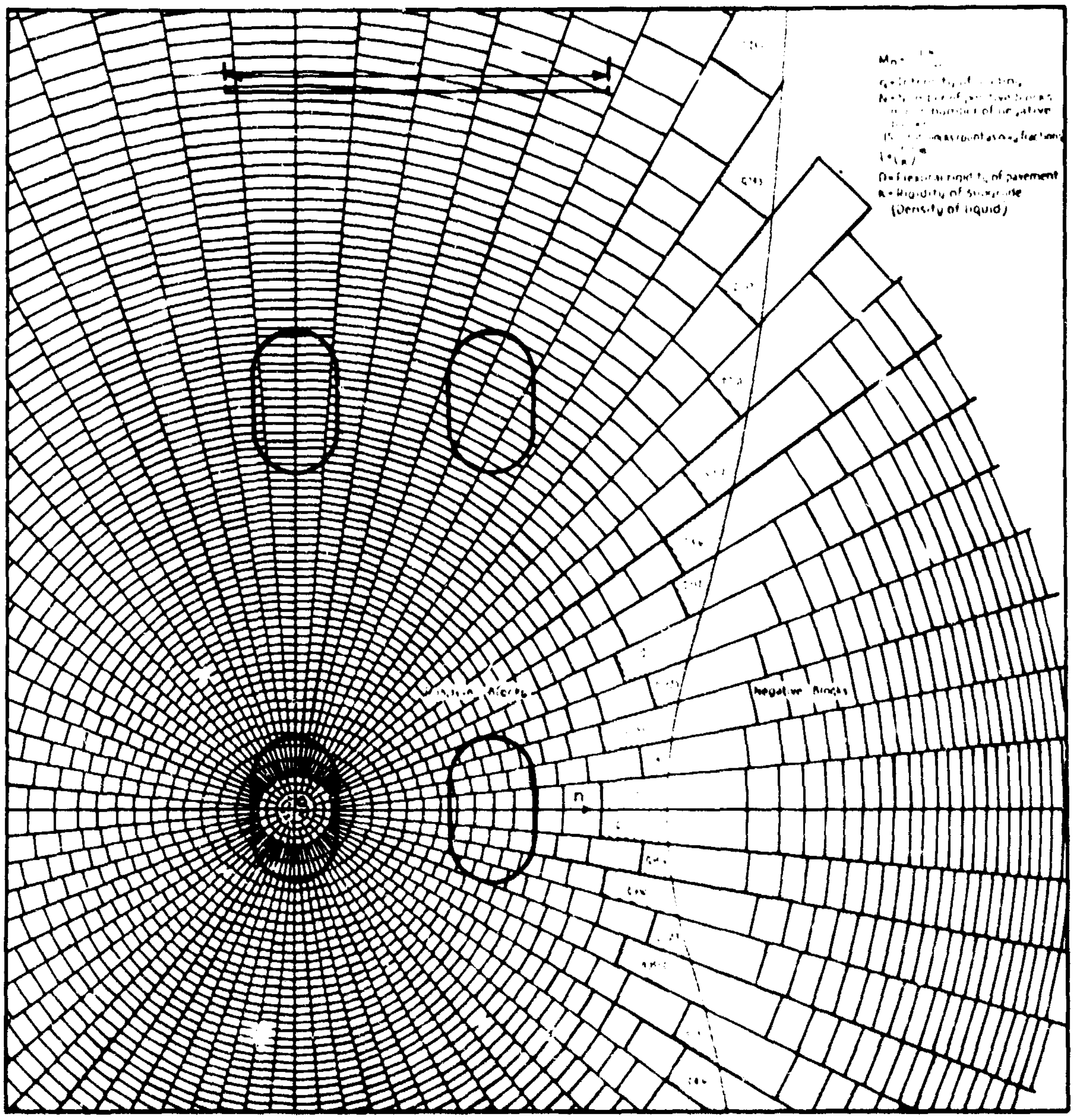
$$\ell = \sqrt[4]{\frac{Eh^3}{12\,(1-\mu^2)\,k}}$$

The scale on the influence chart is then assigned the value of ℓ and the gear configuration, drawn to the same scale, is superimposed over the chart. The tire footprint area (wheel load divided by tire pressure) is assumed to be equal to .5227 times the square of the imprint length. Imprint width is .6 of the length so the footprint shape is that of a rectangle with semicircular ends.

The number of influence chart blocks covered by the tire imprints is then counted, and the superimposed gear tracing is moved until a point is found at which a maximum number is covered. Using the formula in Exhibit 12, moment is then computed. The flexural stress can now be found by multiplying moment by the section modulus of the slab.

(3) FAA Method

Utilizing the influence charts developed by Pickett from Westergaard's formulae, the FAA has prepared standard curves for estimating rigid pavement thickness. These three curves are assumed to be representative of all aircraft using single, dual, and dual-tandem wheel assemblies, respectively. They are based on gross aircraft weight, as seen in Exhibit 13. It is necessary to find the required thickness of subbase from the lower half of Exhibit 13. No subbase is needed for Ra subgrades.



Note: (1) Subgrade is assumed to be a dense liquid. Poisson's ratio for pavement is assumed to be 0.15.

EXHIBIT 12 - INFLUENCE CHART FOR THE MOMENT M_n IN A CONCRETE PAVEMENT DUE TO A LOAD IN THE INTERIOR OF THE SLAB

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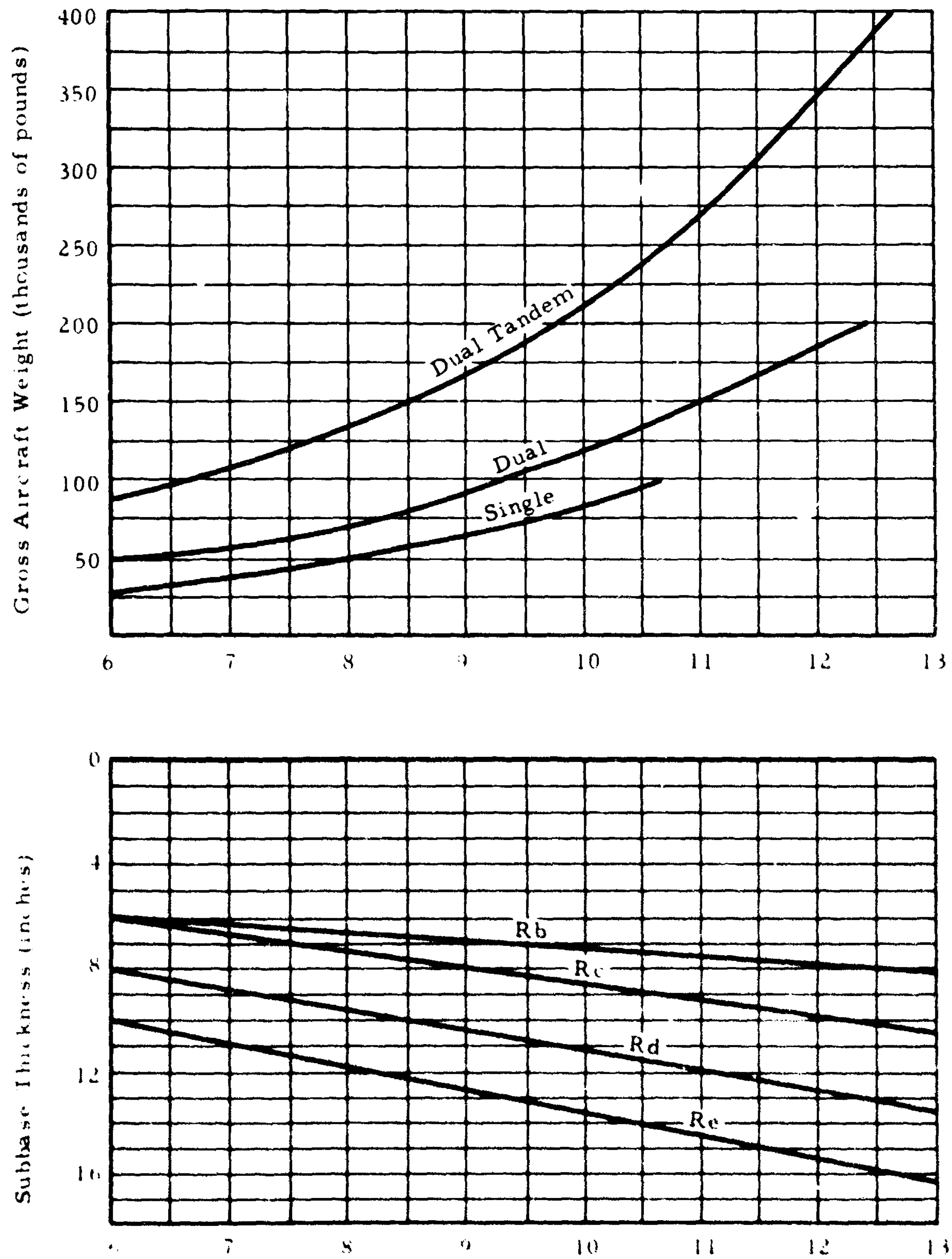

Source: (a) Federal Aviation Agency, Advisory Circular, AC 150/5320-6, Airport Paving, 10 June 1964, Appendix 1, p. 32

EXHIBIT 13 - DESIGN CURVES, RIGID PAVEMENT, CRITICAL AREA

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In order to form these general curves, special assumptions were necessary. They are: k = 300 psi/i, 400 psi working stress, 150 psi tire pressure, E = 4,000,000 psi, and μ = 0.15.

The gear dimensions were assumed to be: for dual wheels, 20 inches center-to-center for the lower aircraft weights and 30 inches for the heavier aircraft, and for dual-tandem gear, 20 x 45 inches for the lower end of the weight scale and 30 x 55 inches for the heavier weights. Five percent of the weight is assumed on the nose wheel in all cases. Thicknesses are again reduced by 20 percent for noncritical areas.

(4) Portland Cement Association Method

Exhibit 14 is an example of the type of graphical analysis performed by the Portland Cement Association. This chart is taken directly from the influence charts previously discussed. The assumptions regarding tire imprint, modulus of elasticity, and Poisson's ratio which were used by Westergaard are retained. The formula for loads in the interior of a slab is assumed to be applicable because adequate load transfer devices between slabs enable a paved area to act as one large slab.

Safety factors are established before using the design chart (Exhibit 14). They are 1.7 to 2.0 (depending on the number of operations by planes with the design wheel load) for critical areas, and 1.25 to 1.5 for central portions of runways. This factor is applied to the modulus of rupture of the concrete to find allowable stress, which is on the left vertical axis in Exhibit 14. Entering the chart at that point, proceed horizontally to the appropriate k factor, then vertically to the applicable gear-load curve. Continuing horizontally and to the right, read required thickness from the right axis. The procedure may be reversed to determine stress when thickness is already known.

Although the methodology does not preclude consideration of unusual gear configurations (through development of special design charts by using the influence charts), only single, dual, and dual-tandem gear of specified dimensions are charted in the Association's booklet. Where

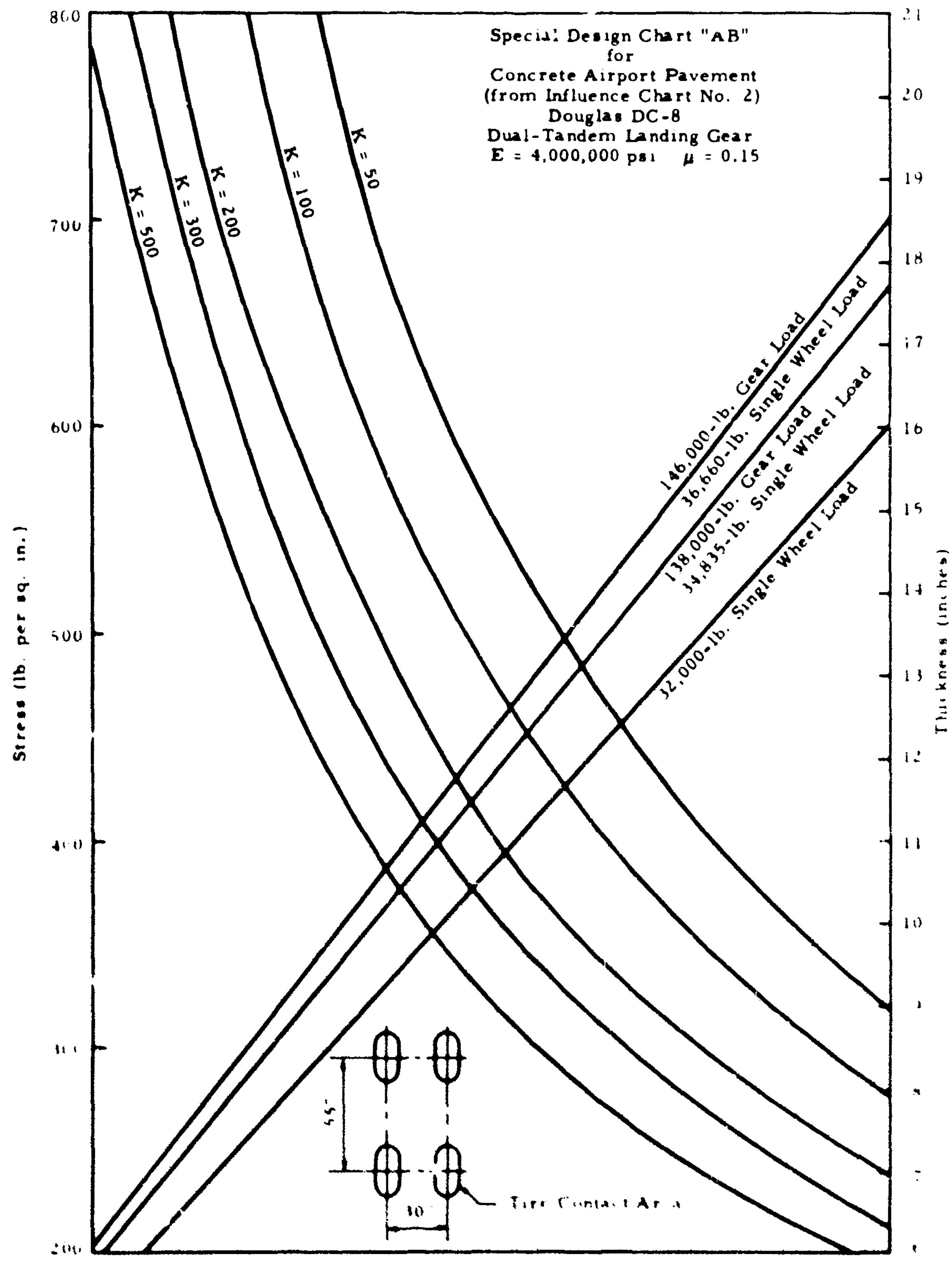

EXHIBIT 14 - PORTLAND CEMENT ASSOCIATION DESIGN CHART

thicknesses for aircraft with other dimensions are required, the following suggestions make possible the use of the charts presented:

- For increases in center-to-center spacing up to 10 inches, the required thickness should be reduced by 0.6 percent for each inch.
- For each inch decrease in dual spacing up to 10 inches, the required thickness should be increased by 0.6 percent.

(5) Load Classification Number Method

A procedure known as the Load Classification Number system for classifying airports and aircraft was developed by the British Air Ministry. Briefly, the supporting capacity of a pavement is expressed in terms of a number known as LCN. This number is obtained by making plate bearing tests on the pavement. Likewise, the equivalent single-wheel load in any aircraft can also be expressed in terms of LCN. This latter number, of course, is dependent on the configuration of the gear, tire pressure, and type and thickness of runway. In a simplified analysis, if the LCN of an airfield pavement is larger than the LCN of an aircraft, that aircraft can be assumed to be safe in utilizing that facility. The LCN of an aircraft is determined in the following manner: first, the equivalent single-wheel load is computed with the use of any appropriate procedure, such as the Corp of Engineers or FAA method. Next, the contact area for each equivalent single-wheel load is computed, under the assumption that the contact pressure is the same as that for the wheel assembly. With this data, a graph with tire pressure as the vertical axis and equivalent single-wheel load as the horizontal axis is constructed, in which LCN curves intersect contact area curves to give the LCN for a particular aircraft.

In order to determine the pavement's capacity to withstand loads and express it as a single LCN, the idea of a standard load classification curve was introduced, which expresses empirical relationships between equivalent single-wheel load and contact areas. Failure load is then expressed as a function of loaded contact area for various pavements, and an average curve was introduced which has the form:

$$\frac{W1}{W2} = \frac{A1}{A2}^{.44}$$

2. <u>The Problem of Nonuniform Pavement Analysis Techniques to Aircraft Designers</u>

a. <u>Aircraft Landing Gear Design as a Function of Pavement Strength</u>

Because of the extreme weight projected for future large aircraft, it has been necessary to design landing gear which have highly unusual configurations in comparison with the standard dual and dual-tandem gear arrangements of the present family of commercial transports. Proposals have been made which include triple-tandem and quadruple-tandem arrangements, as well as combinations of two or more dual- or triple-tandem sets under each wing. As many as 30 wheels have been proposed for a single aircraft.

It is obvious that determination of flotation requirements for these advanced systems is more complex than it has been in the past. In fact, it is highly improbable that the d/2 and 2S measurements are appropriate for configurations other than the dual or dual-tandem. The Westergaard mathematics and the determination of the point of maximum deflection have become more important in relation to other methodologies.

b. <u>Absence of Correlation Among Pavement Analysis Methods</u>

It should be noted that in the consideration of flexible pavement design, the required thickness of the flexible pavement may be influenced substantially by the method of analysis in use. Experience suggests that use of the FAA method will result in a thickness requirement somewhat below that resulting from use of the Corps of Engineers method. The Air Force SEFL method is, perhaps, the most conservative of all, and may result in a thickness requirement greater than either the FAA or Corps of Engineers method. However, it is possible to use any one of the three methods if the results are tempered by experience and comparison with existing pavements.

Perhaps the most important element in the derivation of thickness requirements is the manner in which the subgrade is tested. An FAA subgrade rating can only be related to a CBR rating through gross approximation (see Exhibit 11). It is possible that the different tests, conducted at different times and by separate individuals, may not be able to be equated, and the results may indicate differences in thickness out of proportion to the normal variance. As an example, tests were recently made at Los Angeles International Airport, resulting in an FAA soil classification of Fa and a CBR rating of 10. This results in pavement thickness requirements for the DC-8-55 of 11.5 inches by the FAA method, and 32.5 inches by the Corps of Engineers method. In contrast, soil tests taken at Miami International Airport present an FAA rating of Fa and a CBR of 60. This results in a requirement for the DC-8 of 11.5 inches by the FAA method, and 7 inches by the Corps of Engineers method.

As a further example of the lack of correlation between the various subgrade testing methods, the test data for 15 major U.S. airports were examined. An attempt was made to relate the k factor, F number, and CBR value wherever more than one of these tests had been taken at the same location. The lack of correlation is demonstrated by Exhibit 15.

The FAA methodology for rigid pavement analysis further adds to the possibility of error by using curves which are derived from assumed landing gear dimensions. In addition, the curves for dual and dual-tandem gear are compromises between larger spacings at the heavier weights and smaller spacings at the lower end of the scale. This results in a design curve which overstates the thickness requirement by 1 to 2 inches. Suggestions made by the Portland Cement Association are also conducive to approximation, as the curves are only designed for single, dual, and dual-tandem arrangements. As

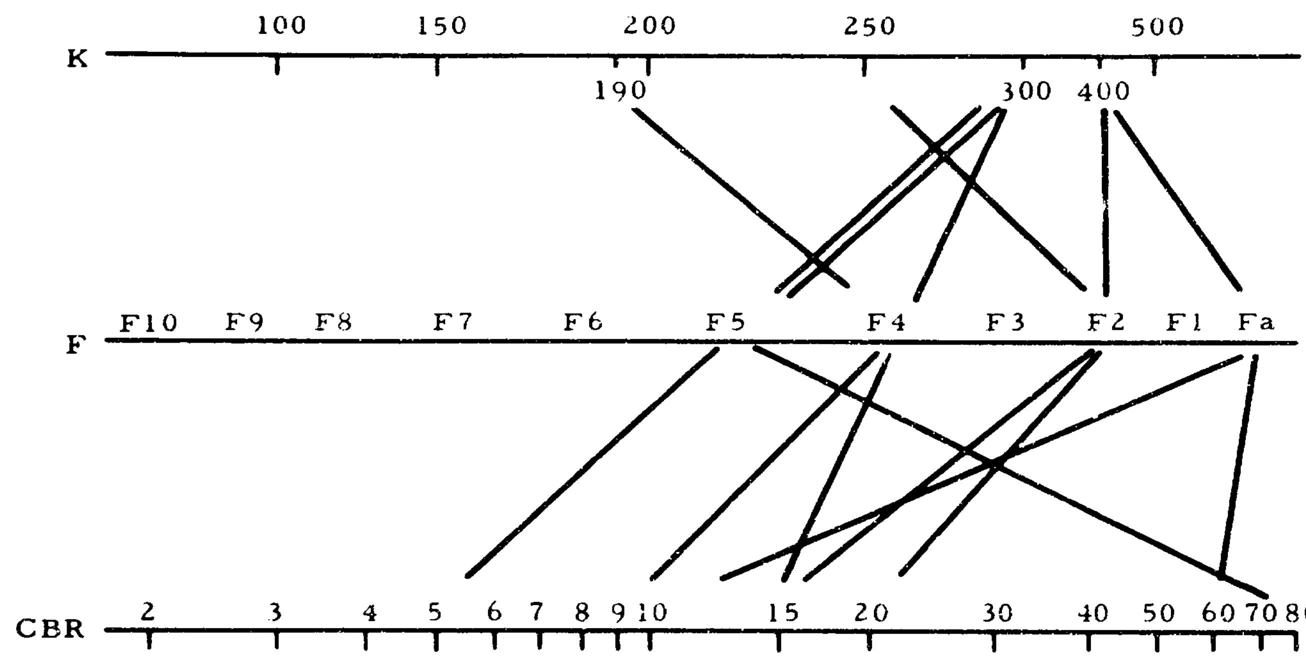

EXHIBIT 15 - ATTEMPTED CORRELATION OF SUBGRADE TESTS
AT 15 MAJOR AIRPORTS

previously stated, the FAA method for determining flexible pavement thickness must use d/2 and S or S_D, because these measurements are most applicable to dual or dual-tandem arrangements.

The influence charts developed by Pickett to simplify the mathematics associated with the Westergaard method also produce results that vary slightly from an all-mathematical analysis. This variance is attributable to the difficulty in counting squares, and especially in determining the maximum count as the tracing of the gear is rotated on the influence chart. This variance may result in a difference of 2 to 3 percent. Another contribution to the variance is the shape of the contact area: Westergaard used an ellipse while Pickett used a rectangle with semi-circular ends.

For these and other reasons, the Westergaard equations (and their direct use rather than their use through compromise curves or influence charts) and the Corps of Engineers method of determining the point and depth of maximum deflection become more important and more applicable to determination of pavement thickness for future aircraft.

In the inclusion of analyses of flexible pavements by the FAA method, it is recognized that a discrepancy will result in the case of aircraft with six-wheel gear. That is, the Corps of Engineers method will produce less favorable flotation characteristics for six-wheel gear than will the FAA method. It is impossible to state which is most nearly correct at the present time, because experience with such gear configurations has not provided empirical data.

It is believed that with careful soil classification, the Corps of Engineers method for flexible pavement and the Westergaard analysis for rigid pavement will result in satisfactory determination of pavement thickness for the future heavy aircraft and for uncommon gear configurations. However, it seems advisable to apply the SEFL correction regarding low thickness and high CBR values to the Corps of Engineers methodology.

3. Compatibility of Present Airport Pavements with Large Commercial Aircraft

a. Methodology Used in Computations

The U.S. supersonic transport airframe competitors, Lockheed and Boeing, are proposing designs which incorporate maximum gross weights of 595,000 and 675,000 pounds respectively. In addition to these aircraft, the Lockheed L-500 (the commercial version of the C-5A), the Boeing 747, the DC-8-63, and the supersonic Concorde will be considered and their compatibility with airport pavements analyzed. For comparative purposes, the Boeing 707 which weighs 336,000 pounds and the DC-8-55 with 328,000 pounds are added to the list.

Each of these aircraft is assumed to operate with a center of gravity at maximum gross weight such that the nose wheels carry 5 percent of the weight. Although this assumption is in accordance with FAA procedures, it is not accurate. It is believed to be close to reality, however, and is necessary to render the load per tire on the main gear comparable for each airplane.

(1) Rigid Pavement

The induced stress in rigid pavements was determined for various thicknesses and k values by means of the Westergaard formula. The results for each airplane were plotted on charts in which concrete thickness was plotted against stresses at various k values. (See charts in subsection B.) For evaluation of an airport, the pavement thickness and k value give concrete stress, which is then compared to the allowable stress at the airport being considered.

The required overlay was determined by the reverse procedure, i.e., the charts were entered with the allowable stress and given k value, which determined the needed thickness. The allowable stress was based on the flexural strength of concrete that was at least 90 days old.

The induced stress is directly related to the wheel load, but is rather insensitive to small changes in the wheel spacing and contact area.

(2) Flexible Pavement

In the analysis of flexible pavements, the FAA method is used wherever F numbers are available. Determination of d and S_D have not been standardized for new gear configurations. It was assumed in the case of aircraft using four dual-tandem bogies that one dual tandem was representative, that all tires were equally loaded, and that S_D is a diagonal center-line distance on one bogie regardless of the effects of an adjacent set of wheels. For the triple-tandem arrangement, S_D was measured from the center line of one front tire to the center line of the opposite rearmost tire without regard to the effects of the dual wheels in the middle, except for wheel-load determination. The same is true independently for the L-500, which uses triple tandems fore and aft.

The Corps of Engineers method is used wherever CBR data is available. Deflection factors are summed for all wheels in the triple-tandem cases, but for the aircraft which use four dual-tandem main gear, the bogies are treated as independent units. This assumption was derived through calculation of the distance between centers of the nearest tires of two adjacent bogies. The result was approximately 16 and 14 radii for the B-2707 and the B-747, respectively. Using the information in Exhibit 9, an offset value of 14 (if it were shown), would give deflection factors of .05 or lower at all depths. This is considered negligible in relation to actual deflection factors of 1.00 or more at relevant depths.

The Corps of Engineers analysis was accomplished by determining the maximum deflection factor at spacing intervals of 3 inches throughout the relevant area covered by the landing gear. This was repeated for a total of 10 depths from 5 to 80 inches.

Using the formula:

$$\frac{t}{\sqrt{A}} = \sqrt{\frac{\frac{ESWL}{SWL}}{8.1\,\frac{CBR}{p}} - \frac{1}{\pi}}$$

where t = thickness or depth
ESWL = equivalent single wheel load
SWL = actual load on one wheel
A = tire imprint area
p = tire inflation pressure
CBR = California Bearing Ratio

the required CBR at each depth for a given aircraft weight and gear configuration was computed and plotted. In evaluating airports, this CBR/depth chart is used by entering with the actual CBR and determining required depth to support a given airplane in unlimited operation. As previously stated, the SEFL modification for shallow depths is incorporated in the computations.

B. Aircraft Pavement Loading Effects

Exhibits 16 through 46 summarize the computations involved in flexible and rigid pavement thickness determination. Gear configuration, aircraft data, FAA chart, CBR chart, and concrete stress chart are shown for each aircraft in turn.

Gross Ramp Weight	% of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire Imprint Area (sq in.)	Tire Pressure (psi)	d/2 (in.)	2 SD (in.)
595,000	95	47,100	50 x 18	255	185	11.9	239.7

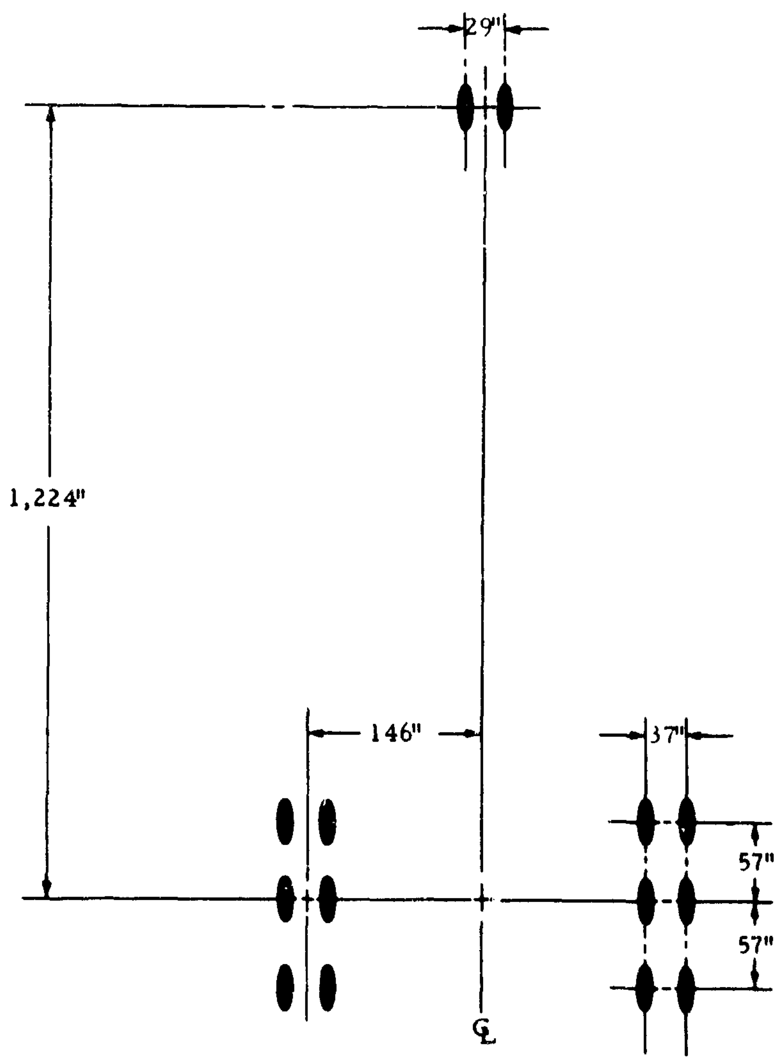

EXHIBIT 16 - L-2000 PAVEMENT LOADING SUMMARY

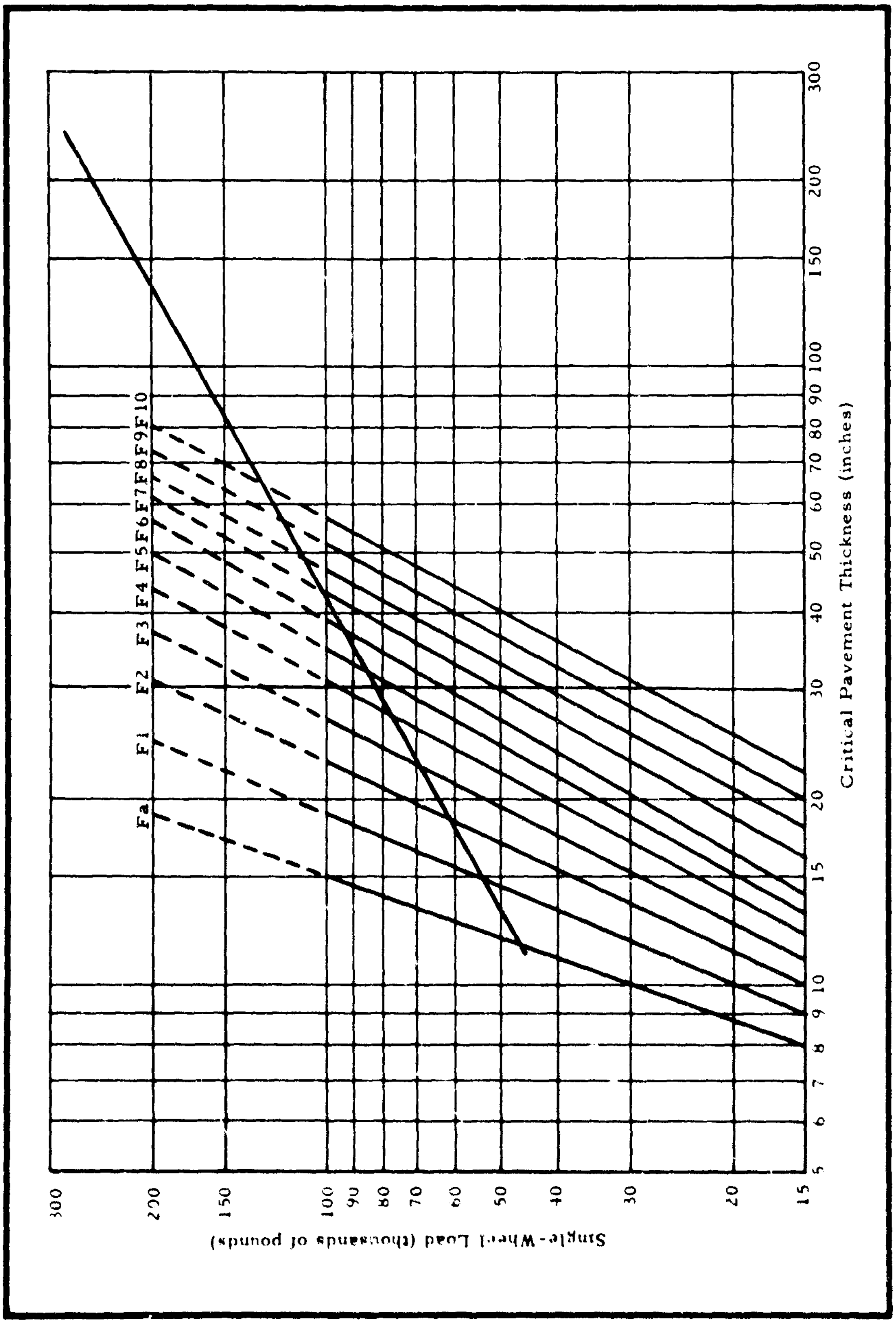

EXHIBIT 17 - L-2000 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

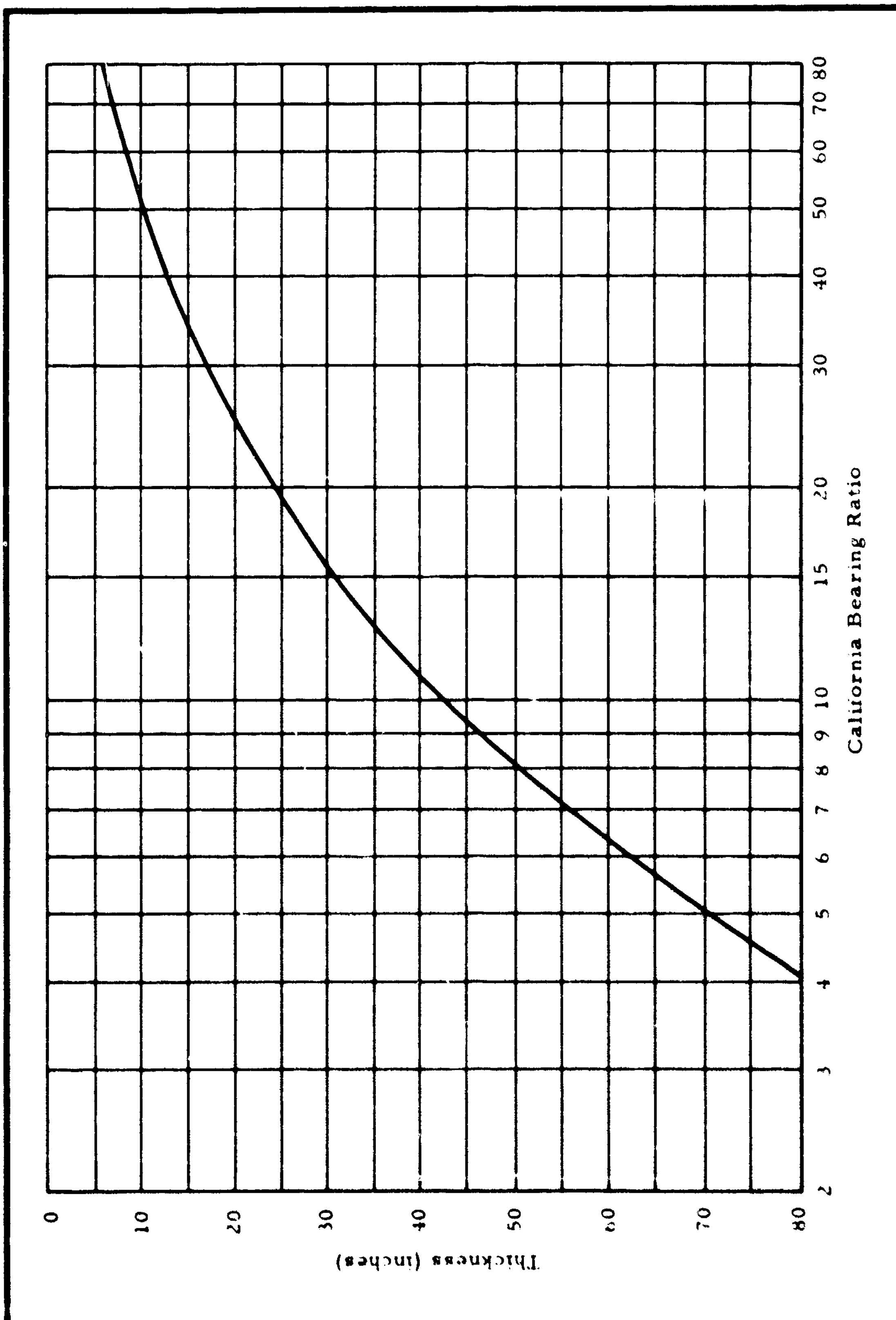

EXHIBIT 18 - L-2000 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

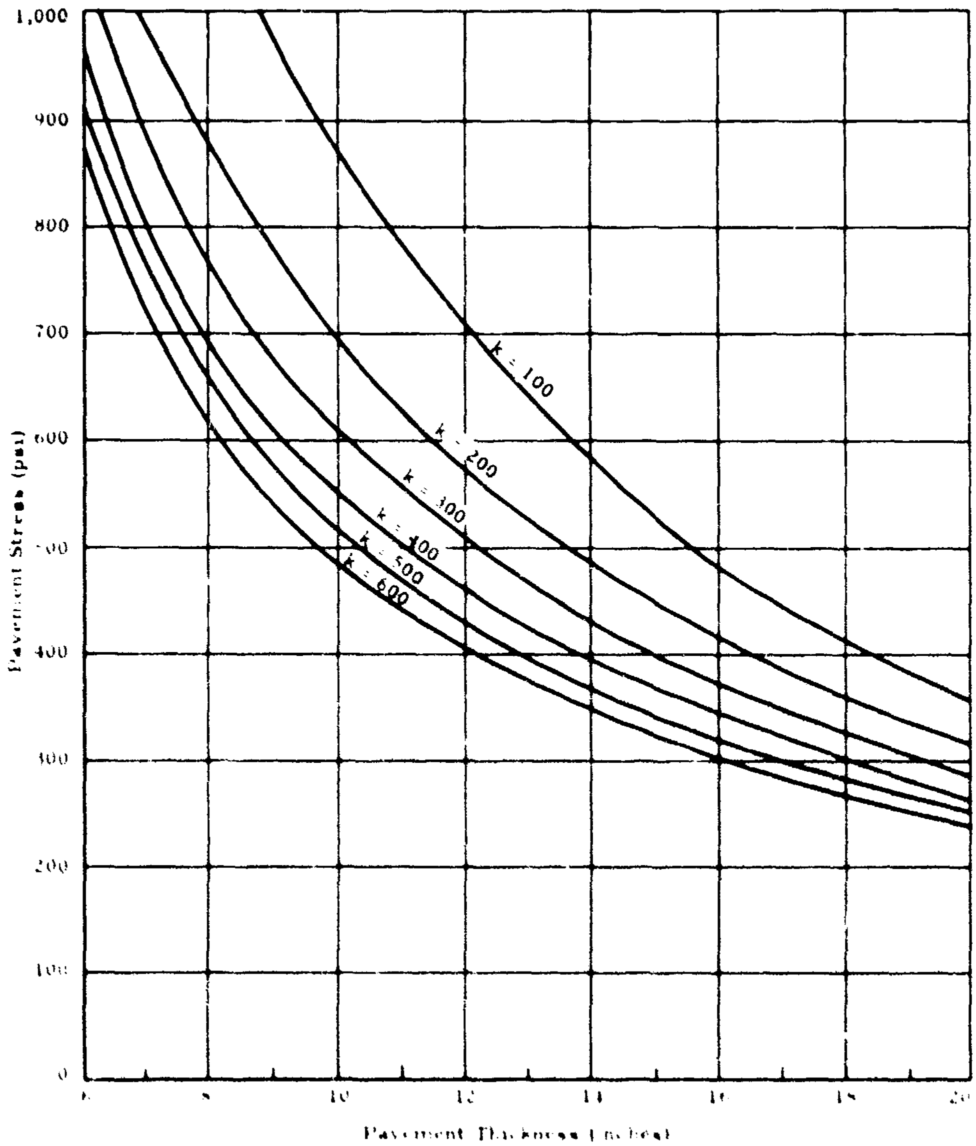

EXHIBIT 19 - L-2000 RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	% of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire Imprint Area (sq. in.)	Tire Pressure (psi)	d/2 (in.)	2SD (in.)
675,000	95	40,100	45 x 19.2	217	185	12.4	133.0

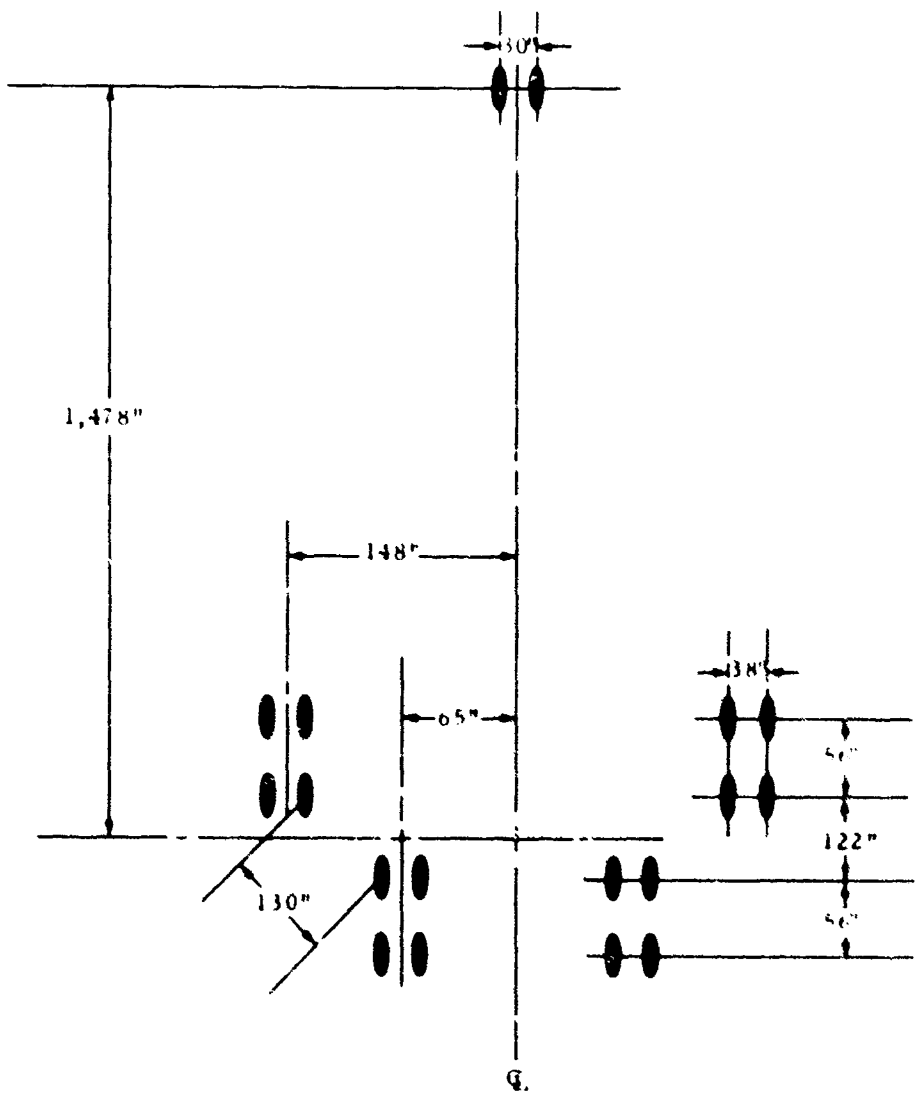

EXHIBIT 20 - B-2707 PAVEMENT LOADING SUMMARY

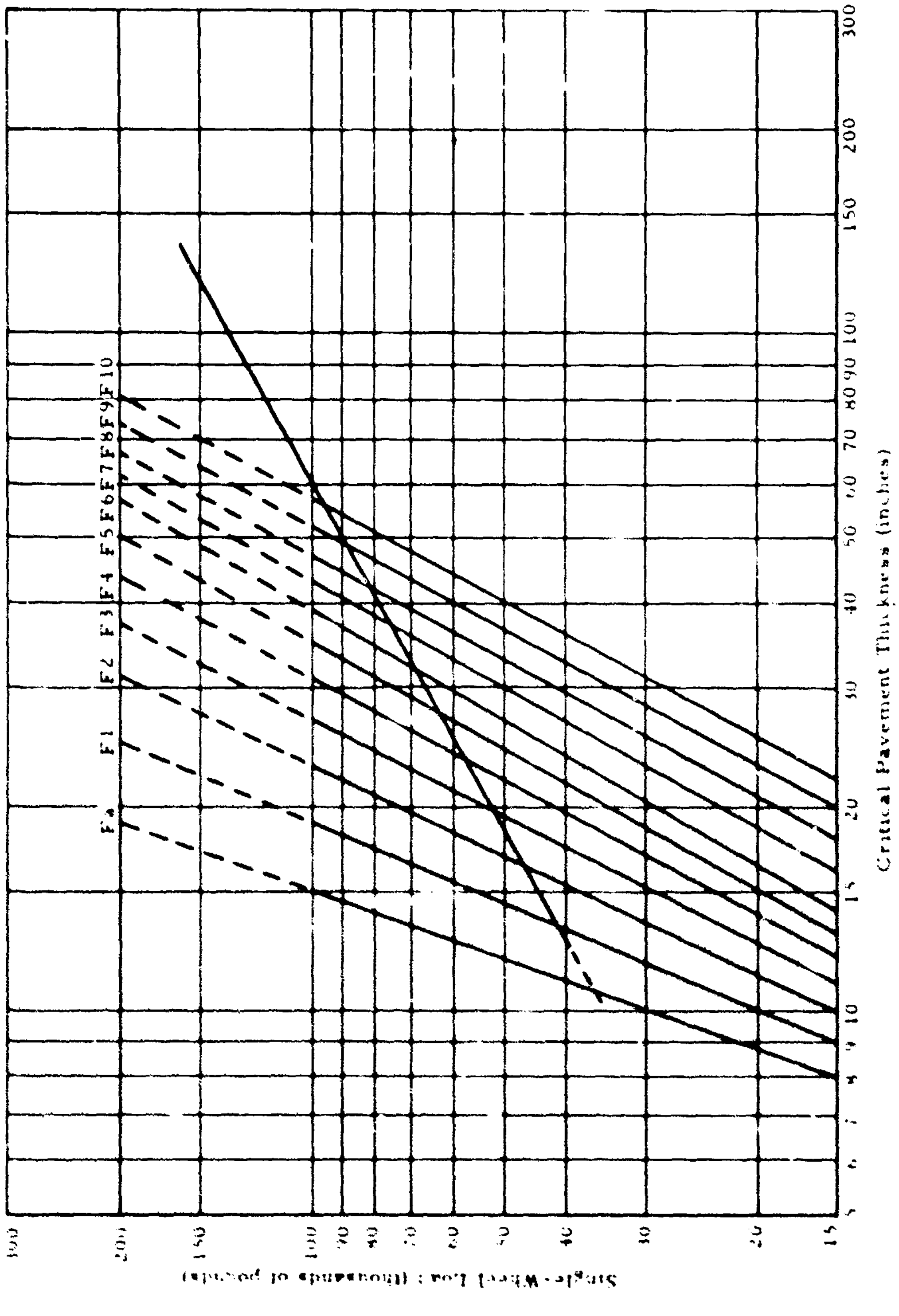

EXHIBIT 21 - B-2707 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

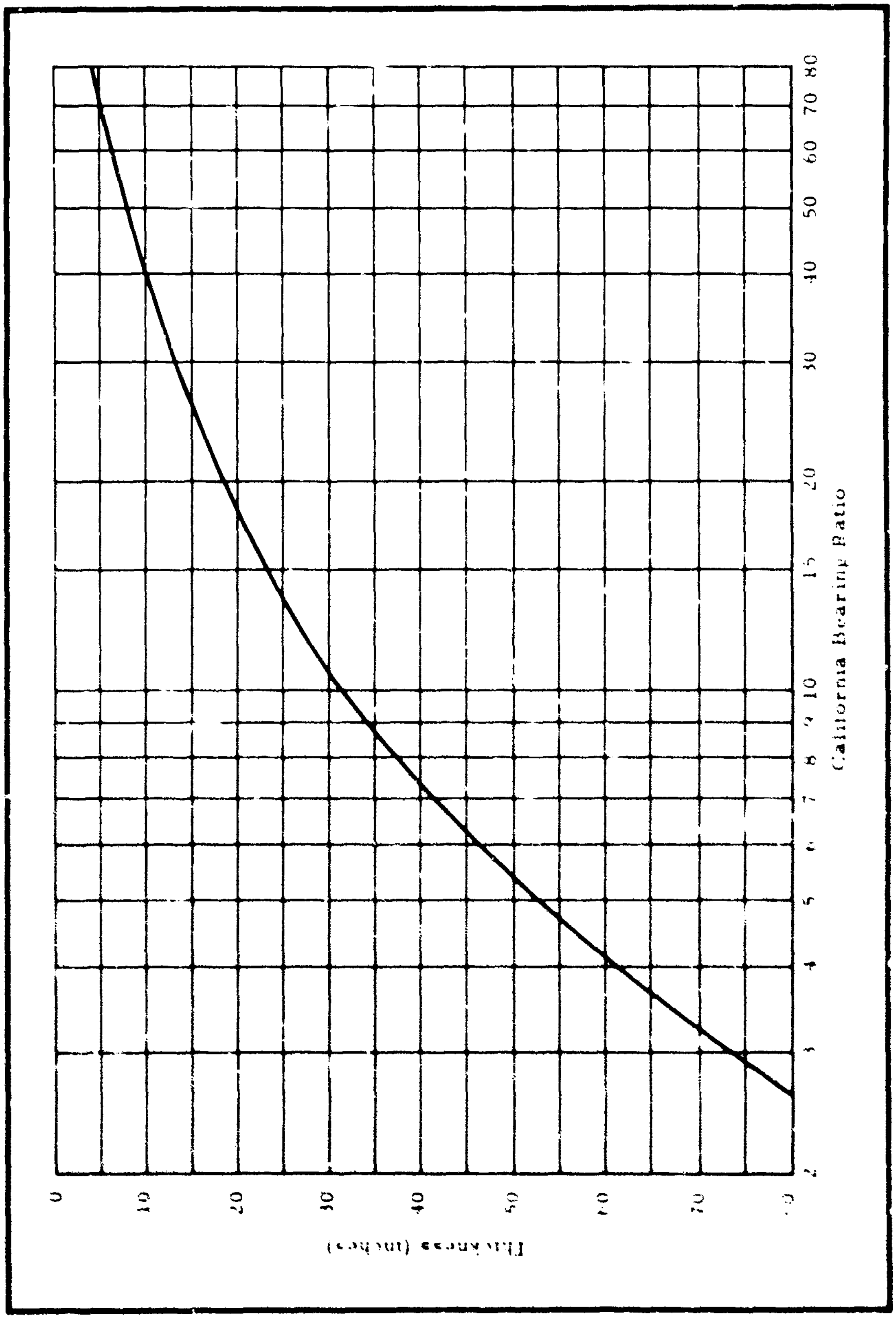

EXHIBIT 22 - R-2707 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

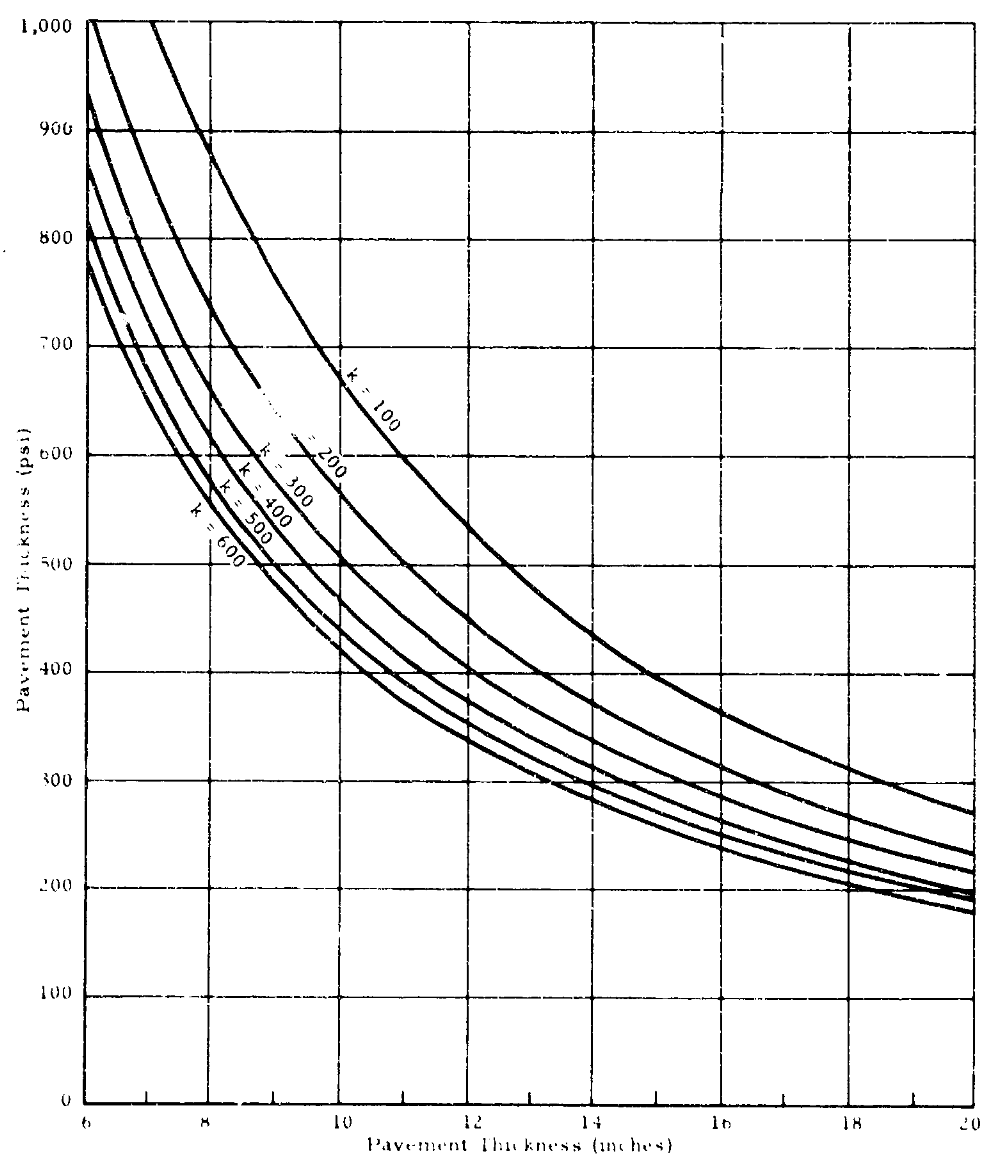

EXHIBIT 23 - B-2707 RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	% of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire Imprint Area (sq. in.)	Tire Pressure (psi)	d/2 (in.)	2 SD (in.)
340,000	95	40,400	45 x 15.75	205	197	7.8	136.2

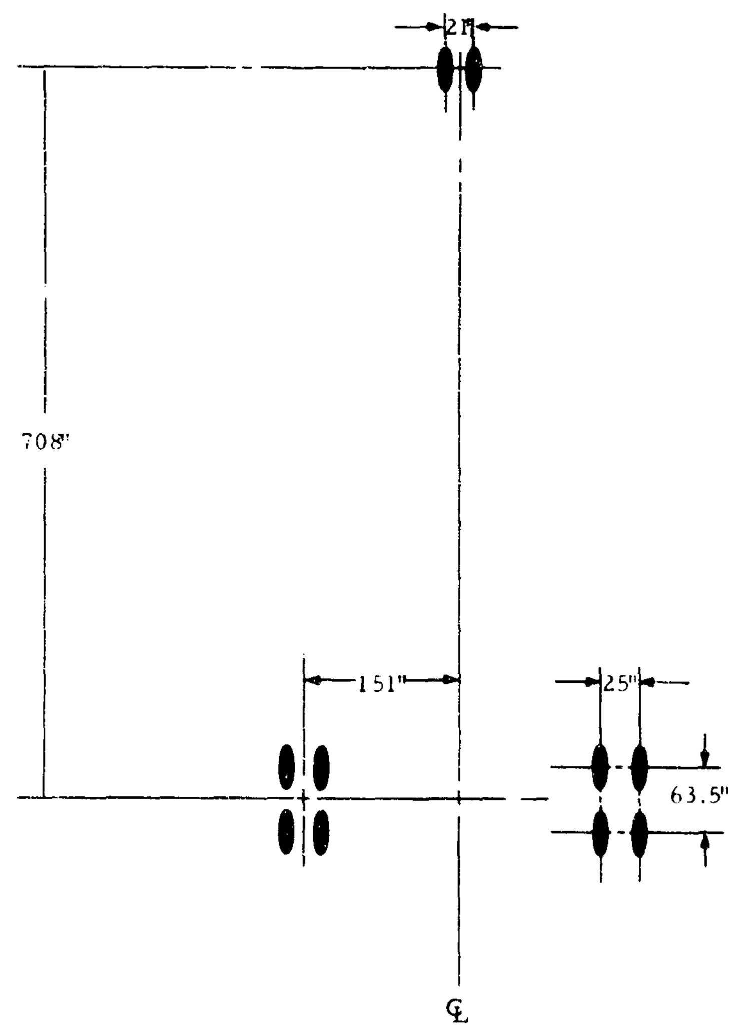

EXHIBIT 24 - CONCORDE PAVEMENT LOADING SUMMARY

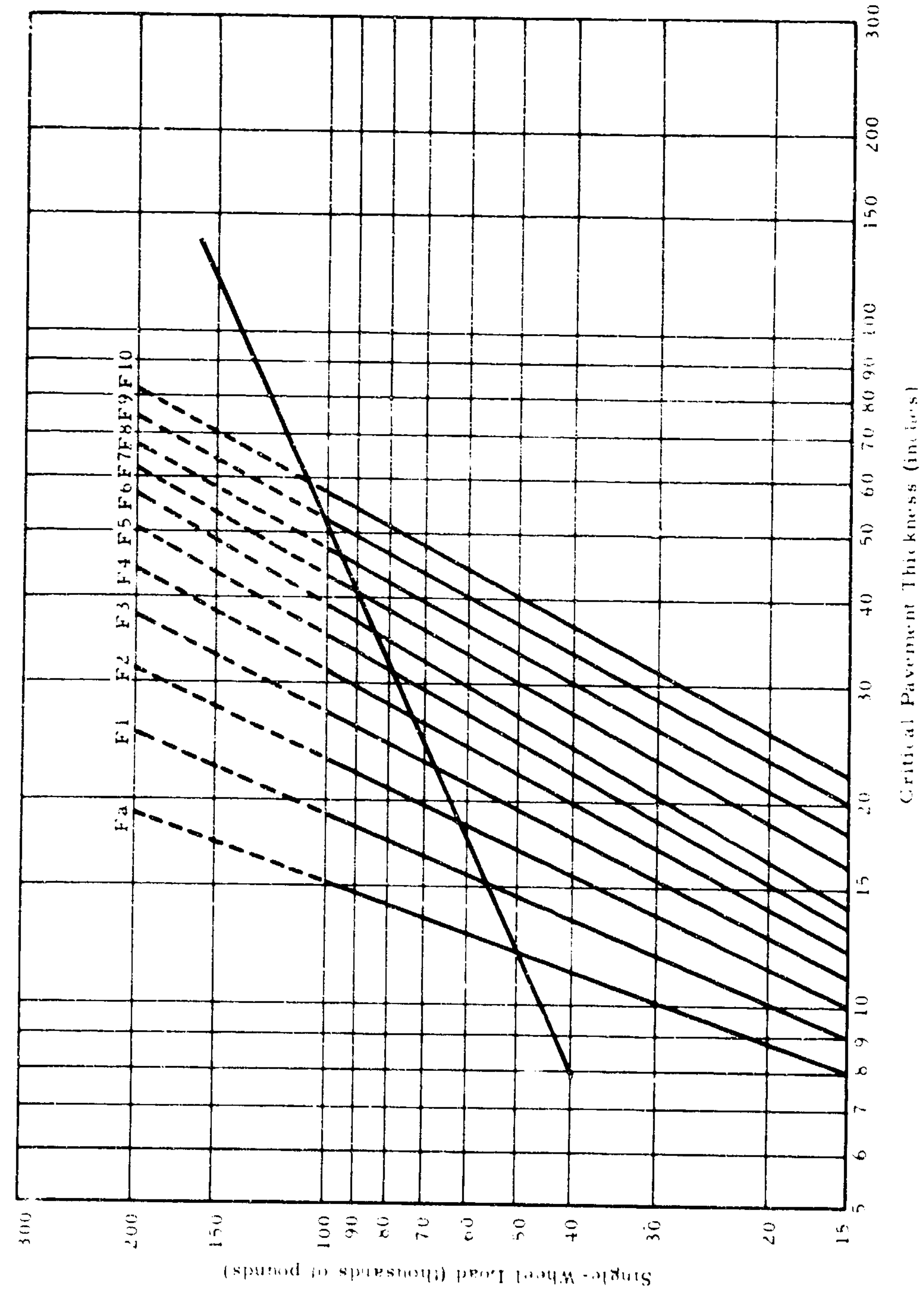

EXHIBIT 25 - CONCORDE FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

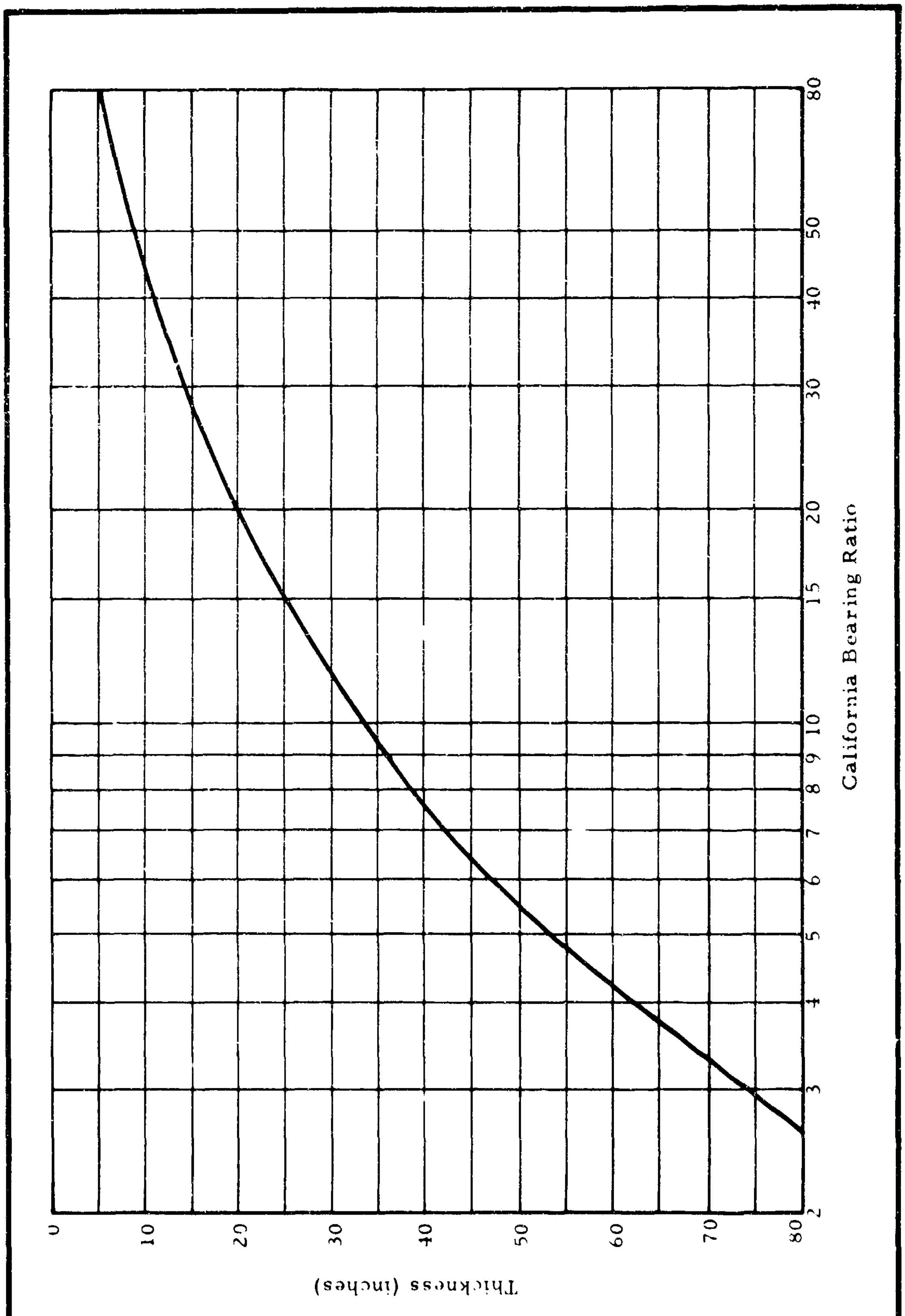

EXHIBIT 26 - CONCORDE FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

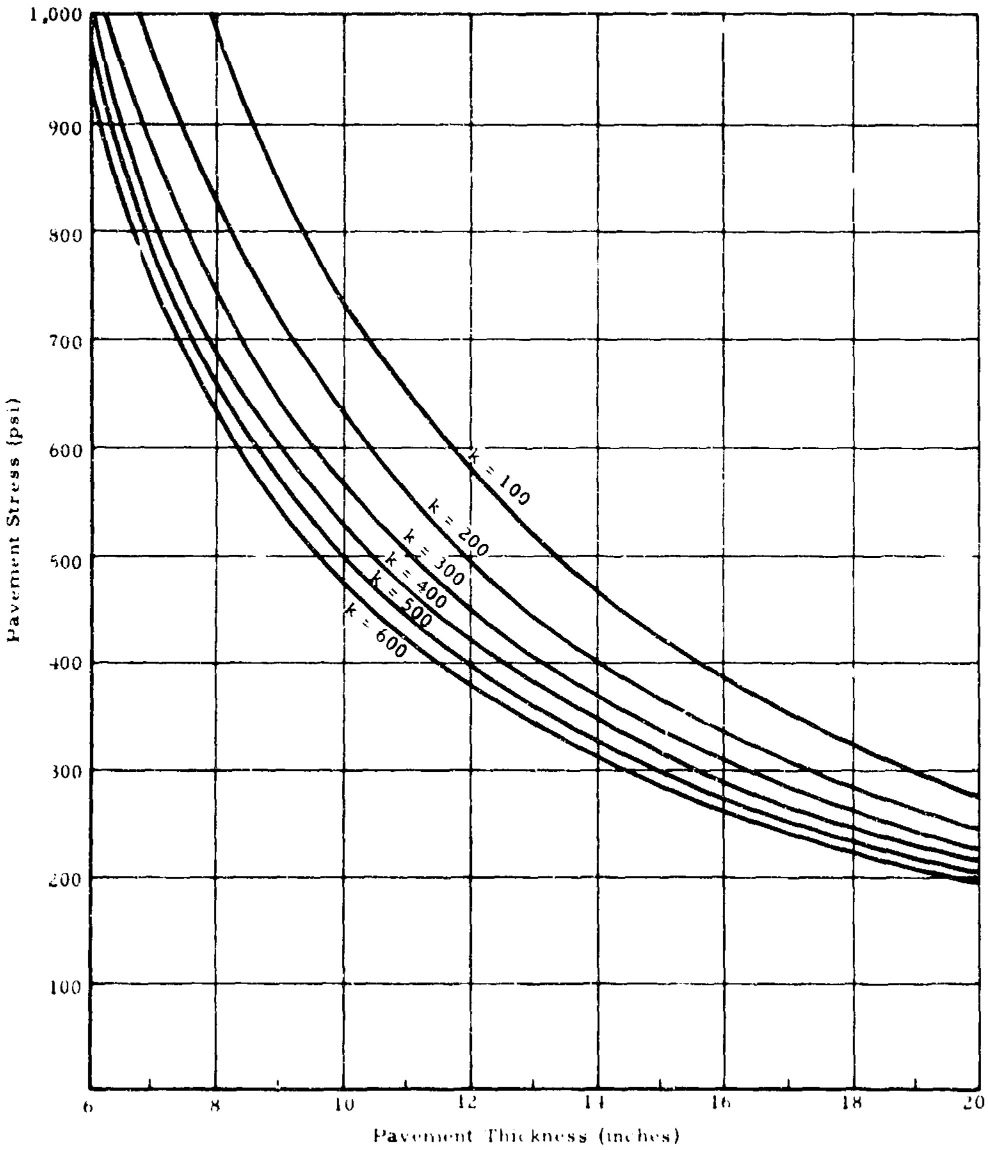

EXHIBIT 27 - CONCORDE RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	% of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire Imprint Area (sq. in.)	Tire Pressure (psi)	d/2 (in.)	2 SD (in.)
683,000	95	40,600	46 x 16	194	209	17.2	157.6

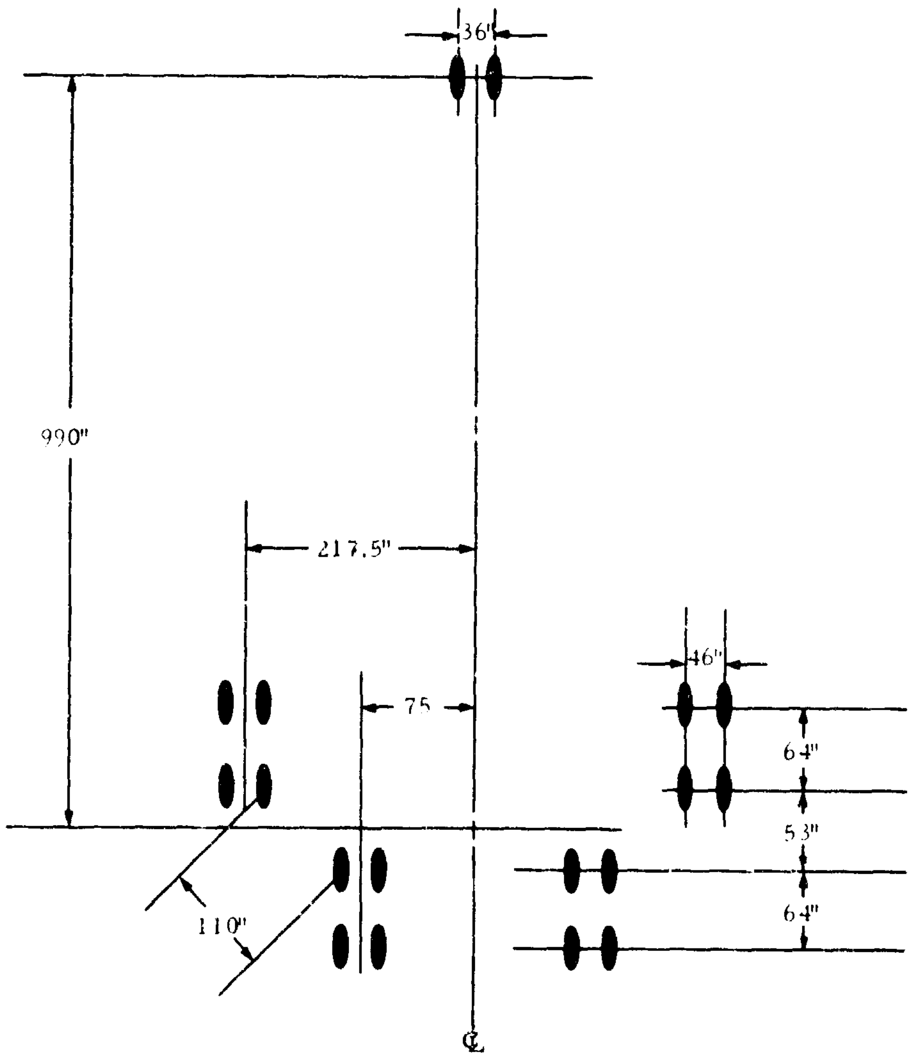

EXHIBIT 28 - B-747 PAVEMENT LOADING SUMMARY

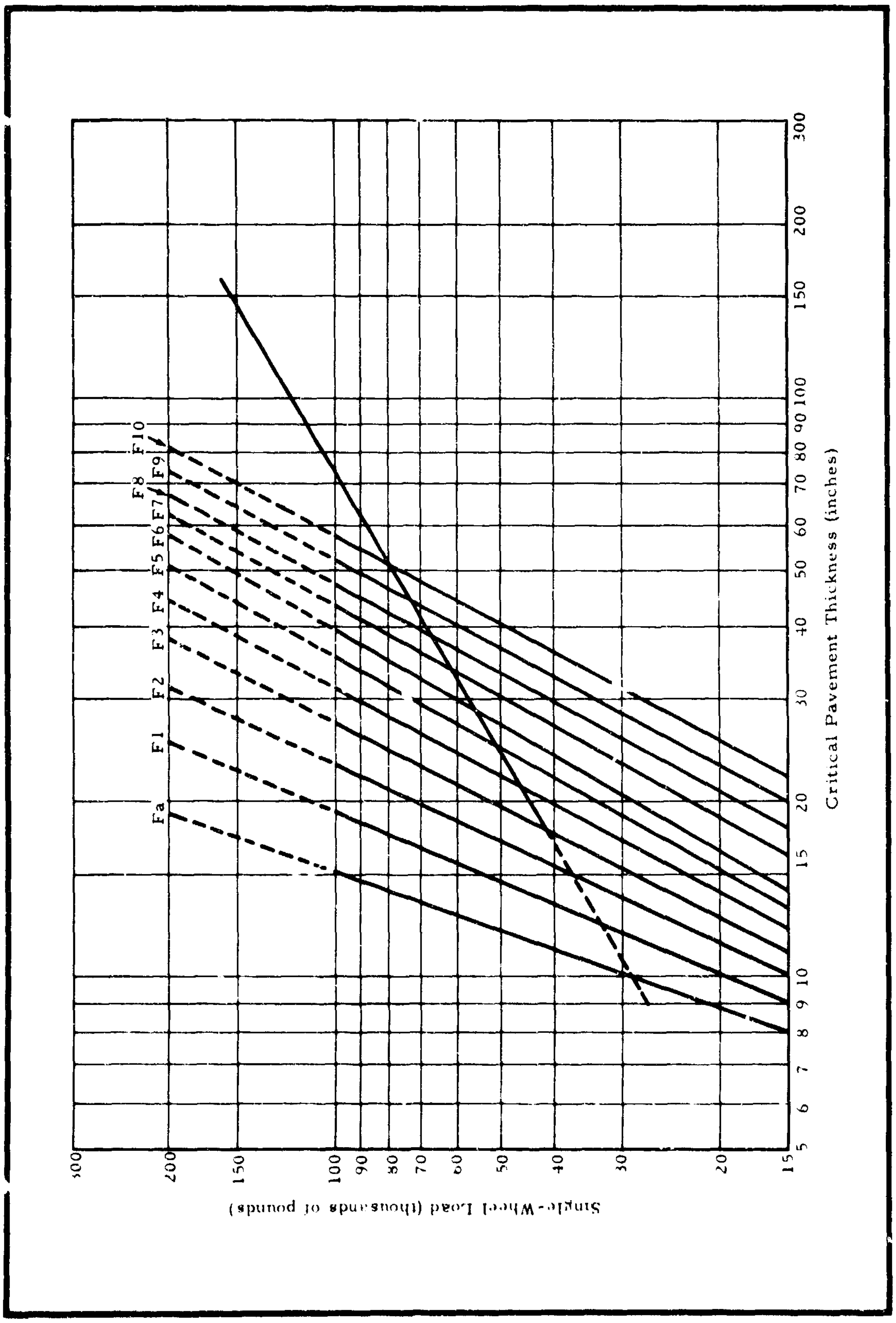

EXHIBIT 29 - B-747 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

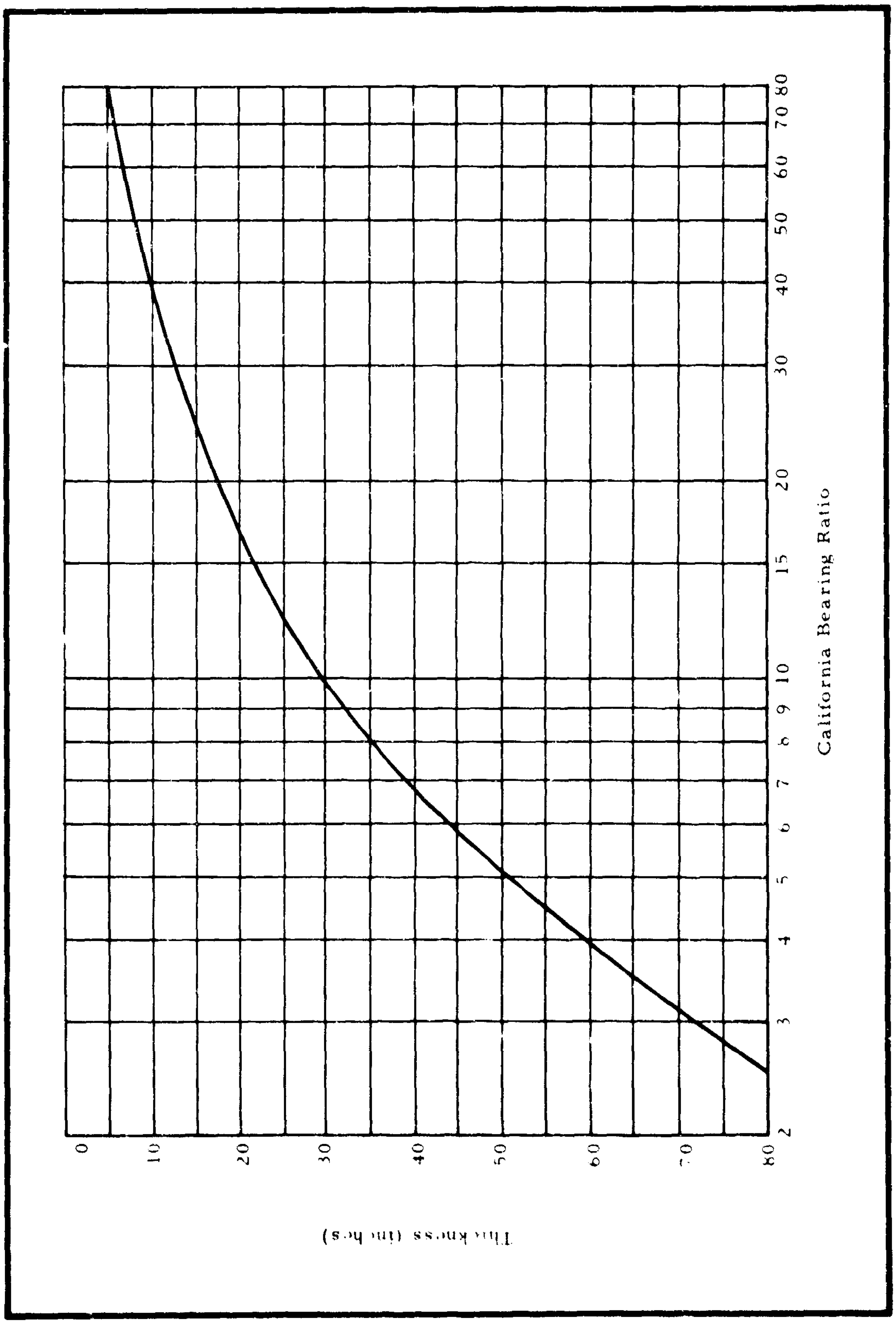

EXHIBIT 30 - B-747 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

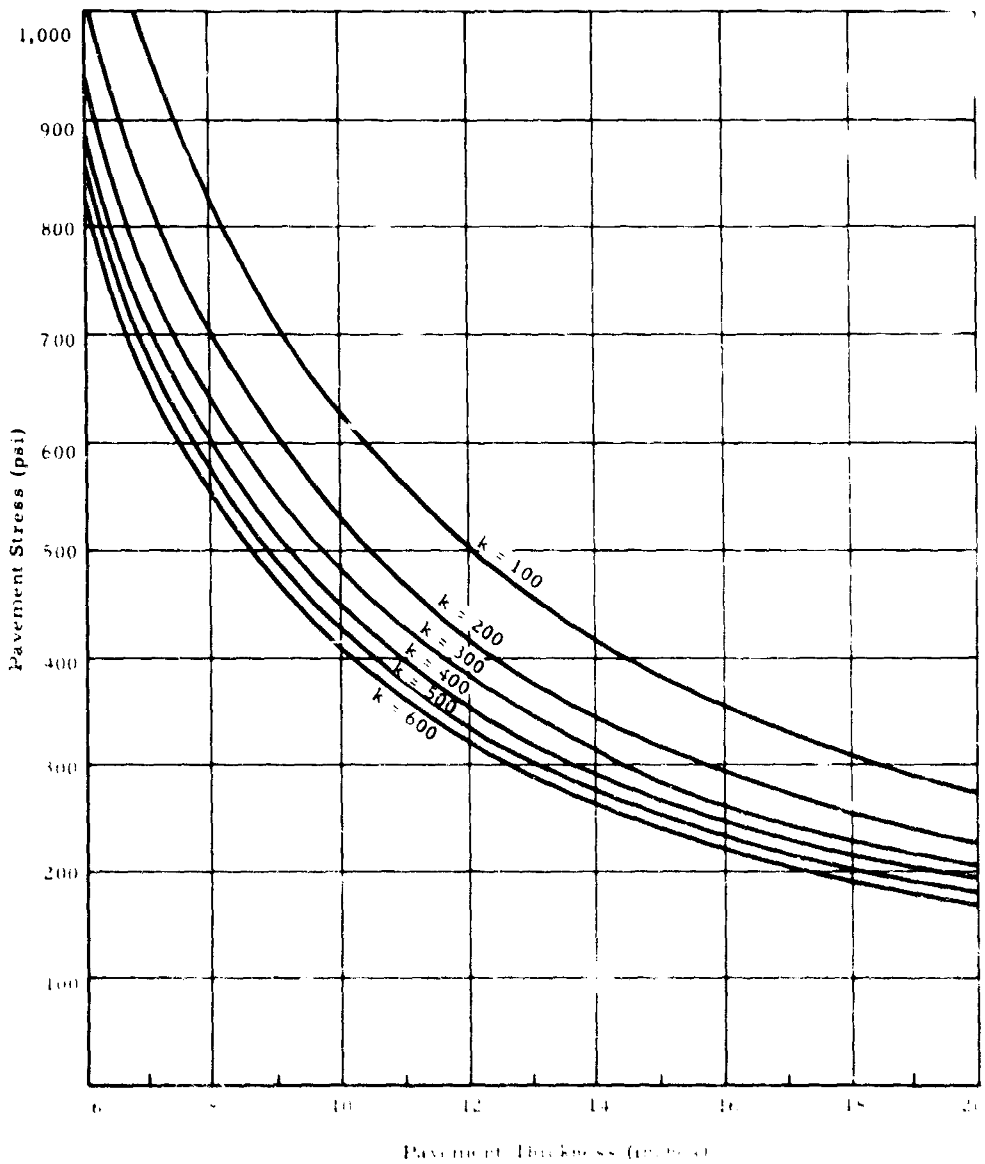

EXHIBIT 31 - B-747 RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	Percent of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire imprint Area (sq. in.)	Tire Pressure (psi)	d/2 (in.)	2SD (in.)
728,000	95	28,900	44 x 13	179	162	17.6	213.2

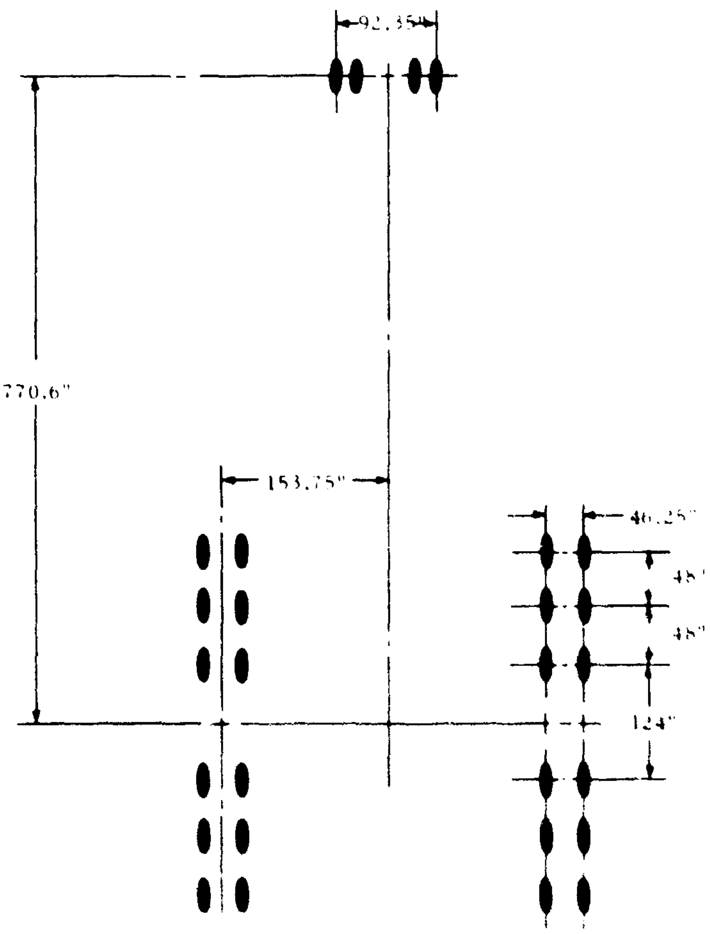

EXHIBIT 32 - L-500 PAVEMENT LOADING SUMMARY

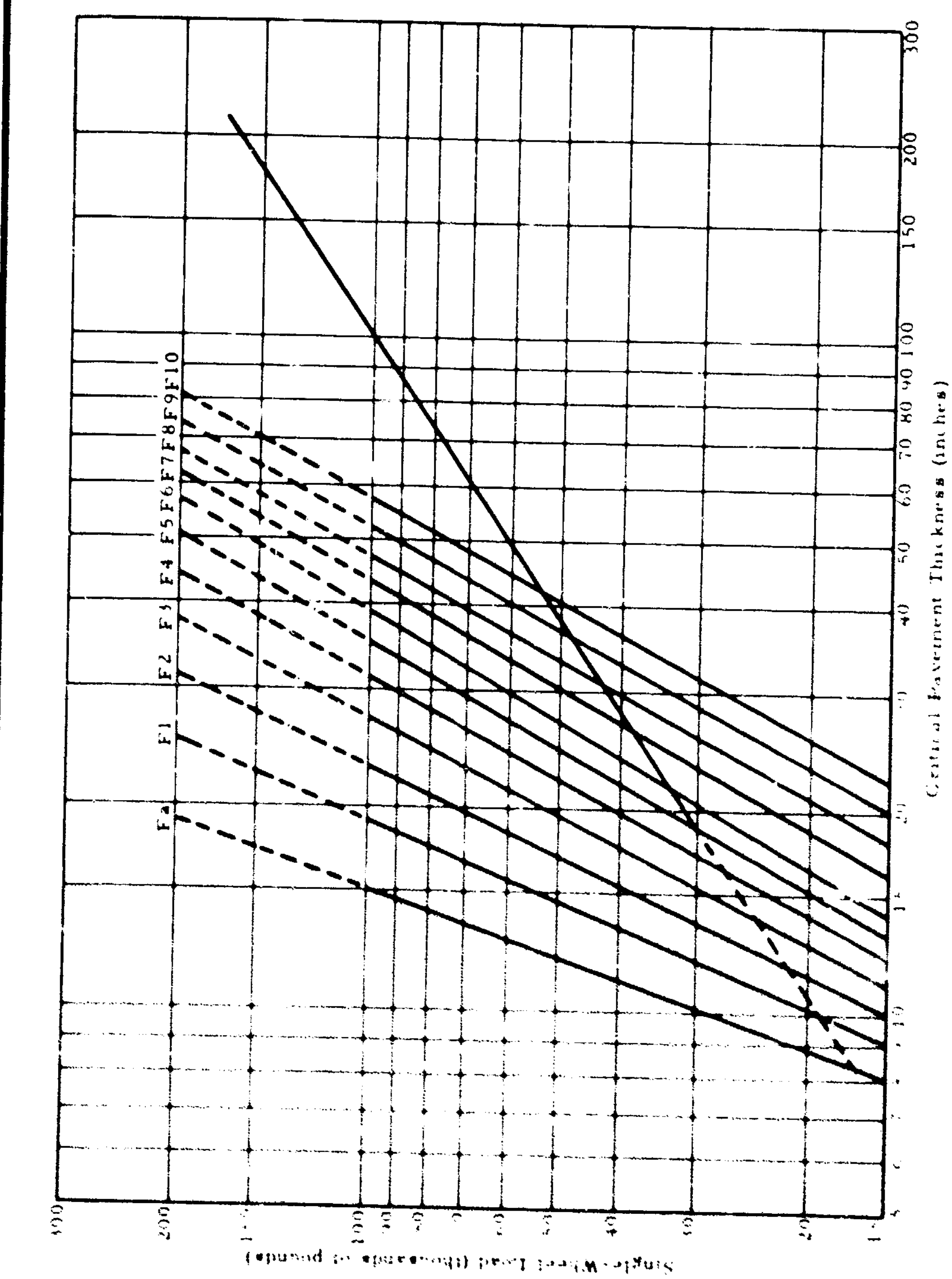

EXHIBIT 34 - L-500 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

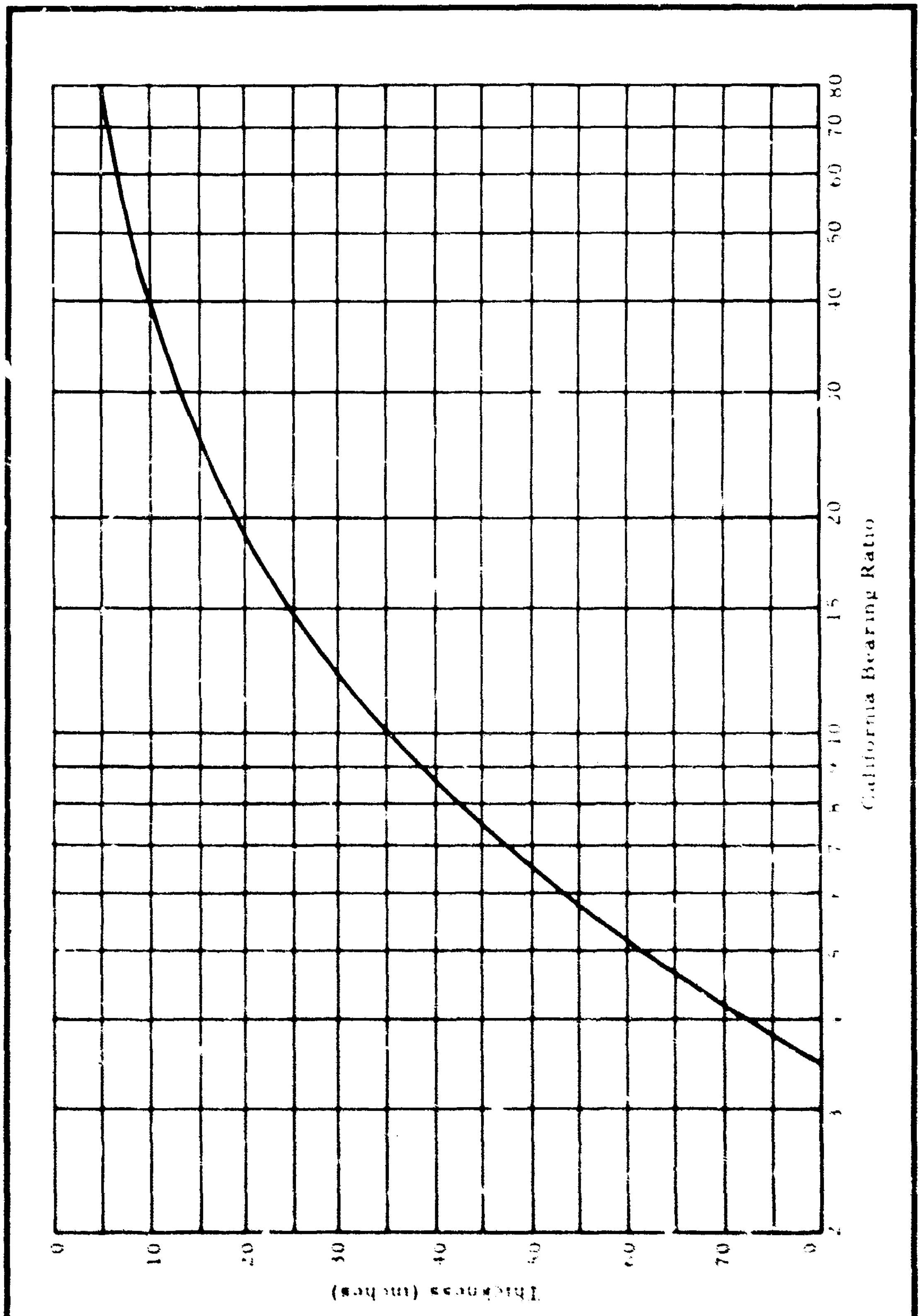

EXHIBIT 54 - L-500 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

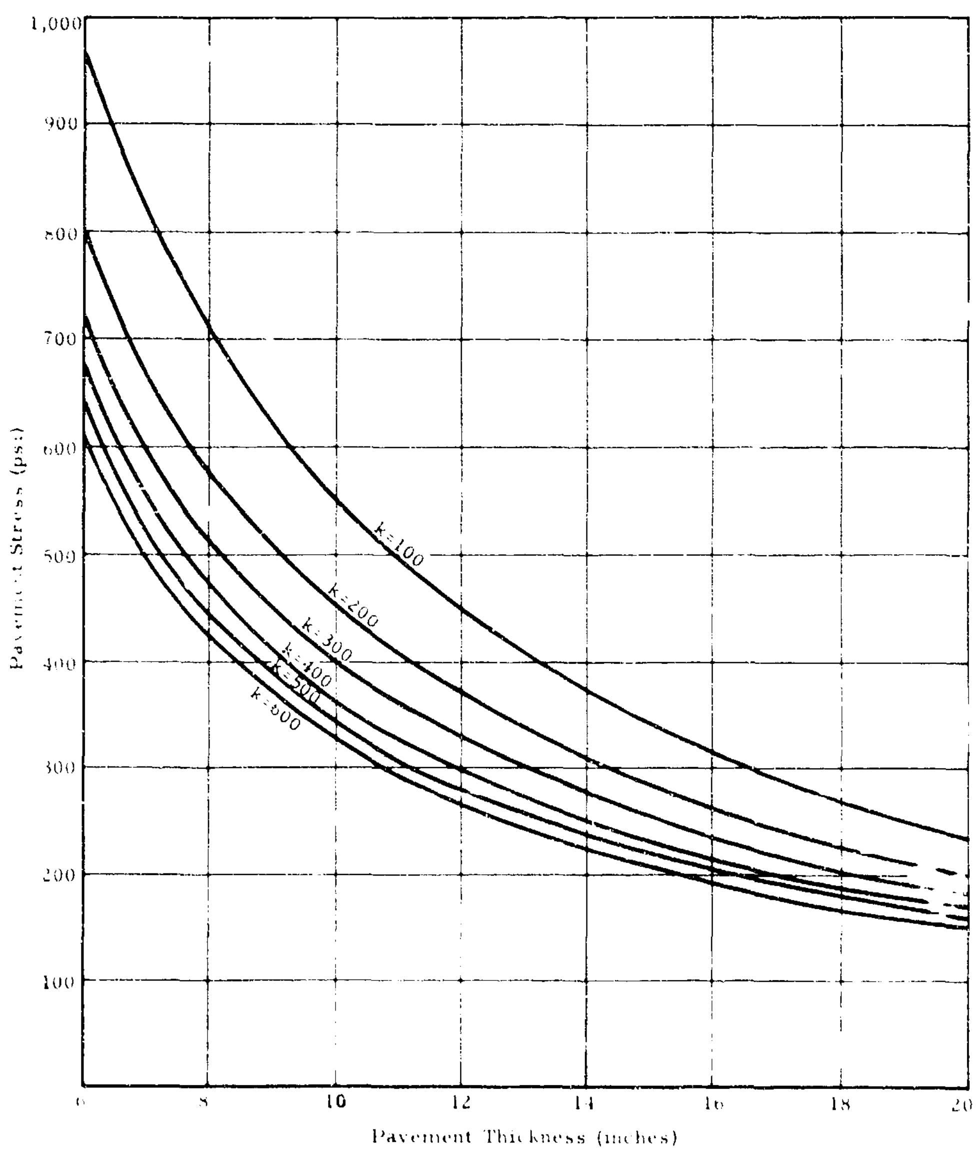

EXHIBIT 35 - L-500 RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	Percent of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire im-print Area (sq. in.)	Tire Pressure (psi)	2 (in.)	2SD (in.)
353,000	95	41,900	46 x 16	212	198	9.6	126.6

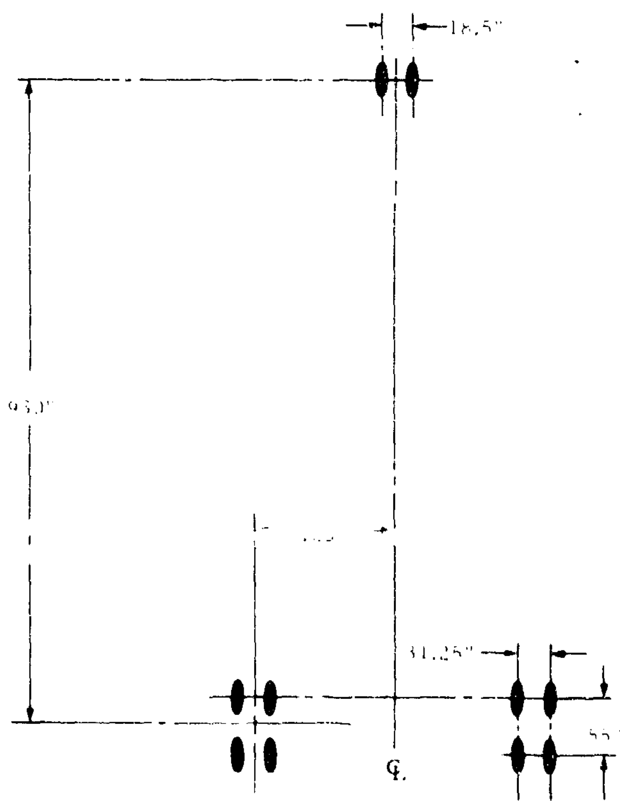

EXHIBIT 36 - DC-8-63 PAVEMENT LOADING SUMMARY

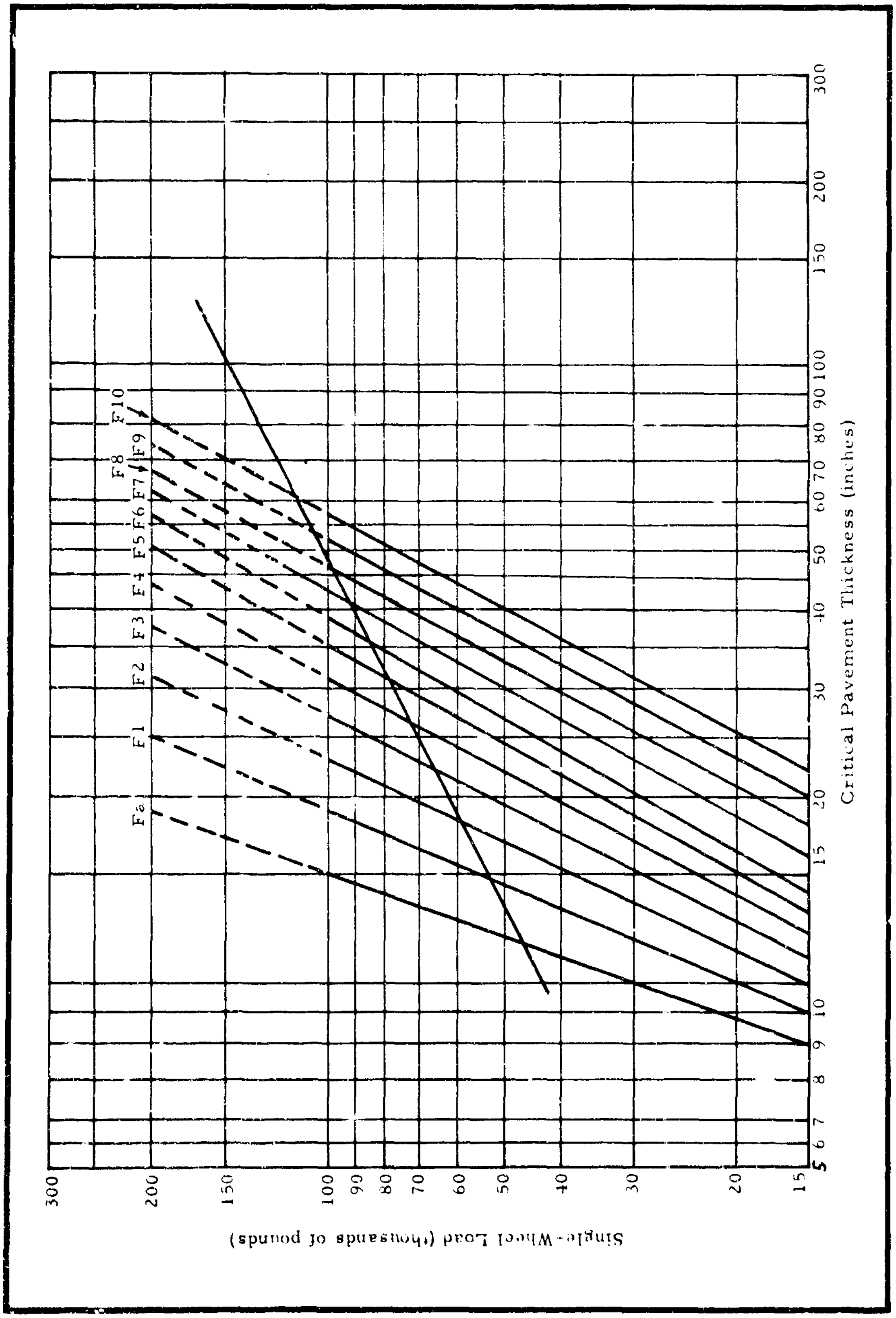

EXHIBIT 37 - DC-8-63 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

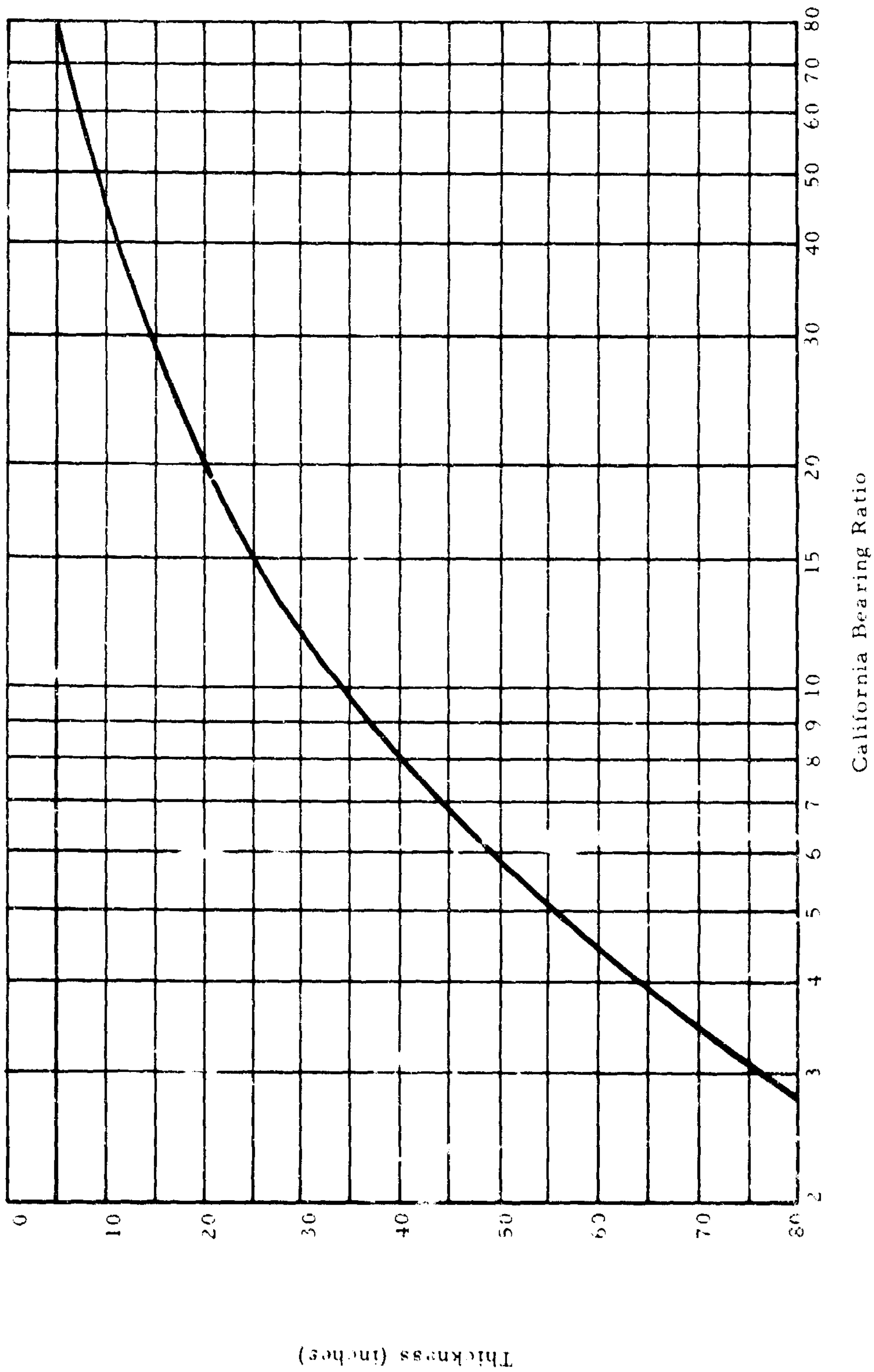

EXHIBIT 38 -DC-8-63 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

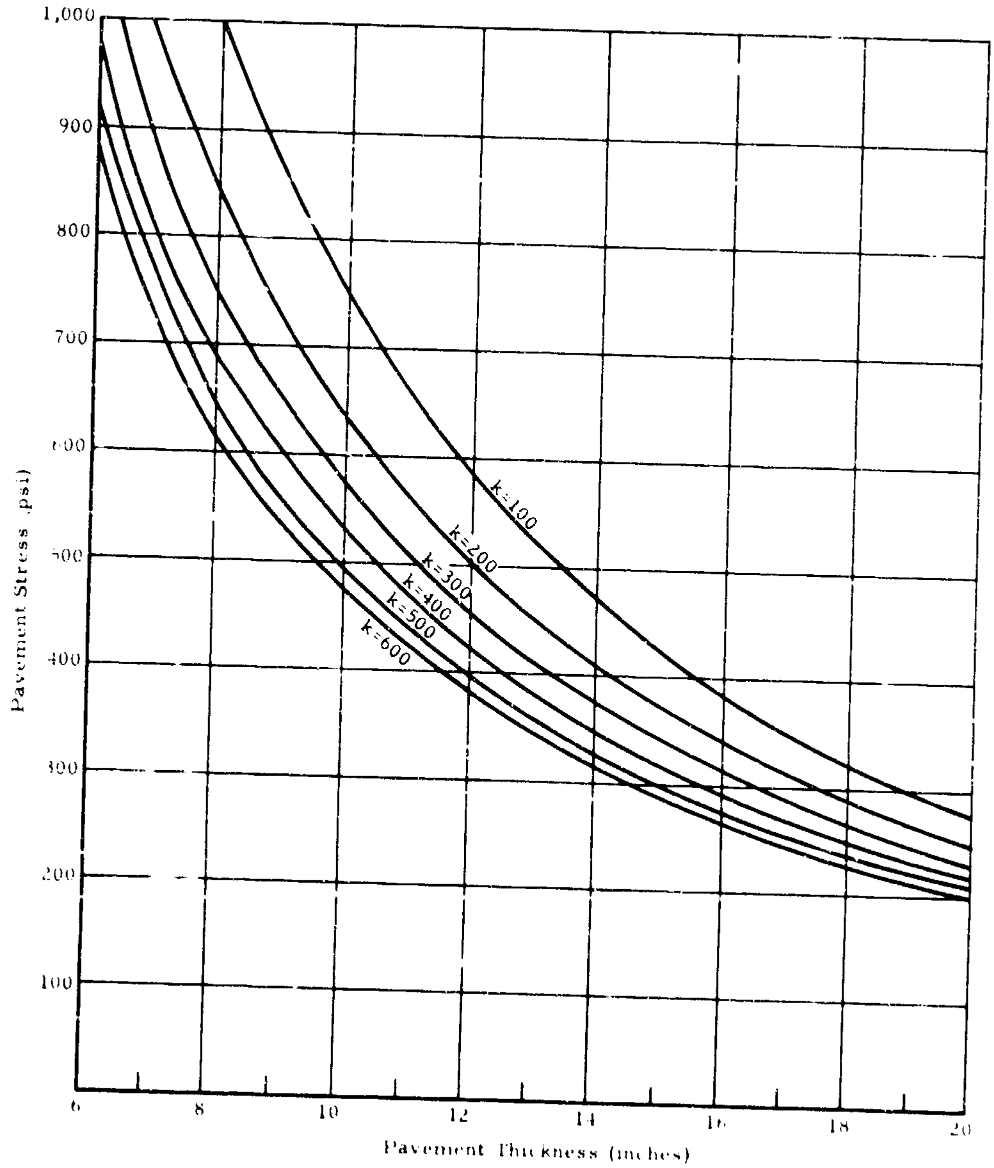

EXHIBIT 39 - DC-8-63 RIGID PAVEMENT STRESS, WESTERGAARD METHOD

Gross Ramp Weight	Percent of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire im-print Area (sq. in.)	Tire Pressure (psi)	d/2 (in.)	2SD (in.)
336,000	95	40,000	46 x 16	222	180	11.4	131.0

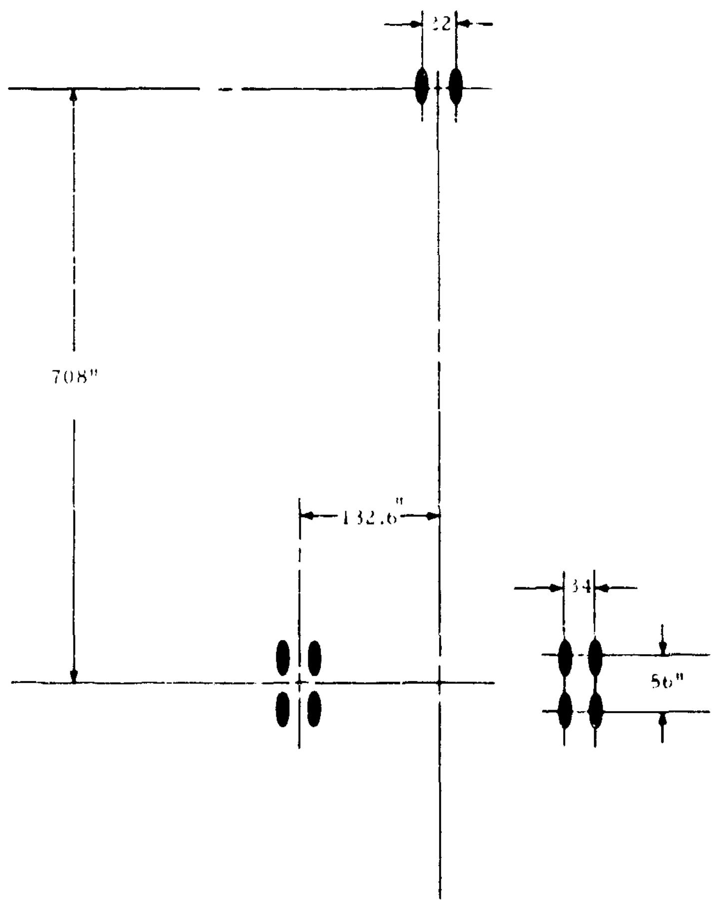

EXHIBIT 40 - B-707 PAVEMENT LOADING SUMMARY

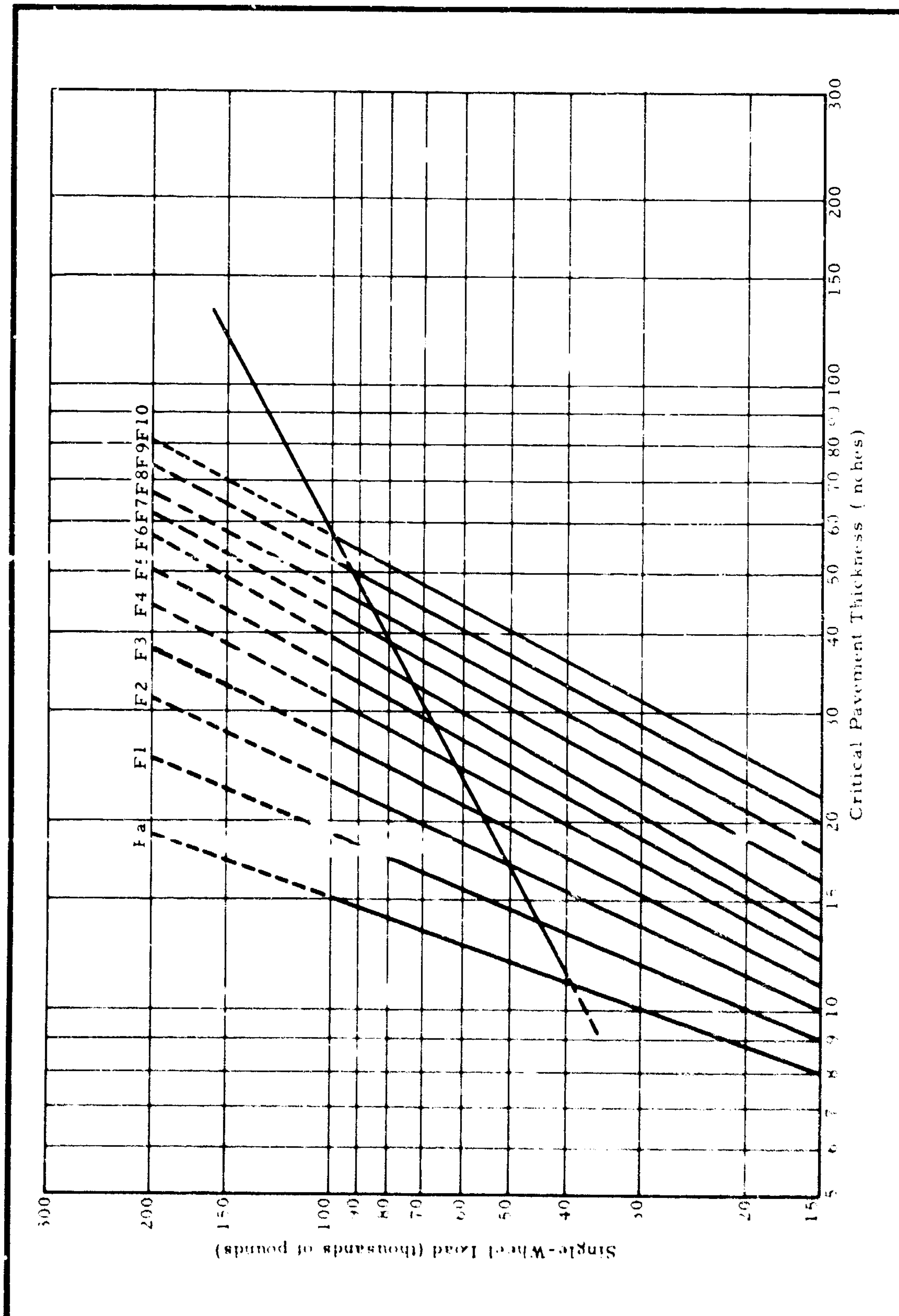

EXHIBIT 41 - B-707 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

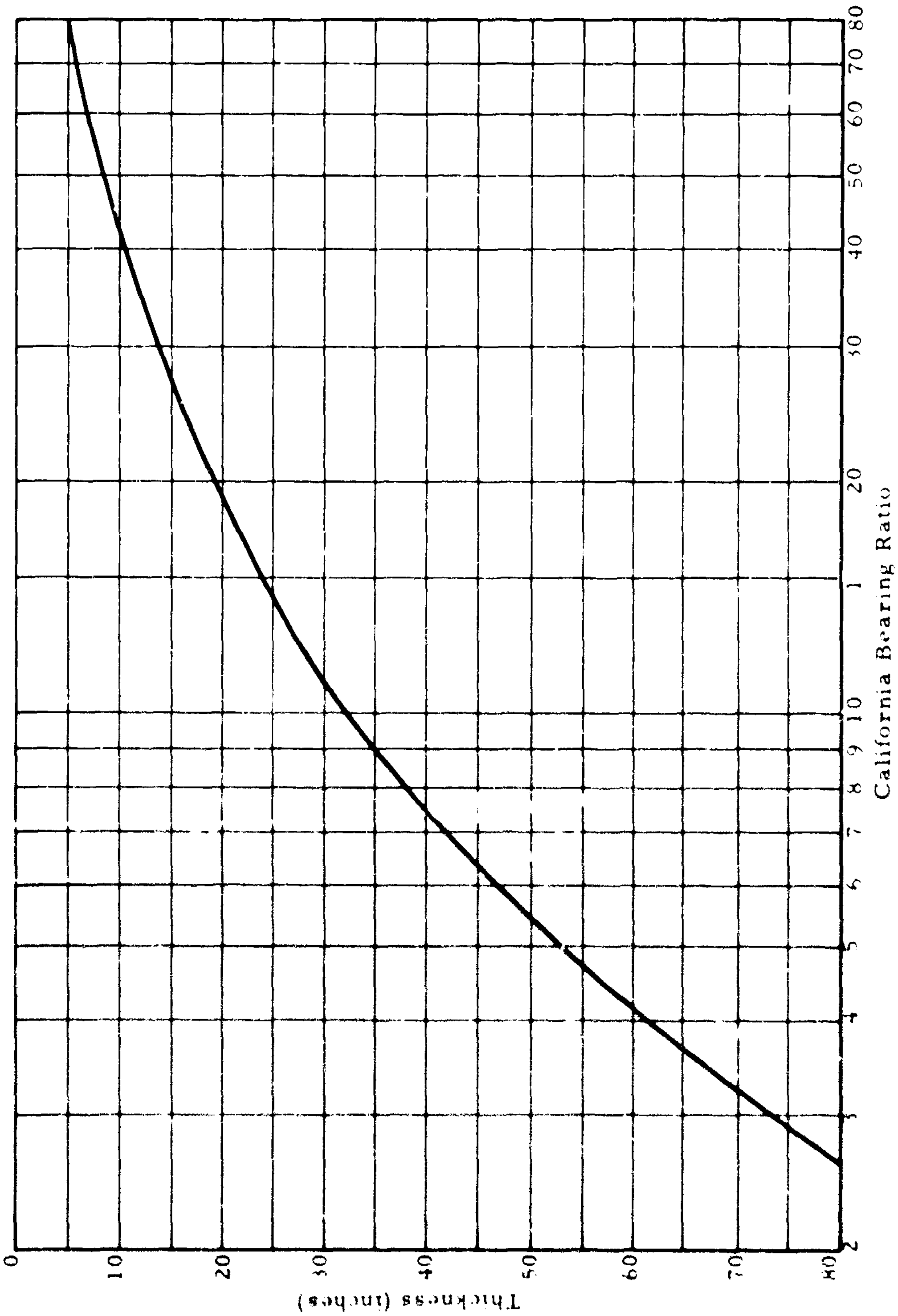

EXHIBIT 42 - B-707 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

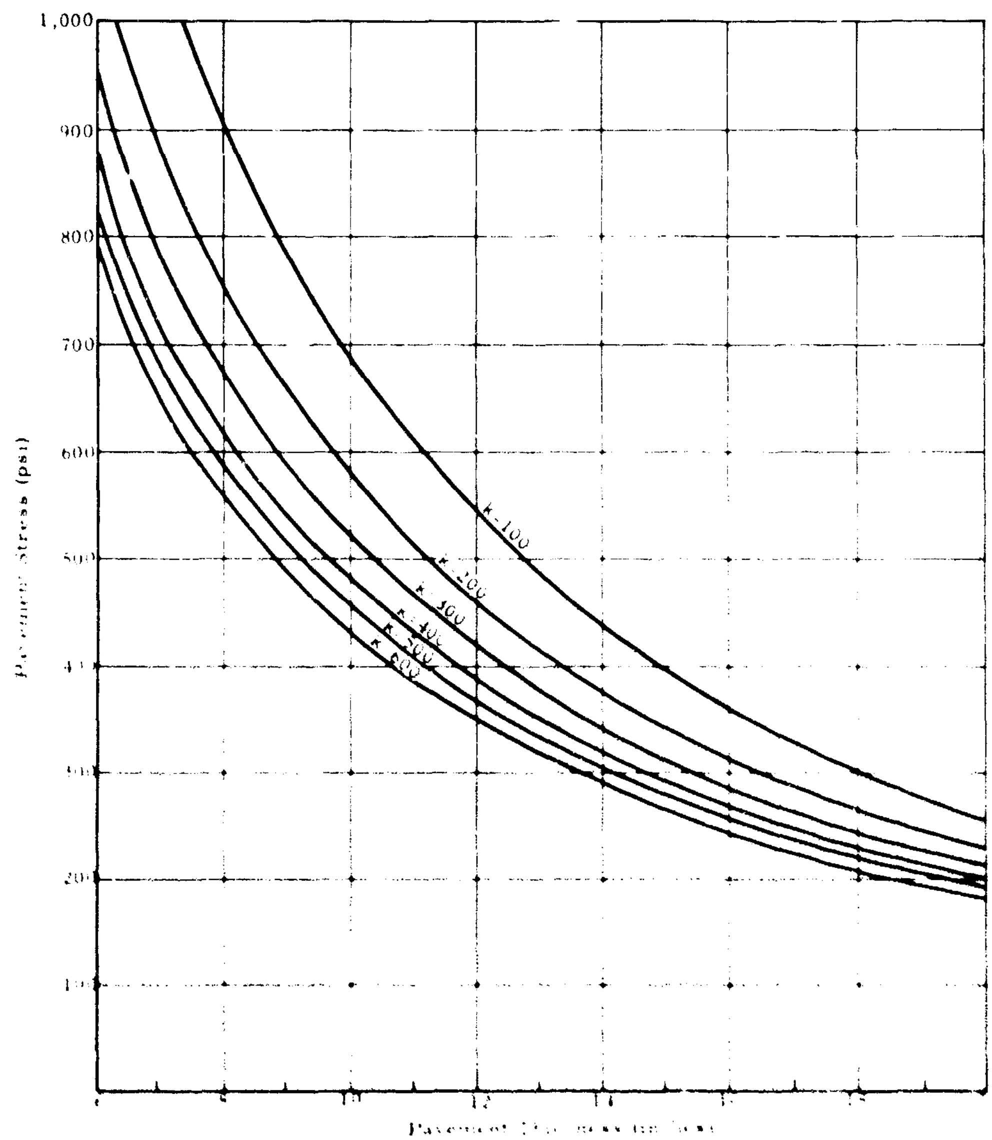

EXHIBIT 43 - B-707 RIGID PAVEMENT STRESS,
WESTERGAARD METHOD

OFFICIAL USE ONLY

Gross Ramp Weight	% of Weight on Main Gear	Load per Tire (lbs.)	Tire Size	Tire Imprint Area (sq. in.)	Tire Pressure (psi)	α-z (in.)	2 SD (in.)
328,000	95	[illegible],900	44 x 16	214	182	[illegible]4	125.4

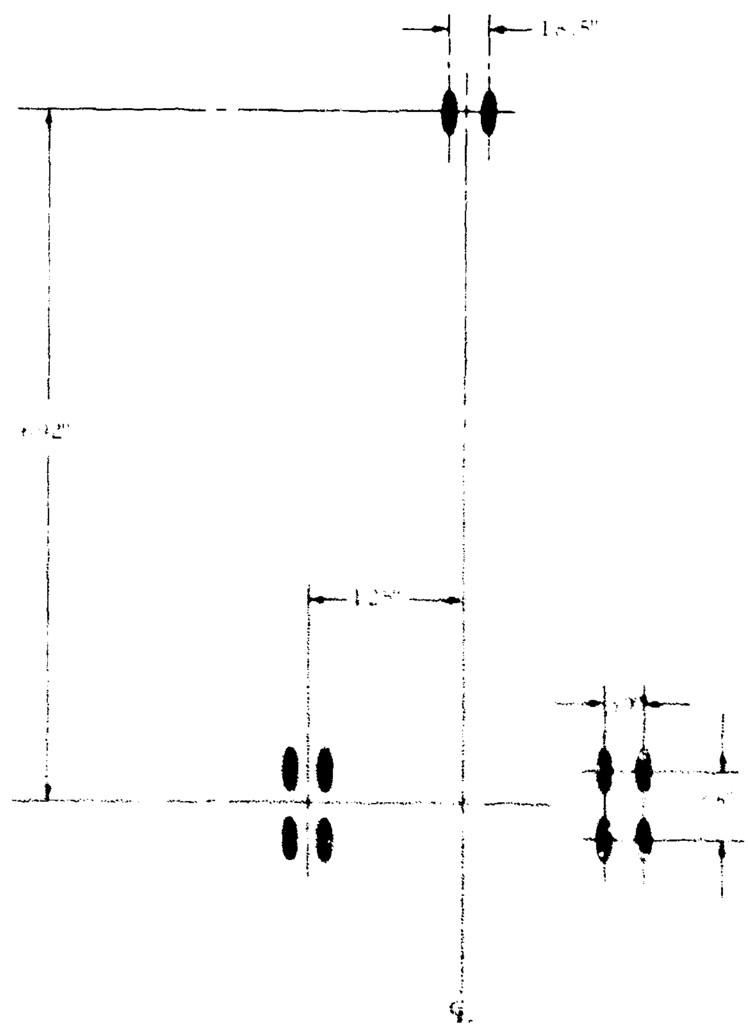

EXHIBIT 44 - DC-8-55 PAVEMENT LOADING SUMMARY

OFFICIAL USE ONLY

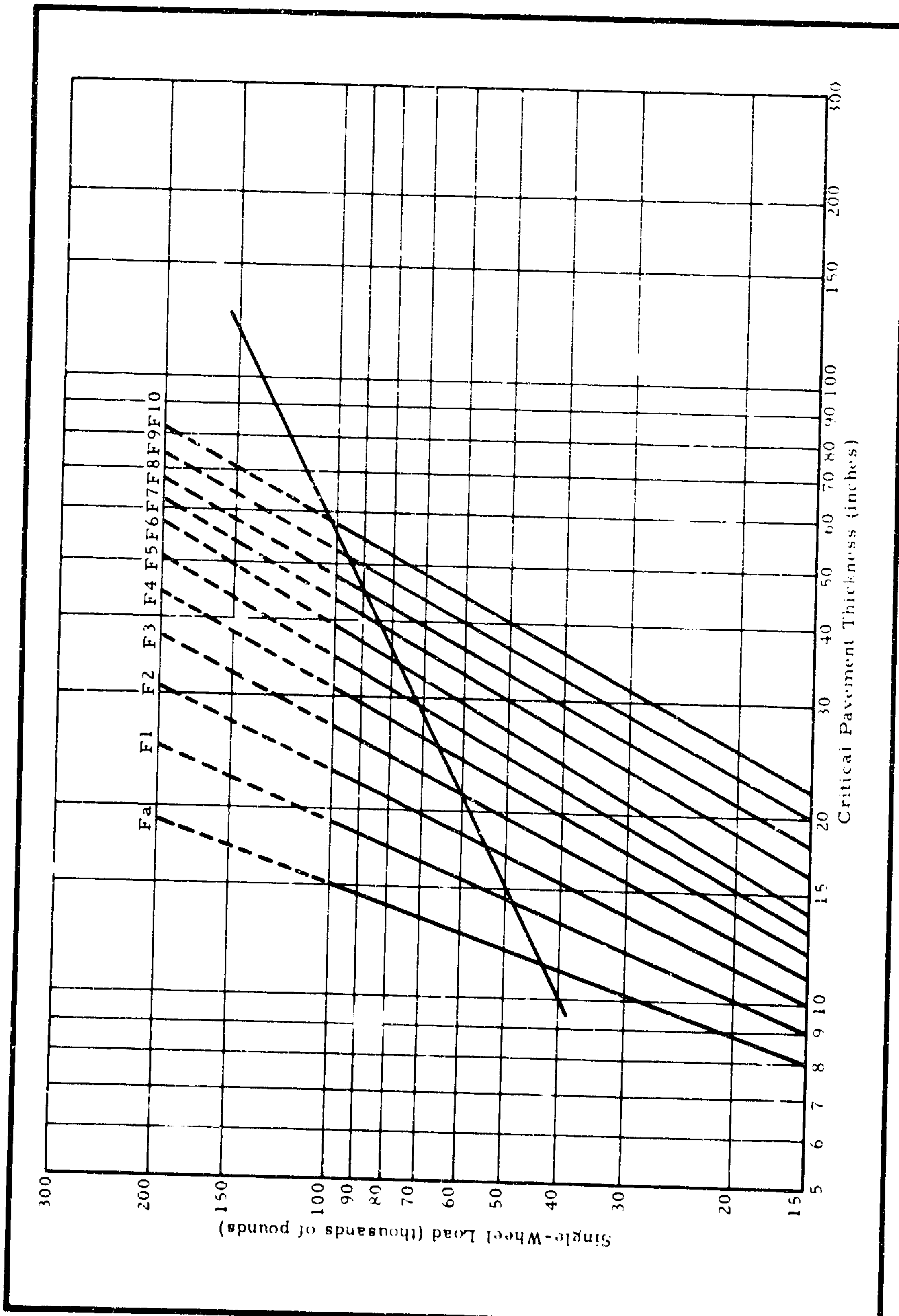

EXHIBIT 45 - DC-8-55 FLEXIBLE PAVEMENT CRITICAL THICKNESS, FAA METHOD

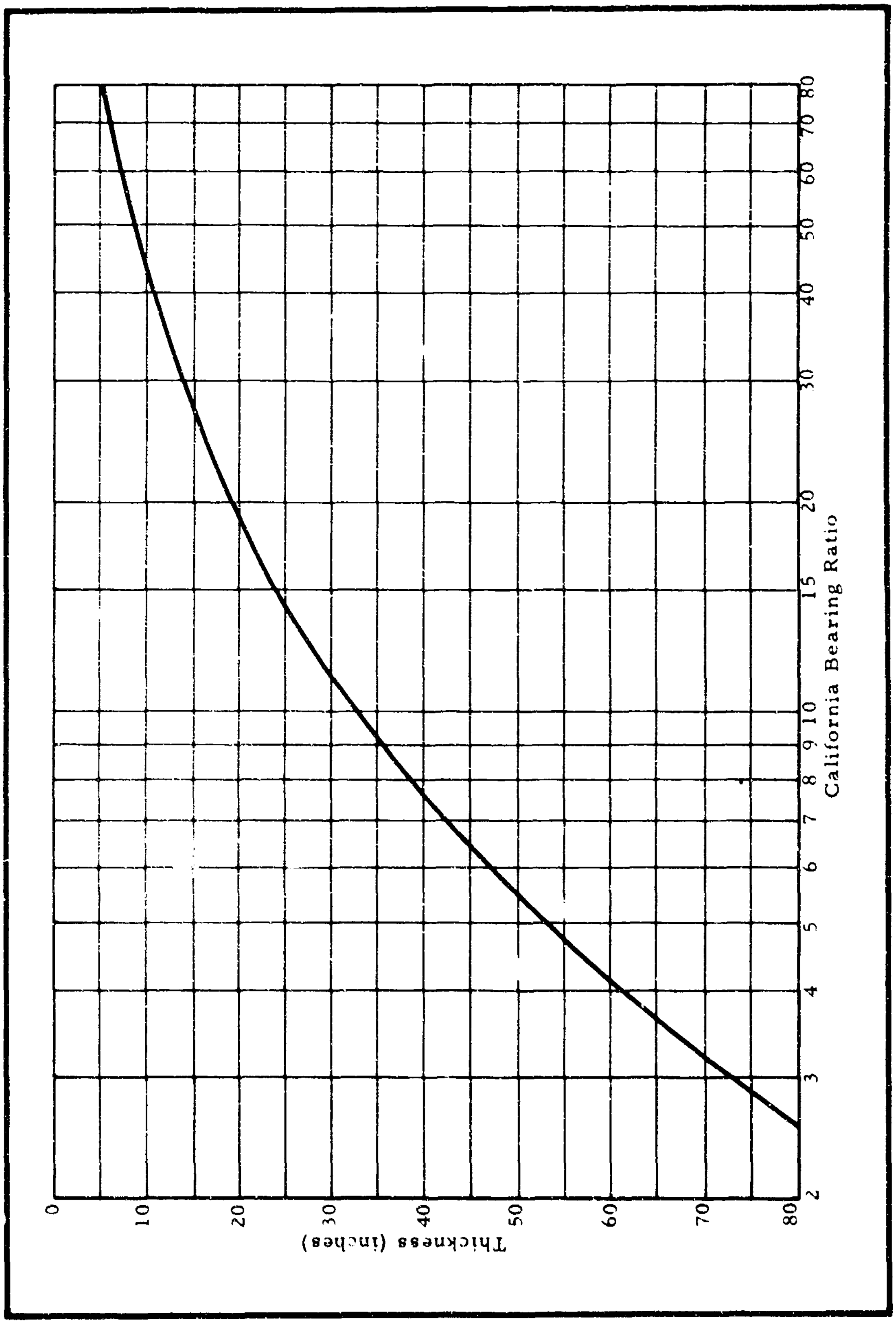

EXHIBIT 46 - DC-8-55 FLEXIBLE PAVEMENT CRITICAL THICKNESS, CBR METHOD

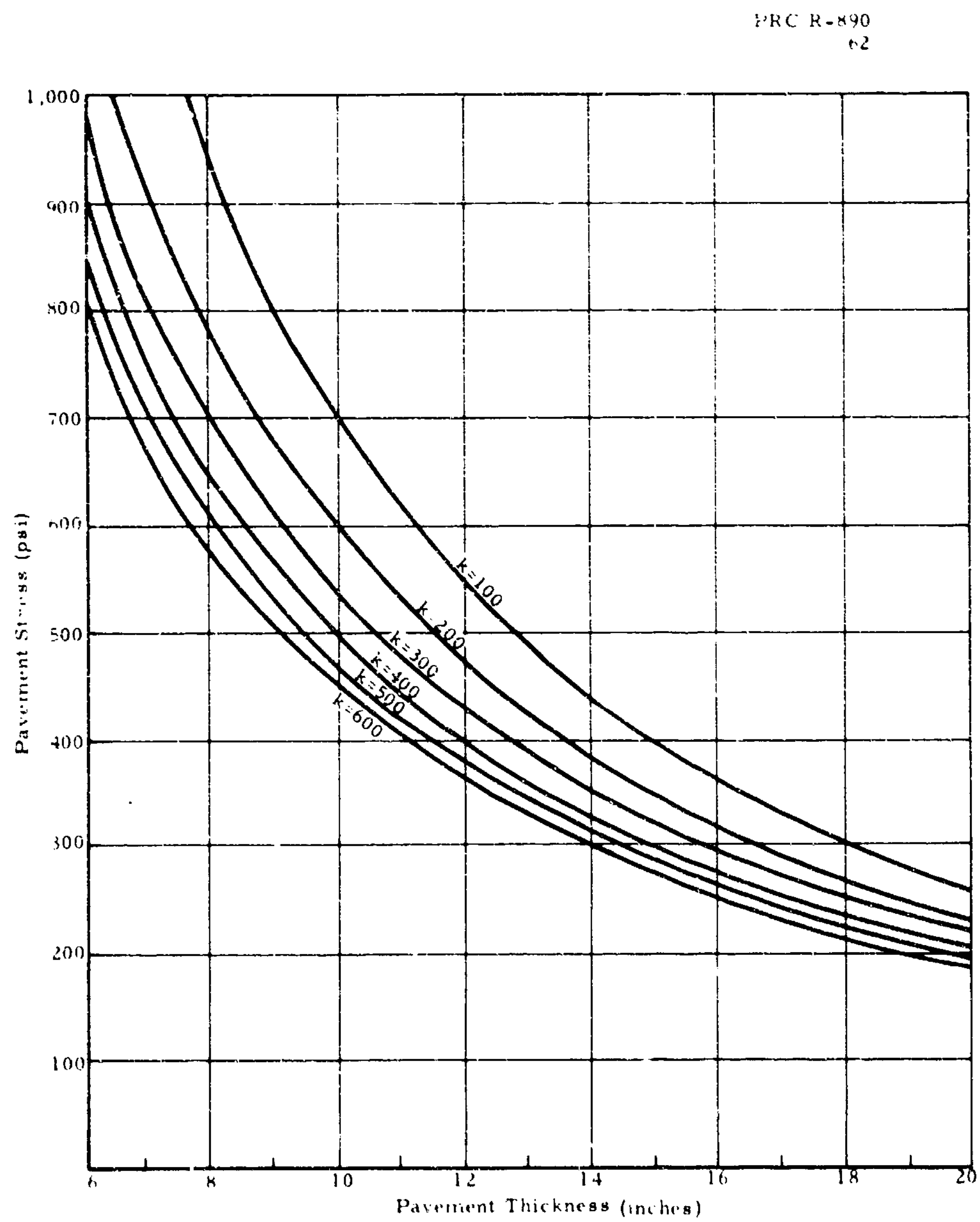

EXHIBIT 47 - DC-8-55 RIGID PAVEMENT STRESS, WESTERGAARD METHOD