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RUNWAY DESIGN METHODS FOR MULTIPLE WHEEL LANDING GEARS

Prepared in the Air Navigation Bureau and published by authority of the Secretary General

INTERNATIONAL CIVIL AVIATION ORGANIZATION
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INTRODUCTION

Dual wheel landing gears first made their appearance on civil aircraft following the end of the second world war. Although this new type of undercarriage was introduced for purely aeronautical reasons (decrease of total weight of wheels and reduction of the amount of space required in the fuselage or in the wings for housing the undercarriage), it also proved of benefit from the point of view of the problem of runway strength. Since that time, with the increasing weight of aircraft, main undercarriage legs fitted with four, or even eight-wheel bogies have been developed. During this period tire pressures were also increased for the same purely aeronautical reasons. In the case of certain military aircraft, pressures of over 200 p.s.i. (14 kg/sq.cm) are now used. For civil aircraft, however, tire pressures for prototypes under development do not yet exceed 140 p.s.i. (14 kg/sq.cm). This increase has made it necessary for engineers of Public Works departments to draw new curves for the design strength of runways.

The first two sessions of the AGA Division of ICAO proposed rules regarding runway strength requirements, using as a basis the total weight of aircraft. This value is not sufficient, however, for calculation of stresses in pavements, since it does not indicate the manner in which the load is distributed. In 1947, therefore, the Third Session of the Division proposed that runway strength should be defined in terms of single isolated wheel load, i.e., in terms of a hypothetical single wheel which would produce the same maximum stresses in the pavement as would all the wheels of the aircraft. Knowing the single isolated wheel load and the tire pressure, an aerodrome designer can easily calculate the required thickness for the pavement of any aerodrome planned. This same datum was frequently used by AGA committees of regional air navigation meetings in framing their recommendations concerning development of aerodromes in the region concerned. Conversely, knowing the single isolated wheel load that can be supported by the pavement of an existing aerodrome, it is possible, by means of certain calculations, to determine whether that pavement can support a given aircraft, the wheel arrangement of which is known.

The object of this Circular is to gather together information received from various States or found in various technical reviews, on the landing gears of various types of commercial aircraft currently in use or which will be used within the next few years, and on runway design methods for multiple wheel landing gears.

The Circular is divided into three Parts. Part I covers available data on aircraft. Part II explains design methods for rigid pavements and Part III design methods for flexible pavements.

The Conclusion attempts to outline the problem now facing the operators and considers possible solutions.

PART I

TECHNICAL DATA ON THE LANDING GEARS OF SOME COMMERCIAL AIRCRAFT

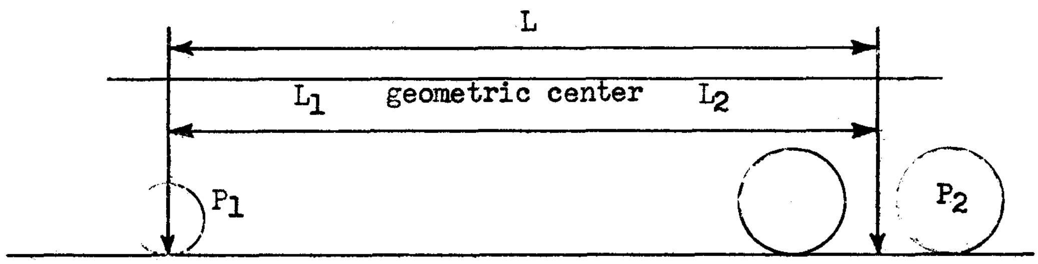
1. Table 1 provides information on the characteristics of certain aircraft, but lists only those characteristics which have a bearing on runway design. Wheel-base and tread-width have not been included, since these dimensions in the case of the aircraft types listed are such that there is no possibility of interference between the stresses caused by each landing gear unit. Data concerning the forward landing gear unit, which is not the one which causes the greatest stresses,were nevertheless included, as it was felt that it might be interesting to show the trend of design in this particular field: more widespread use of dual wheels and increases in tire pressures. All the figures in Table 1, except those marked with an asterisk and those under "load on forward gear", "load on each main landing gear" are those provided by the States of manufacture, either in reply to a letter from the Secretariat on the subject or in their preparatory documentation for recent regional air navigation meetings. Figures marked with an asterisk are taken from a pamphlet entitled "Design of Concrete Airport Pavement" published by the Portland Cement Association.

2. The figures indicating the distribution of the over-all weight of the aircraft over the different units of the landing gear were determined as follows: only the static distribution of the aircraft load was taken into account; it is realized, however, that the transfer of loads resulting from the dynamic effect due to braking tends to increase the load on the forward landing gear unit and decreases the load on the main units which transmit the heaviest load. It is known, moreover, that when an aircraft is in motion the resulting stresses in the pavement are less than those caused by a stationary aircraft. It is the static load, therefore, that interests us.

The static distribution of the load between the forward unit and the main unit group is (see figure 1):

$P_1L_1 = P_2L_2$; P_2 being expressed in terms of the total load of the aircraft, P, and the ratio $\frac{L_1}{L}$ we obtain $P_2 = \frac{P\,L_1}{L}$

$\frac{L_1}{L}$ generally falls between 0.85 and 0.90, hence $\frac{P_2}{P}$ also falls between the same limits. A fixed value of 0.9 was used for all the types of aircraft included in the table, thus allowing a safety margin in certain cases.



$P = P_1 + P_2$

Figure 1

3. Photographs of three of the most commonly used landing gear wheel arrangements are reproduced through the courtesy of the Portland Cement Association (see figures 2, 3 and 4).

Part II

RIGID PAVEMENTS

1. Stress calculations for a concrete slab, and therefore the determination of the thickness of slabs are at present based on two methods involving different assumptions. In the first method, the runway subgrade is considered as an elastic, isotropic and homogenous body of semi-infinite dimensions to which the theory of elasticity is wholly applicable (Hogg, Burmister and Bergström); in the second, the runway subgrade is considered as a dense liquid, deformation in which is proportional to pressures applied (Westergard and de l'Hortet). It is not within the scope of this circular, however, to discuss the advantages and disadvantages of either method. Naturally, in most cases the subgrade does not behave either in accordance with the first or the second of these two hypothesis. Only the second method, however, has produced systematic calculations and generally applicable graphs and diagrams. It is therefore essentially this second method that is presented here.

2.- USE OF THE WESTERGARD METHOD*

2.1 The Westergard formula appeared in the ICAO Secretariat Doc 4209-AGA/509 of 22 April 1947, at the AGA Division's third session. This formula is difficult enough to use in the case of a simple load and cannot be applied without the aid of influence charts, if the problem becomes more complex. Two American engineers (Gerald Pickett and G.K. Ray**) in the Proceedings of the American Society of Civil Engineers, set up these influence charts for the following cases:

a) load at the centre of a slab;

b) load near the edge of a slab;

* This portion of the circular was drafted through the courtesy of the Portland Cement Association, Chicago, Illinois, who have authorized ICAO to use their "Design of Concrete Airport Pavement" and to reproduce excerpts therefrom.

** Proceedings of the American Society of Civil Engineers, Vol. 76, No. 12, April, 50, Influence charts for concrete pavements by Gerald Pickett and G.K. Ray from ASCE.

c) load at a distance from the edge approximately equal to half the radius of relative stiffness of the slab.

These charts enable the moments and deflections of any wheel arrangement to be determined, provided that the law of superposition of stresses is accepted.

2.2 Using the influence charts prepared by Pickett and Ray for loads at the centre of slabs, the Portland Cement Association was recently able to publish three design charts which are shown in this circular in figures 5, 6 and 7. The first one applies to single wheel loads (figure 5); the second to dual wheel loads, the wheel spacing being the one most currently used in the United States for the various loads (figure 6); the third to loads produced by the dual tandem assembly of a B-36 (figure 7). These charts were determined for concrete having a modulus of elasticity E of $4x10^6$ p.s.i. (280 000 kg/sq. cm) and a Poisson's ratio μ of 0.15. According to the Portland Cement Association booklet, the effects of varying the values of E and μ are approximately the following: a decrease from $4x10^6$ p.s.i. (280 000 kg/sq.cm) to $3x10^6$ p.s.i. (210 000 kg/sq.cm) in the value of E, produces a 5% decrease in the stresses, while an increase in E from $4x10^6$ p.s.i. (280 000 kg/sq.cm) to $5x10^6$ p.s.i. (350 000 kg/sq.cm) produces a 4% increase in the stresses; an increase in the value of μ from 0.15 to 0.20 causes a 4% stress increase; an increase in μ from 0.15 to 0.25 raises the stress values by 8%.

2.3 The charts have been established using as tire contact area a rectangle, such that the width is equal to 3/5 of the length, and with semi-circular ends. Its area is equal to the wheel load divided by the tire pressure.

2.4 For the use of these charts, we quote the explanations given in the Portland Cement Association booklet:

2.4.1 "The allowable working stress is obtained by dividing the modulus of rupture of the concrete by appropriate safety factors as given below:

Installation	Safety Factor
Aprons, taxiways, runway ends, hangar floors	1.8 - 2.0
Runways (central portion)	1.3 - 1.5

On very busy aerodromes, safety factors of 2 and 1.5 are used; on fields where operations are less frequent, values of 1.8 and 1.3 are adequate.

2.4.2 The "k" value of the subgrade must be determined.

2.4.3 The load and its distribution, as well as the tire pressure of the aircraft for which the required slab thickness must be designed, are naturally known beforehand.

2.4.4 To use the chart, a point on the "allowable stress" ordinate is selected. A straight line is drawn through it, parallel to the x axis until it meets the "k" curve (existing or interpolated); from this point of intersection a parallel to the y axis is drawn until it meets the straight line (existing or interpolated) which represents the characteristics of the given aircraft. From this new point of intersection, a parallel to the x axis is traced, giving the slab thickness."

2.4.5 These charts may of course be used in reverse i.e., it is possible to determine the stresses produced in a given pavement due to a certain load, if the "k" value is also known. They therefore constitute a means of determining the strength of an existing runway.

2.5 It must be noted that these charts do not provide an accurate solution to every problem. They are fully applicable only to certain loads and to specific wheel assemblies and tire pressures. In other cases, it is necessary to interpolate if approximate results are acceptable or, when accuracy is sought, to perform calculations with the help of influence charts provided by Pickett and Ray in the afore-mentioned publication.

2.6 For dual wheel assemblies of other types, the Portland Cement Association booklet gives the following approximate correction factors:

1) For increases in tire spacing of up to 10 in. (25.4 cm), the required thickness should be reduced by 0.6 per cent for every inch (2.54 cm) increase.

2) For every inch (2.54 cm) decrease in this spacing, the required thickness should be increased by 0.6 per cent.

2.7 It is important to note that these influence charts were successfully tested by the U.S. Corps of Engineers on both reduced and full scale models. The results obtained proved the charts, and hence the Westergard formula, to be correct.

2.8 Although the Portland Cement Association's design charts do not provide means of determining immediately the equivalent isolated wheel load, it is sometimes possible to do so indirectly as shown by the following example:

2.8.1 The subgrade reaction modulus k of a runway is 100 lbs. per cu. in. (2.77 kg/cu. cm), the modulus of rupture of the concrete is 450 p.s.i. (31 kg/sq. cm) and the slab thickness is 12 inches (30.5 cm). According to the Portland Cement Association's charts, and using a safety factor of 1.3 (maximum allowable stress is 350 p.s.i. (24.5 kg/sq cm)) the runway could support a load of 45 000 lbs. (18 000 kg) per isolated wheel, 60 000 lbs. (27 000 kg) per dual wheel, and 110 000 lbs. (50 000 kg) per four wheel bogie, the tire pressure in each case being 100 p.s.i. (7 kg/sq. cm). Therefore, in this particular case the isolated wheel load which is equivalent to that of 110 000 lbs. (50 000 kg.) on a four wheel bogie or of 60 000 lbs. (27 000 kg) on dual wheels, is 45 000 lbs. (18 000 kg).

3.- THE HOGG - BURMISTER METHOD

This runway design method, described in particular by Mr. Nils Odemark in his work "Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity", published in Swedish in 1949*, enables, in each case, stresses within the concrete to be determined. The soil characteristics are not expressed in terms of the modulus of reaction k, but in terms of the modulus of elasticity of the soil when it is homogeneous, or of the mean modulus of elasticity of a homogeneous soil equivalent to the one considered. The curves of figures 11 and 12 in the above publication, which are not reproduced here, enable in each case, stresses to be determined for loads per single wheel or per multiple wheel assembly.

* "Undersökning av elasticitetsegenskaperna hos olika jordarter samt teori för beräkning av beläggningar enligt elasticitetsteorin". Statens Väginstitut Stockholm, 1949.

Part III

FLEXIBLE PAVEMENTS

1. Stress calculationsin flexible pavements have given rise to much more need for study than those in rigid pavements; the complexity of the problem is increased by the fact that stress analysis is undertaken within a medium usually made up of different layers of soil, in which the characteristics may not be determined as easily as in concrete. Our examination will be limited to the CBR (California Bearing Ratio) method given in the afore-mentioned Doc 4209-AGA/509, and to the method developed in Canada by Dr. McLeod.

2.- CBR METHOD

2.1 It is known that the CBR method is purely empirical, and was developed by the U.S. Corps of Engineers on the basis of studies made by the California Division of State Highways. The first curves established by the Corps of Engineers dealt only with single isolated wheel loads up to 100 000 lbs (44 000 kg) and with tire pressures of approximately 100 p.s.i. (7 kg/sq. cm). Later, curves for tire pressures of 200 p.s.i. (14 kg/sq. cm) were set up.

2.2 When the problem of dual wheel landing gears arose, an experimental study of it was effected by the Corps of Engineers, in which the stresses and deflections for single and dual wheel assemblies were compared. It underlined the importance of two criteria: 1) the maximum depth to which either wheel acts on the foundation independently of the other, 2) the depth at which the two wheels begin to act on the foundation in the same way as an isolated wheel carrying the same load.

2.3 When the criteria were evaluated for a B-29, the first one was found to be 10 inches (25.4 cm) and the second, 75 inches (190.5 cm) (fig. 8). An empirical relationship was established in this case, between these criteria and the dual wheel assembly characteristics; the 10 inch depth

(25.4 cm) is in fact half the clear distance between contact areas of tires spaced 20 inches (50.8 cm) apart; the 75 inch (190.5 cm) depth is twice the distance between centres of contact areas of tires spaced 37 1/2 inches (95.25 cm). For base and pavement thicknesses of 10 inches (25.4 cm) and less the curve giving pavement thicknesses is the same as that for a single isolated wheel, with a load equal to half that of the assembly (30 000 lbs or 13 500 kg). For base and pavement thicknesses of 75 inches (190.5 cm) and greater the pavement thickness curve is the same as that for an isolated wheel carrying a load equal to the total load on the unit (60 000 lbs or 27 000 kg). Between these above-mentioned two thicknesses the values were interpolated by joining by a straight line the points showing these two limits on the CBR chart. The order of accuracy of the results thus obtained was later corroborated by tests.

2.4 By studying other dual wheel or dual tandem wheel assemblies and by extrapolating the results obtained for the B-29, the Corps of Engineers arrived at the following general method:

2.4.1 If d is the clear distance between contact areas of dual or dual tandem tires, and s the distance between centres of contact areas of dual tires or the diagonal distance between centres of contact areas of dual tandem tires (figure 9), then $\frac{d}{2}$ is the maximum thickness base and pavement at which each wheel of a dual or dual tandem arrangement stresses the subgrade as an independent unit. 2s is then the minimum base and pavement thickness at which a multiple wheel arrangement stresses the subgrade as one single wheel carrying the same load.

2.4.2 The representative curve of the arrangement is shown on the CBR chart by horizontal lines up to an abscissa of $\frac{d}{2}$, and beyond an abscissa of 2s, and by a sloping line joining these two points (figure 10). This rather bold extrapolation from a specific case to the general method seems to have been confirmed experimentally, at least with sufficient accuracy. Those who are particularly interested in this subject, are referred to the work of Messrs Boyd and Foster*.

2.4.3 It may be noted that the required thickness is not affected appreciably by minor variations in the values of $\frac{d}{2}$ and 2s. Variations of the order of 10% bring about changes in thickness of about 1 inch (2.5 cm).

2.4.4 Figures 11, 12 and 13 show the latest curves published by Messrs. McFadden and Pringle. By means of these curves and the associated

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* "Design curves for very heavy multiple wheels assemblies" by Messrs. Boyd and Foster, Transactions of the American Society of Civil Engineers, Volume 115, pp. 534-546.

method it is possible to design flexible pavement thicknesses for certain specific wheel assemblies (B-29 and B-36)*, and to determine approximately, the single isolated wheel which would be equivalent to wheel assemblies other than those considered, provided the tire pressure is of the same order (about 175 p.s.i (12 kg/sq. cm) for figures 12 and 13).

3.- DR. MCLEOD'S METHOD**

3.1 Based on numerous tests on existing runways in Canada, Dr. McLeod evolved the following empirical formula: in the design of the thickness of a pavement supporting a single isolated wheel load,

$$T = K \log \frac{P}{S}$$

where T is the total pavement thickness, P the single wheel load, S the value of subgrade support with a 0.2 inch deflection (0.5 cm) for 10 repetitions of loading, the contact area being that of the simple isolated wheel P; K is the pavement characteristic and is the reciprocal of the load supported by this pavement per centimetre thickness; its value falls with decrease in diameter of the contact area (supposedly circular). Dr. McLeod's method provides pavement thicknesses which are generally less than those of the CBR method.

3.2 Dr. McLeod has drawn curves (figures 14 and 15) giving the thicknesses T as a function of the load per single isolated wheel. The first graph refers to a tire pressure of 100 p.s.i. (7 kg/sq. cm) and the second to a pressure of 200 p.s.i. (14 kg/sq. cm).

3.3 Multiple wheel landing gears

3.3.1 For calculations associated with multiple wheel landing gears Dr. McLeod based these on the work of the U.S. Corps of Engineers. On his charts he plotted the two points on the abscissa $\frac{d}{2}$ and 2S for the B-36, the Stratocruiser and the Canadair North Star (figure 14), and the two points for the B-36 alone, on figure 15; he then joined each set of two points by straight lines. The Corps of Engineers used a straight line on a logarithmic co-ordinate system, while Dr. McLeod used the same form of curve with semi-logarithmic

* McFadden and Pringle, Recent developments of the Corps of Engineers in airport pavement design, Proceedings of the Conference on ground facilities for Air Transportation, September 12-14, 1950, Massachusetts Institute of Technology, Cambridge, Mass.

** This portion of the circular has been prepared through the courtesy of Dr. McLeod who presented to ICAO a very comprehensive paper explaining his method.

co-ordinates. According to Dr. McLeod, the resulting error is not greater than 10% and it is doubtful whether any current method associated with flexible pavements is of comparable accuracy.

3.3.2 For a given multiple wheel assembly, Dr. McLeod's charts provide not only the required pavement thickness, but also the equivalent isolated wheel load.

3.3.3 By means of these charts it is also possible to determine the maximum load that a given wheel assembly may support for a pavement thickness of known characteristics, e.g. the load on the four wheel dual tandem assembly of B-36 is 150 000 lbs. (68 000 kg); the subgrade has an S value of 10 000 lbs. (4 500 kg). Therefore the required pavement thickness is 34 inches (86.4 cm). Assume now that the pavement thickness is only 26 inches (66 cm); according to figure 14 this pavement may carry an isolated wheel load of only 30 000 lbs (13 500 kg). Draw a line parallel to the B-36 straight line through the intersection of the 10 000 lbs. (4 500 kg), subgrade characteristic curve with the straight line x = 26 inches (66 cm); this straight line, shown in figure 14 by a broken line, cuts the line x = 136 inches (346 cm) at a point of ordinate equal to 100 000 lbs (45 000 kg). This means that the pavement considered may support a load of only 100 000 lbs (45 000 kg) on the B-36 wheel assembly.

CONCLUSION

1. Having discussed the different runway design methods for multiple wheel landing gear assemblies used at present, it now seems appropriate to consider the matter from a broader point of view. The problem of runway strenght may indeed be examined from very different angles, according to the objectives of those dealing with it.

2.- THE DESIGNER'S POINT OF VIEW

2.1 Those who fix aerodrome design characteristics must express in straight forward manner, the desired runway strength which must not only take into account the characteristics of aircraft that are to use the aerodrome now and in the near future, but also those of possible future aircraft. Therefore the selection of this strength may have an effect upon the design of new aircraft destined to use the aerodrome in question.

2.2 It seems that the best criteria for this purpose are the data on single isolated wheel load and tire pressure. They are moreover, the ones given in Annex 14 (cf. paragraph 1.1.7 of Part III). This paragraph requires that calculation of the single isolated wheel load be made to correspond with the type of aircraft for which the aerodrome is designed, and that the single isolated wheel load selected from table 3.1.2 of the Annex be at least equivalent to that effectively used at the aerodrome. A rough estimate is adequate enough for this purpose. The information in section 7 of Attachment B to Annex 14 may therefore be taken as adequate, provided it is kept up to date from time to time.

3.- THE CONSTRUCTOR'S POINT OF VIEW

3.1 The design charts and diagrams included in this circular are of little use to the constructor as they provide only an approximate idea of the thickness of pavement that is to be constructed. A competent constructor has to examine closely a series of factors which may not be incorporated in necessarily simplified formulae; for instance the soil's water content prior to laying the pavement, the adequacy of the proposed drainage system, the organic and decomposable matter content of the soil, etc. In certain cases he must check whether the designer's rough estimate of the single isolated wheel load is appropriate to the characteristics of a given subgrade and proposed pavement.

To sum up, he must combine science and art in engineering, and this is a field in which no standardization is possible.

4.- THE OPERATOR'S POINT OF VIEW

4.1 As regards the operator, the problem is simple: taking into account the air routes along which he is flying or intends to fly, and the aircraft which are or will be at his disposal, will he be able to use the runways of the aerodromes along such routes?

4.2 At present, the strength characteristics of runways which he may be likely to use are expressed by States in three different ways: the total weight of the aircraft, the type of aircraft that will impose the highest runway strength requirements, or the single isolated wheel load associated with a certain tire pressure.

4.2.1 The first method becomes useful only when a brief description of the wheel assembly is included. For instance in Sweden two strength values for each aerodrome are quoted: the first is the total weight of the aircraft with single wheel main landing gear, the second is the total weight of the aircraft with dual wheel main landing gear.

4.2.2 The second method is very inadequate and may be applied only to aerodromes used by a limited range of aircraft types of known characteristics. It does not enable an operator to determine easily whether a certain new type of aircraft is acceptable.

4.2.3 The third method is best from the theoretical point of view. However, the ability of the runways to stand up to multiple wheel landing gears must be clearly indicated. A good example of information provided in accordance with this method is the NOTAM published by Southern Rhodesia, and reproduced in the Attachment to this circular. In it, the value for the single isolated wheel load (unfortunately without tire pressure) is accompanied by the maximum permissible aircraft weight in terms of the landing gear wheel arrangement.

4.3 Publication of runway bearing strength values could perhaps, be undertaken in accordance with the above example. In view of the very relative accuracy of runway design methods, it should be possible to come to an agreement on conversion factors that could be applied to the majority of runways and aircraft now in operation. Exceptional cases of aircraft with wheel assemblies differing substantially from those in common use, or of runways with extraordinary characteristics due to the special nature of their subgrade, would be dealt with separately. If this proposal were considered favourably, it would be possible, to set up a more comprehensive runway and aircraft load classification than the one provided in Annex 14. This classification could perhaps be influenced by the United Kingdom Air Ministry's "Load classification of runways and aircraft".*

4.3.1 It seems appropriate that this publication's summary and the proposed classification chart (figure 16) be reproduced hereunder.

4.3.1.1 "For the purpose of classification it is shown that the failure load-contact area curve for a runway offers a useful criterion and when referred to a standard curve enables a load classification number to be obtained on a scale of whole numbers ranging from 100 - 10 (English Units) or 45 - 4.5 (metric Units).

4.3.1.2 Over the range of tire contact areas of modern aircraft both in use and projected and having isolated single wheel loads of 10 000 lbs. (4500 kg) and upwards it is found that concrete, tarmacadam and asphalt surfaces behave in a similar way and an average load-contact area curve has been deduced by means of which aircraft wheel characteristics can also be referred to the standard curve and given a load classification number.

4.3.1.3 In practice it would be arranged that the operation of an aircraft would only be permitted from runways bearing an equal or greater classification number.

4.3.1.4 An alignment chart has been prepared which sets out the relationship between the load, the load classification number and the pressure and enables a classification number to be given to any aircraft when wheel load and tire pressure are known. Alternatively the classification

* "Load classification of runways and aircraft". Directory General of Works, Air Ministry, Technical Publication 102/48, London, April 1948.

number of a runway can be determined from the load bearing capacity on a single contact area."

4.3.2 If a classification of this kind were adopted, the operator's problem would be simplified considerably. Each type of aircraft and each runway would have a number assigned to it, and comparison of these two numbers would determine immediately whether a certain aircraft may land on a certain runway.

Without wishing to prejudice any action that might be taken in respect of runway strength by the AGA Division at future meetings, it seems that its primary efforts should be devoted to the evaluation of the load bearing capacity of runways and to the publication of available data in this respect.

TABLE I

CHARACTERISTICS OF PRESENT AND PROPOSED AIRCRAFT TYPES

State	Name of type	Name of Manufacturer	Characteristics of forward landing gear			Characteristics of main landing gear (one leg)			Distance between axes of bogies		Total weight of aircraft		Load on forward landing gear		Load on each leg of main landing gear		Characteristics of tires of forward landing gear						Characteristics of tires of main landing gear					
			Wheel arrangement	Distance between centres of dual contact areas		Wheel arrangement	Distance between centres of dual contact areas																					
				cm	ins.		cm	ins.	cm	ins.	kg (1000)	lb (1000)	kg (1000)	lb (1000)	kg (1000)	lb (1000)	Diameter		Width		Pressure		Diameter		Width		Pressure	
																	cm	ins.	cm	ins.	kg/cm^2	lb/sq. inch	cm	ins.	cm	ins.	kg/cm^2	lb/sq. inch
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
United Kingdom	Brabazon 167-Mk 2	Bristol	Dual			3 wheel bogie	36.2 Distance between centres of dual wheel assembly contact areas 165.7	14¼ 65¼	137.2	54	148.5	330	13.5	30	67.5	150	96.5	38	29.8	11.75	7.3	105	119.4	47	28	11	7.8	112
France	SE-2010	SNCASE	Dual			Dual	81.0	31 89/100			75	168	7	15.4	34	74.8	132	52	49	19.3	7.2	-	152	59.8	44	17.3	9.3	
United States	Stratocruiser 377	Boeing	Dual	50,3*	20"*	Dual	93.9	37"		-	65.7	146	6.0	14	30	66							139.2 143.7	54.79(min) 56.56(max)	48.66 50,60	19.16(min) 19.92(max)	7.3 8.4	105 (inner) 120 (outer)
United Kingdom	175	Bristol	Dual			4 wheel bogie	43.2 68.6	17"(forward) 27"(rear)	121.9	48	58.5	130	5	12	26.5	59	76.2	30	22,9	9	7.1	102	88.9	35	25.4	10	8.7	125
United Kingdom	Comet	de Havilland	Dual			4 wheel bogie	44.5 36.2	17.5 (forward) 14.25(rear)	110.75	43.6	49.5	110	4.5	10	22.5	50	76.7	30.2	23.5	9.25	4.5	65	88.9	35	22.9	9	8.4	120
United States	749-A	Lockheed	Dual	40,6*	16"*	Dual	76.2	30"		-	48.1	107	4.9	11	21.6	48	-						119.55 123.95	47.07(min) 48.80(max)	41.4 44	16.30(min) 17.34(max)	8.4	120
United States	149	Lockheed				Dual	76.2	30"		-	45	100	4.5	10	20.2	45							119.55 123.95	47.07(min) 48.80(max)	41.4 44	16.30(min) 17.34(max)	6.6	95
United States	DC-6	Douglas	Single			Dual	78.7	31		-	40.9	91	4.2	9	18.4	41							111 114.8	43.69(min) 45.20(max)	38.2 40.6	15.04(min) 16.00(max)	7.7	110
United Kingdom	Hermès V	Handley-Page	Dual			Dual	63.5	25		-	37.8	84	3.6	8	17.1	38	80.5	31.7	24.8	9.75	4.9(+0,5 (-0,3	70(+7 (-5	121.9	48	47.8	14.9		70(+7 (-5
United Kingdom	Hermès IV	Handley-Page	Dual			Dual	63.5	25		-	36.9	82	3.6	8	16.6	37	80.5	31.7	24.8	9.75	4.9(+0,5 (-0,3	70(+7 (-5	121.9	48	47.8	14.9		70(+7 (-5
Canada	DC-4M	Canadair	Dual			Dual	78.1	30.75		-	36	80	3.6	8	16.2	36							116.8	46	39.4	15.5	6.3	90
United States	DC-4	Douglas	Single			Dual	66	26		-	32.8	73	3.1	7	14.8	33							111 114.8	43.69(min) 45.20(max)	38.2 40.6	15.04(min) 16.00(max)	6.3	90
Canada	C-102	A V Roë	Dual	40,6	16	Dual	55.9	22			30.6	68	2.7	6	13.9	31	66	26	19.7	7.75	6.3-7	90-100	96.5	38	29.8	11.75	4.9-5.2	70-75
United Kingdom	Airspeed	Ambassador	Dual			Dual	58.4	23			23.6	52.5	2.4	5.5	10.5	23.5	66	26	19.7	7.75	4.2	61	96.5	38	29.8	11.75	5.4	77
United Kingdom	Viscount 701	Vickers	Dual			Dual	48.3	19			22.5	50	2.2	5	10.1	22.5	63	24.8	19.6	7.7	5.7	82	92.5	36.4	27.9	11.0	5.9	85
United Kingdom	Whitworth Apollo	Armstrong	Dual			Dual	45.7	18			20.2	45	2.2	5	9.1	20	61	24	18.4	7.25	3.8	55	91.4	36	27.3	10.75	5.1	73
United States	404	Martin				Dual	59.7	23.5			18.9	42	1.8	4	8.5	19							94 97.6	37.02(min) 38.44(max)	30.4 32.4	11.98(min) 12.75(max)	4.1	58
United States	Liner 240	Convair	Dual	35,6*	14*	Dual	54.6	21.5			18	40	1.8	4	8.1	18							82.2 84.8	32.35 33.40	24.1 25.65	9.50 10.10	6.6	95
United States	202	Martin	Single*			Dual	59.7	23.5			18	40	1.8	4	8.1	18							94.2 97.6	37.09(min) 38.44(max)	30.4 32.4	11.98(min) 12.75(max)	4.2	60
United States	B-36D*	Convair	Dual	76,2*	30*	4 wheel bogie	79.4*	31.25*	155.60*	61.25*	161*	357*	15.7	35	72.4	161					6.3*	90*					12.3*	176*

Note: The B-36D, although a military aircraft, has been added to the list since it served as the basis for the studies carried out by the U.S. Military engineers.

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APPENDIX

SOUTHERN RHODESIA
NORTHERN RHODESIA
NYASALAND

NOTICE TO AIRMEN NO. 39 OF 1951

Belevedere Airport: Weight Restrictions and Night Flying

1. The following weight restrictions have been imposed at Belvedere Airport:

DURING DRY SEASON

(Approximately 15th April to 1st November)	A single isolated wheel load not exceeding 29 000 lbs.

DURING RAINY SEASON

(Approximately 1st November to 15th April)	A single isolated wheel load not exceeding 18 000 lbs.

2. The method of calculating the single isolated wheel load will be as follows:

MAIN UNDERCARRIAGE TYPE	SINGLE ISOLATED WHEEL LOAD
I — I	0.45 x Aircraft weight
II — II	0.30 x Aircraft weight
I)—(I I)—(I	0.30 x Aircraft weight
II)—(II II)—(II	0.25 x Aircraft weight

the above allows the following maximum all-up-weights:

MAXIMUM PERMISSIBLE ALL-UP-WEIGHT NOT TO EXCEED

MAIN UNDERCARRIAGE TYPE	DRY SEASON	RAINY SEASON
I — I	64 500 lbs	40 000 lbs
II — II	96 650 lbs	60 000 lbs
I)—(I I)—(I	96 650 lbs	60 000 lbs
II)—(II II)—(II	116 000 lbs	72 000 lbs

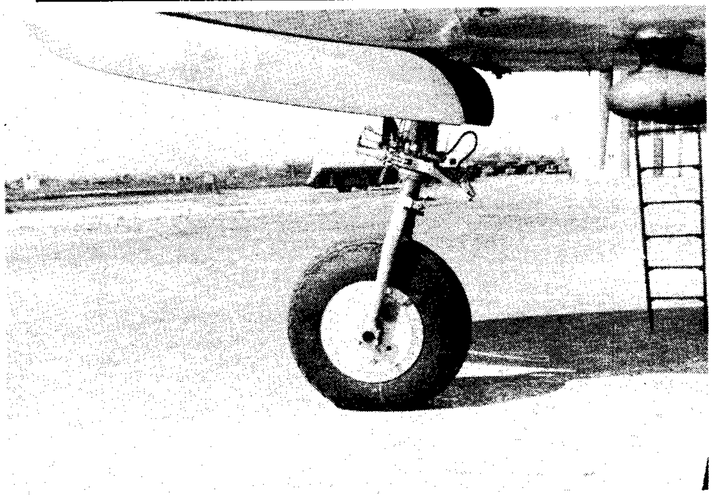

Fig. 2

Single wheel undercarriage
Train d'atterrissage à roue unique
Tren de aterrizaje con rueda simple

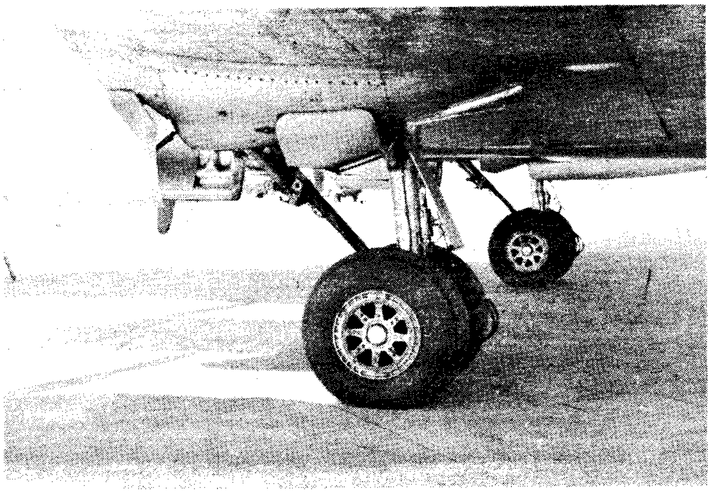

Fig. 3

Dual wheel undercarriage
Train d'atterrissage à roues jumelées
Tren de aterrizaje con ruedas gemelas

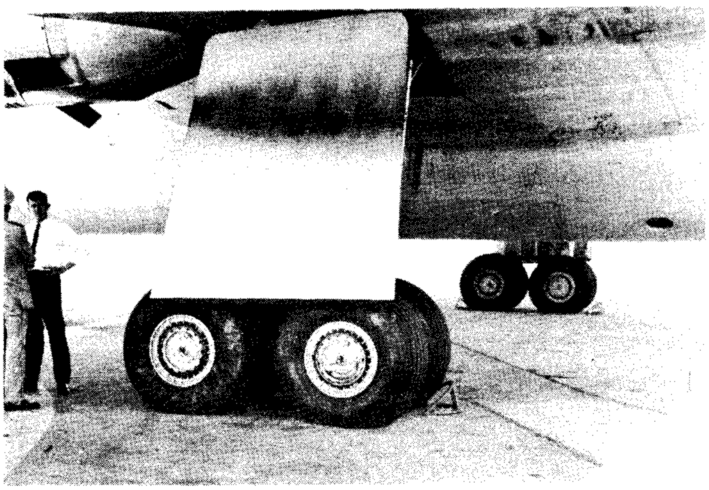

Fig. 4

Dual-tandem wheels undercarriage
Train d'atterrissage à boggie de quatre roues
Tren de aterrizaje con bogie de cuatro ruedas

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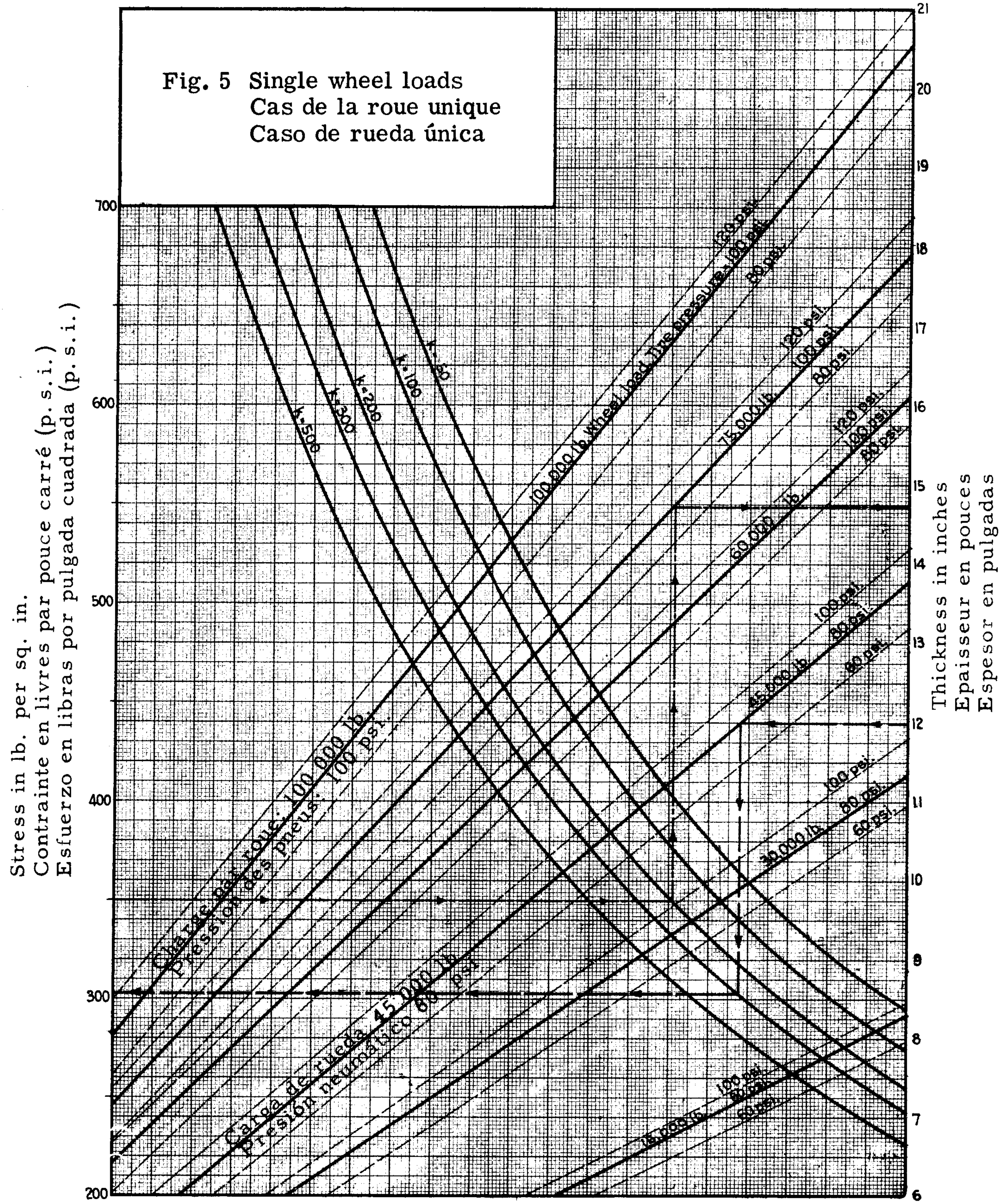
Fig. 5 Single wheel loads
Cas de la roue unique
Caso de rueda única
Stress in lb. per sq. in.
Contrainte en livres par pouce carré (p.s.i.)
Esfuerzo en libras por pulgada cuadrada (p.s.i.)
Thickness in inches
Epaisseur en pouces
Espesor en pulgadas
Charge par roue: 100 000 lb.
Pression des pneus: 100 psi.
Carga de rueda 45 000 lb.
Presión neumático 60 psi
k=500
k=300
k=200
k=100
k=50
100,000 lb. Wheel load Tire pressure 100 psi.
75,000 lb.
60,000 lb.
45,000 lb.
30,000 lb.
15,000 lb.
120 psi.
100 psi.
80 psi.
60 psi.
200
300
400
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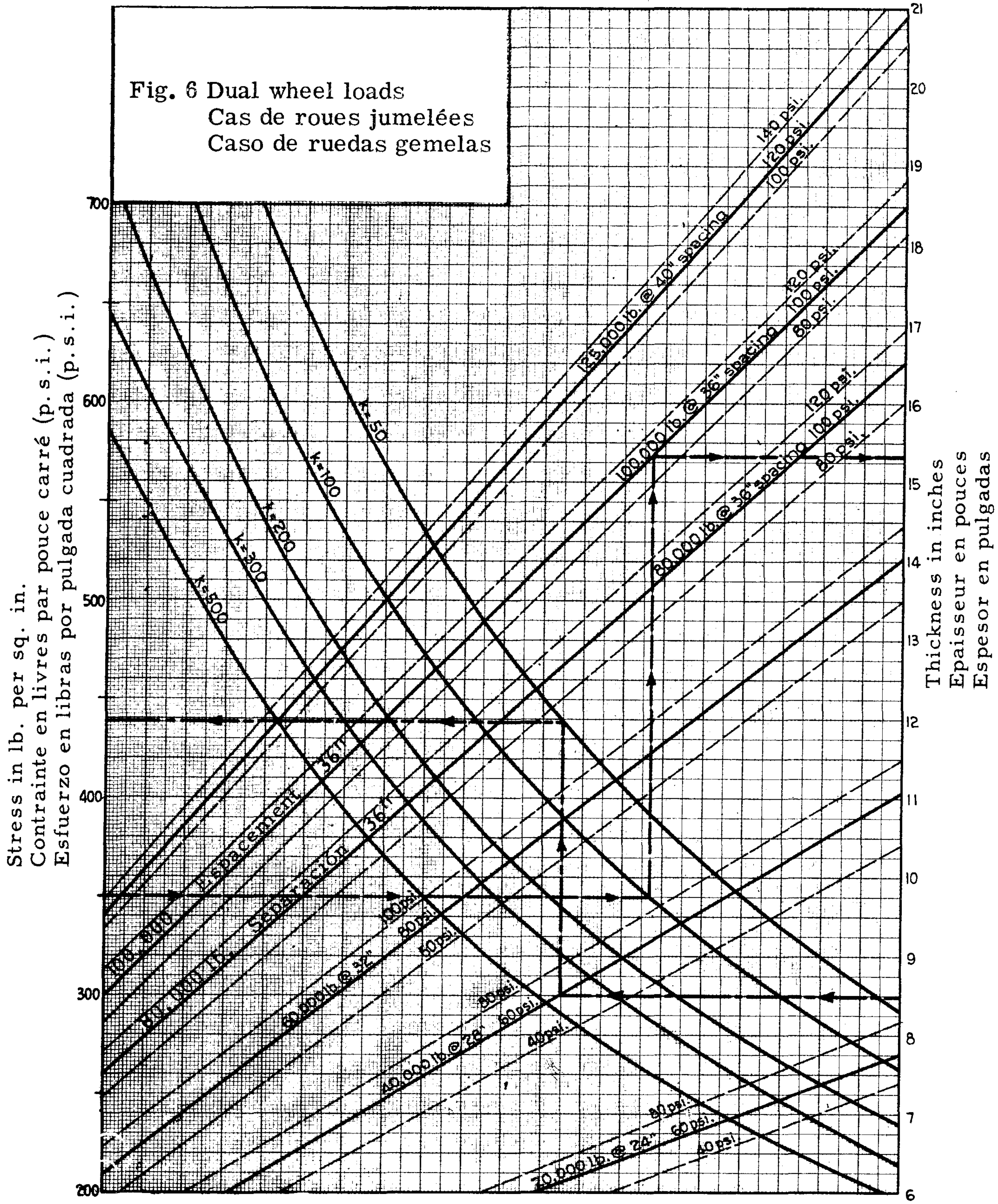

Fig. 6 Dual wheel loads
Cas de roues jumelées
Caso de ruedas gemelas

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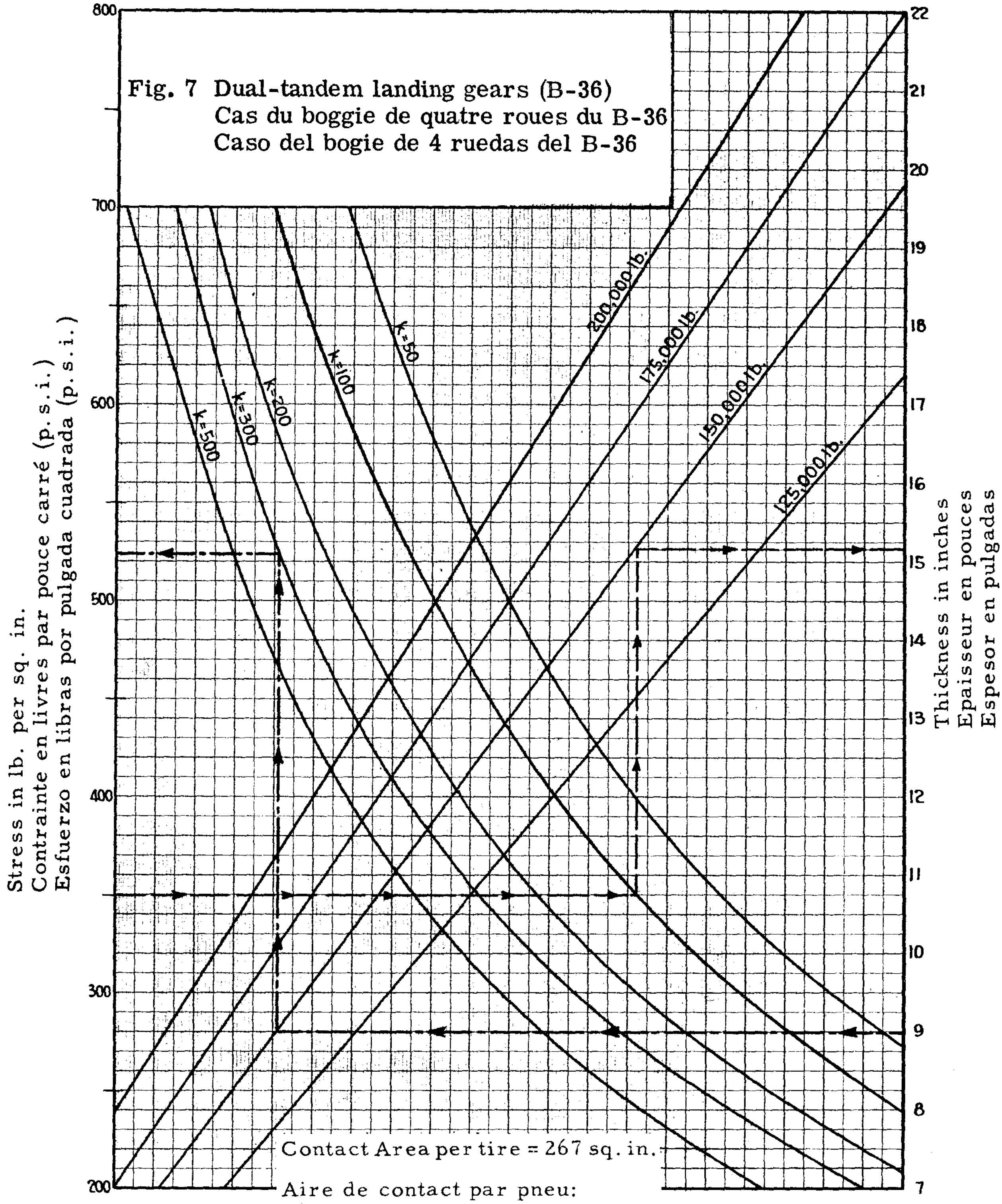

Fig. 7 Dual-tandem landing gears (B-36)
Cas du boggie de quatre roues du B-36
Caso del bogie de 4 ruedas del B-36

Contact Area per tire = 267 sq. in.

Aire de contact par pneu:
267 pouces carrés

Area de contacto por neumático,
267 pulgadas cuadradas.

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Fig. 8 Schematic diagram of B-29 dual wheel assembly
Diagramme schématique des roues jumelées du B-29
Dibujo esquemático de las ruedas gemelas del B-29

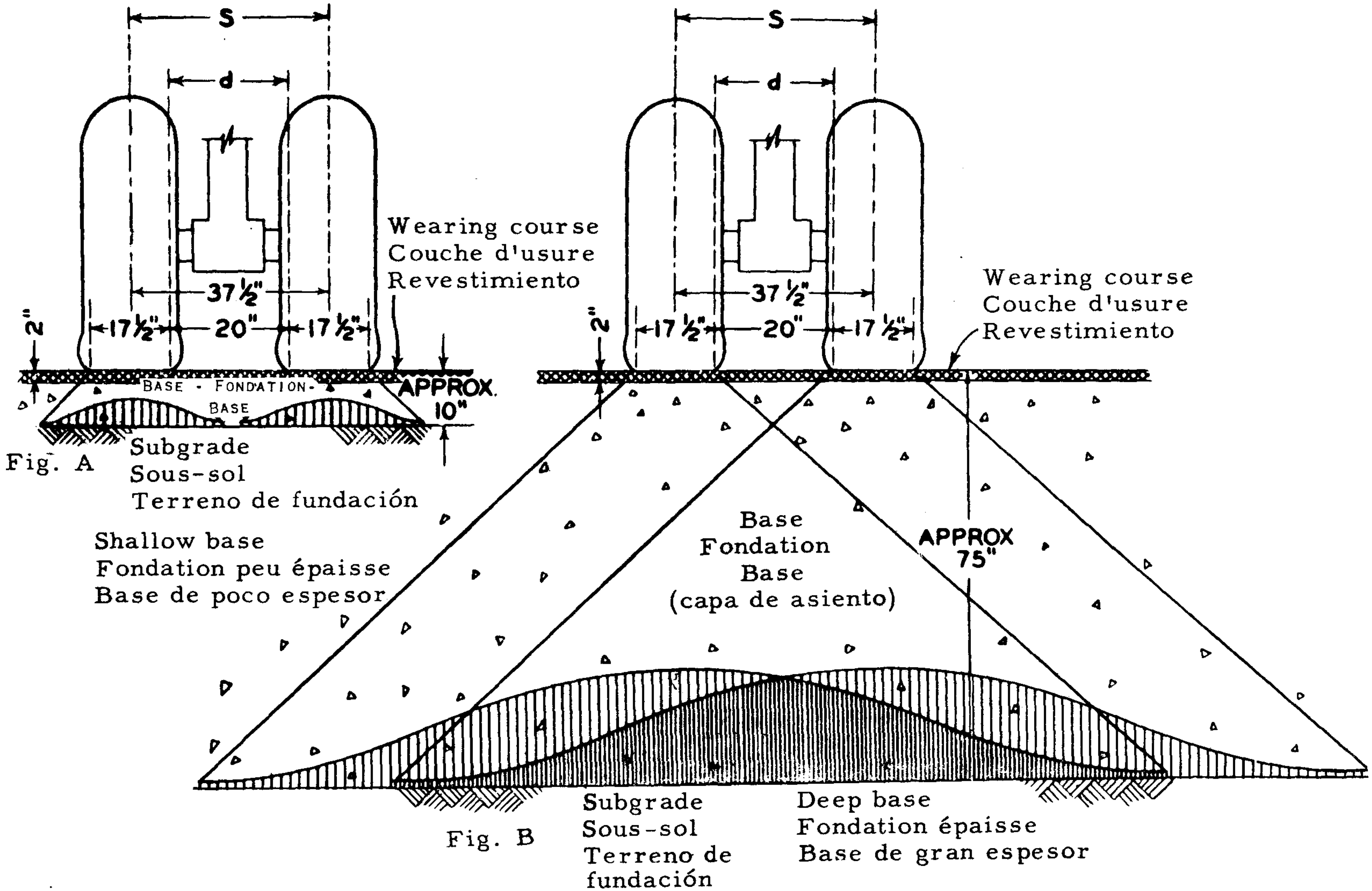

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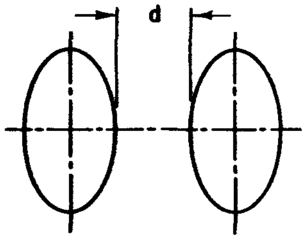
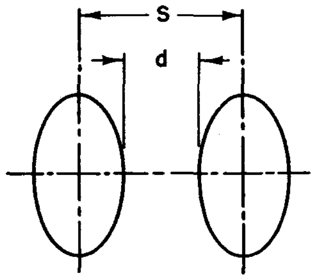
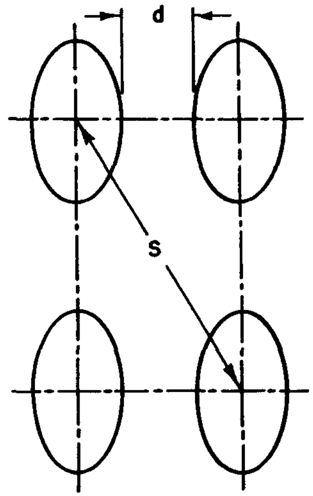
Fig. 9







1.- d = Minimum clear distance between contact areas of dual or dual tandem tires

d = Distance intérieure entre empreintes des pneus

d = Distancia interior entre huellas de neumáticos

2.- s = Distance between centres of contact areas of dual tires

s = Distance entre centres de symétrie des empreintes du jumelage

s = Distancia entre centros de figura de las huellas de los neu.náticos

3.- s = Diagonal distance between centres of contact areas of dual tandem tires

s = Longueur de la diagonale du rectangle constitué par les centres de symétrie des empreintes du jumelage

s = Longitud de la diagonal del rectángulo formado por los centros de las huellas de los neumáticos

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Fig. 10 California bearing-ratio
Indice portant californien
Indice CBR de resistencia de terrenos

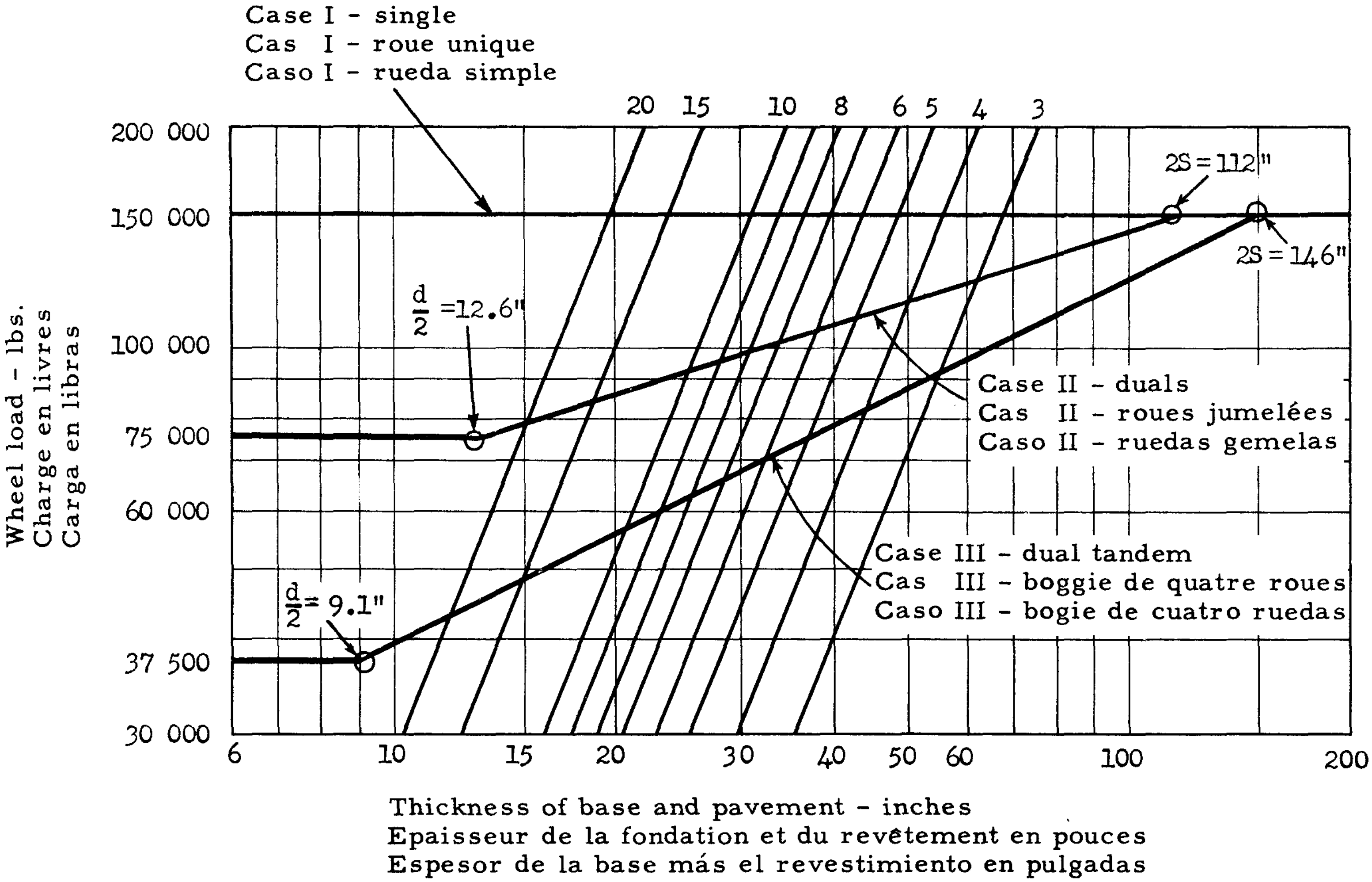

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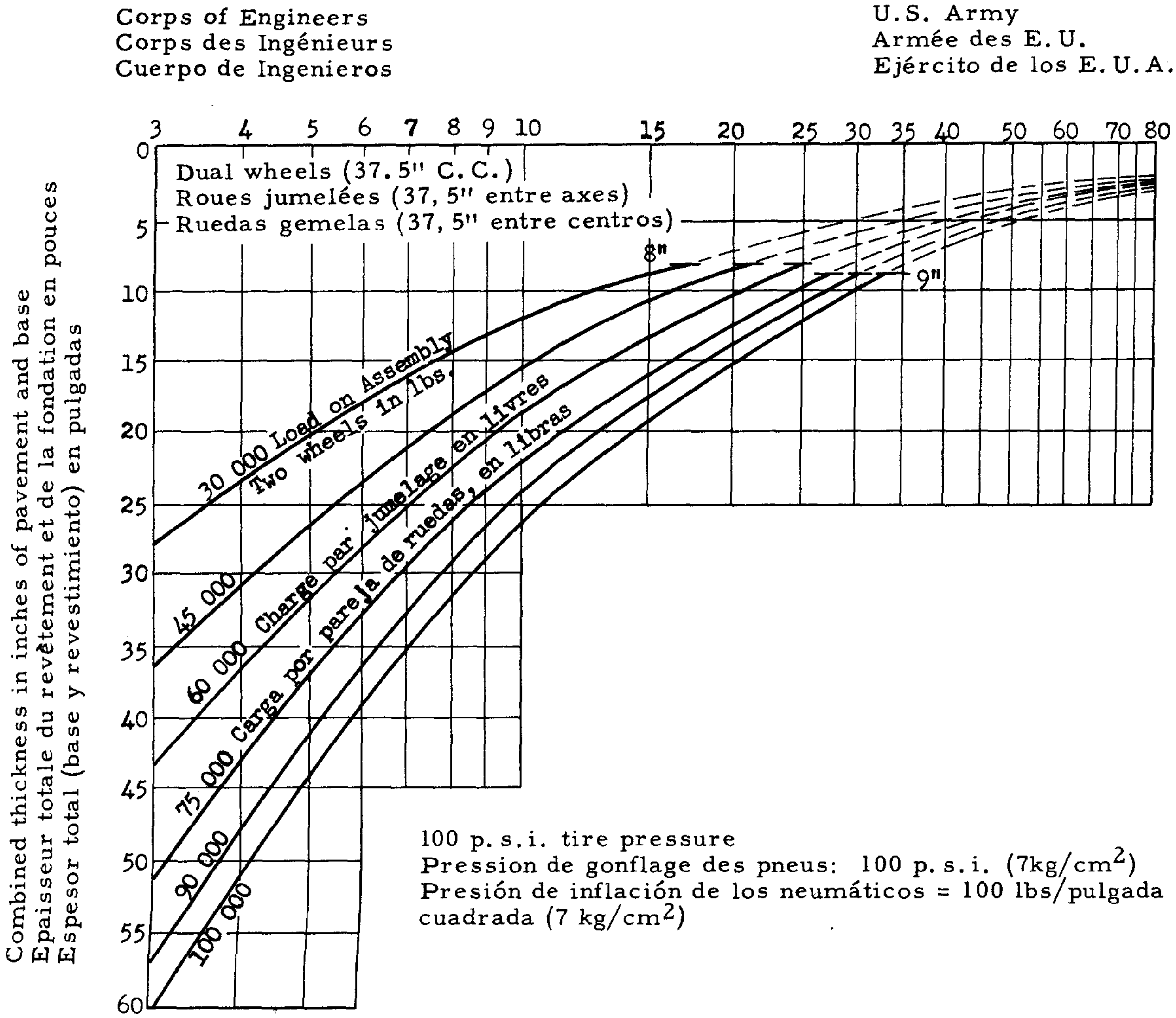
Fig. 11 California bearing-ratio
Indice portant californien
Indice CBR de resistencia de terrenos



(Tentative)
(Courbes provisoires)
(Curvas provisionales)

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Fig. 12 California bearing-ratio
Indice portant californien
Indice CBR de resistencia de terrenos

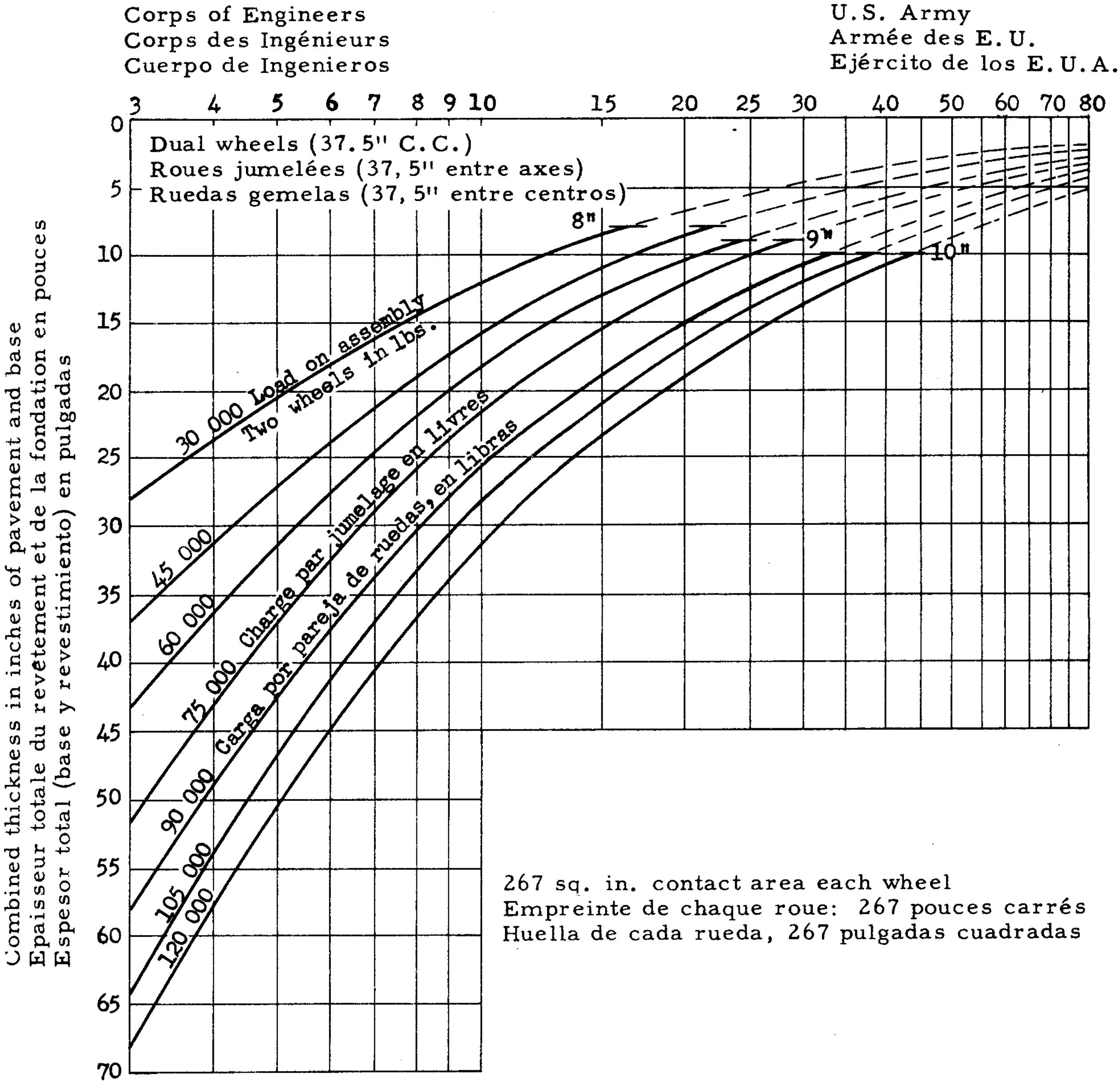

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Fig. 13 California bearing-ratio
Indice portant californien
Indice CBR de resistencia de terrenos

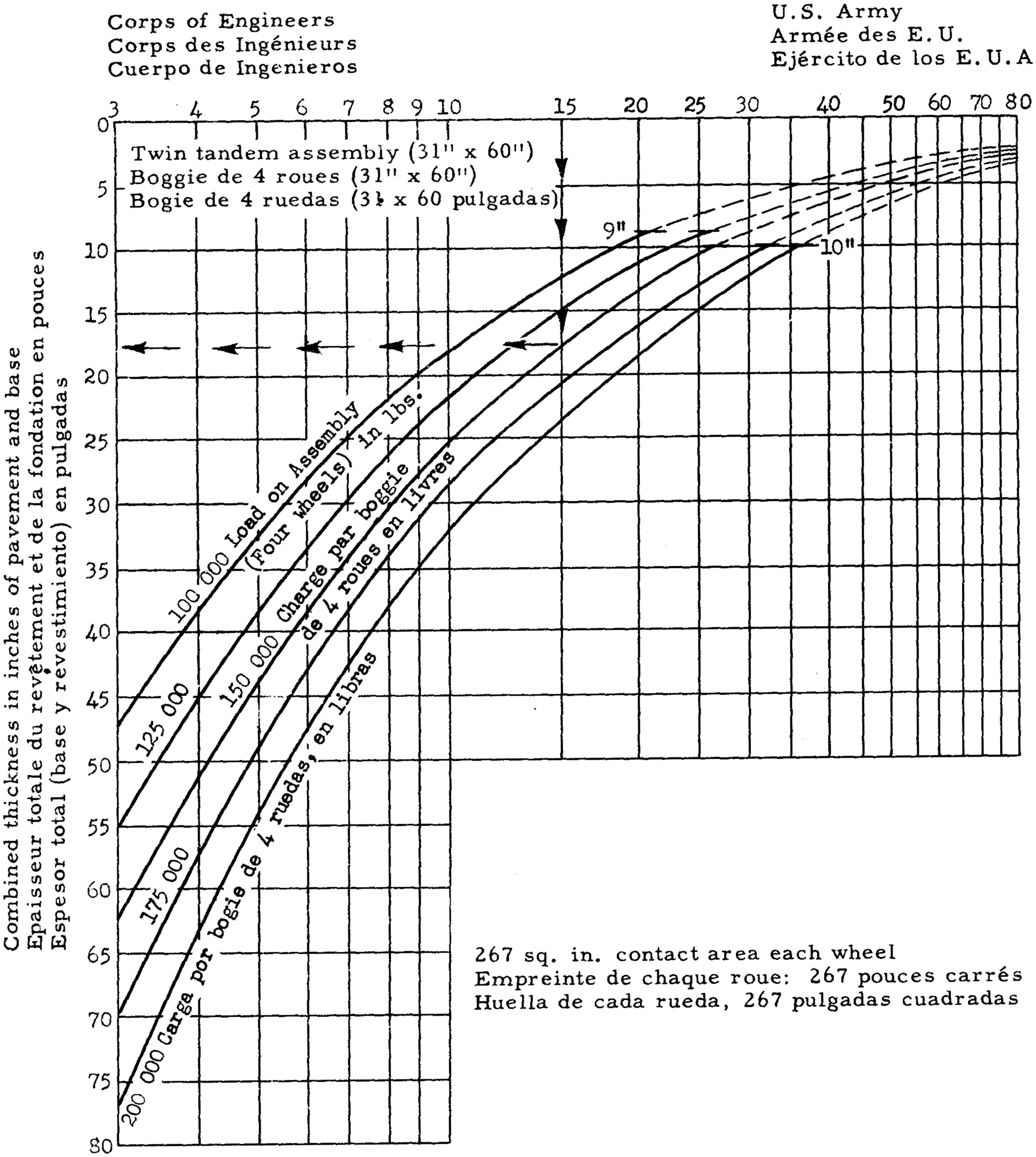

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Fig. 14 Flexible pavement design and evaluation chart for single-wheel and multiple-wheel landing gear assemblies (tire pressure 100 p.s.i.)

Courbes de détermination de l'épaisseur des pistes pour roue isolée ou pour roues multiples (pression de gonflage des pneus 7kg/cm^2 (100 p.s.i.)

Curvas para determinar espesores de pista para rueda aislada o ruedas múltiples con presión de neumáticos de 7kg/cm^2 (100 lbs/pulgada cuadrada)

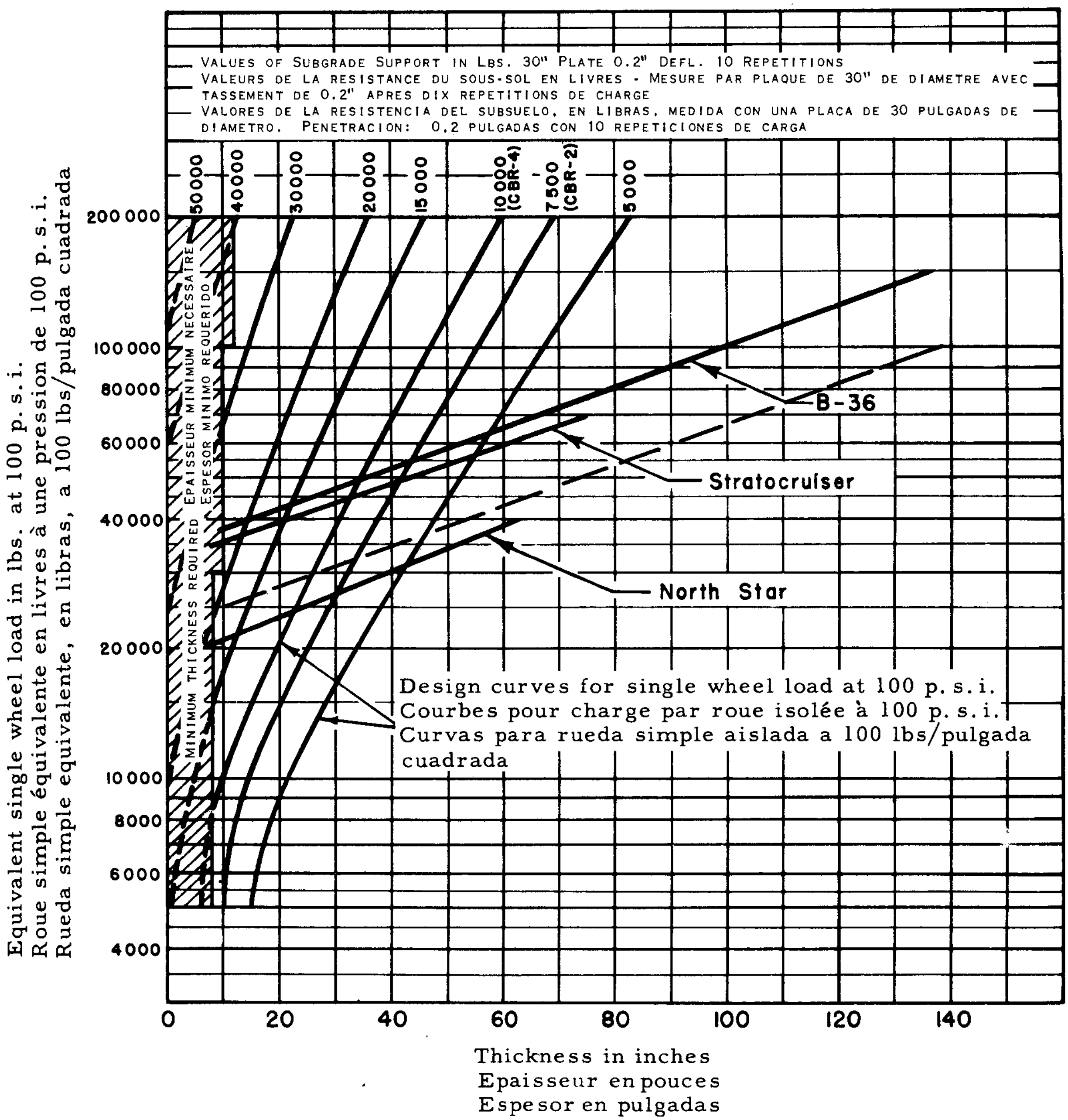

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Fig. 15 Flexible pavement design and evaluation chart for single-wheel and multiple-wheel landing gear assemblies (tire pressure 200 p.s.i.)

Courbes de détermination de l'épaisseur des pistes pour roue isolée ou pour roues multiples (pression de gonflage des pneus 14kg /cm² (200 p.s.i.)

Curvas para determinar espesores de pista para rueda aislada o ruedas múltiples con presión de neumáticos de 14kg/cm² (200 lbs/pulgada cuadrada)

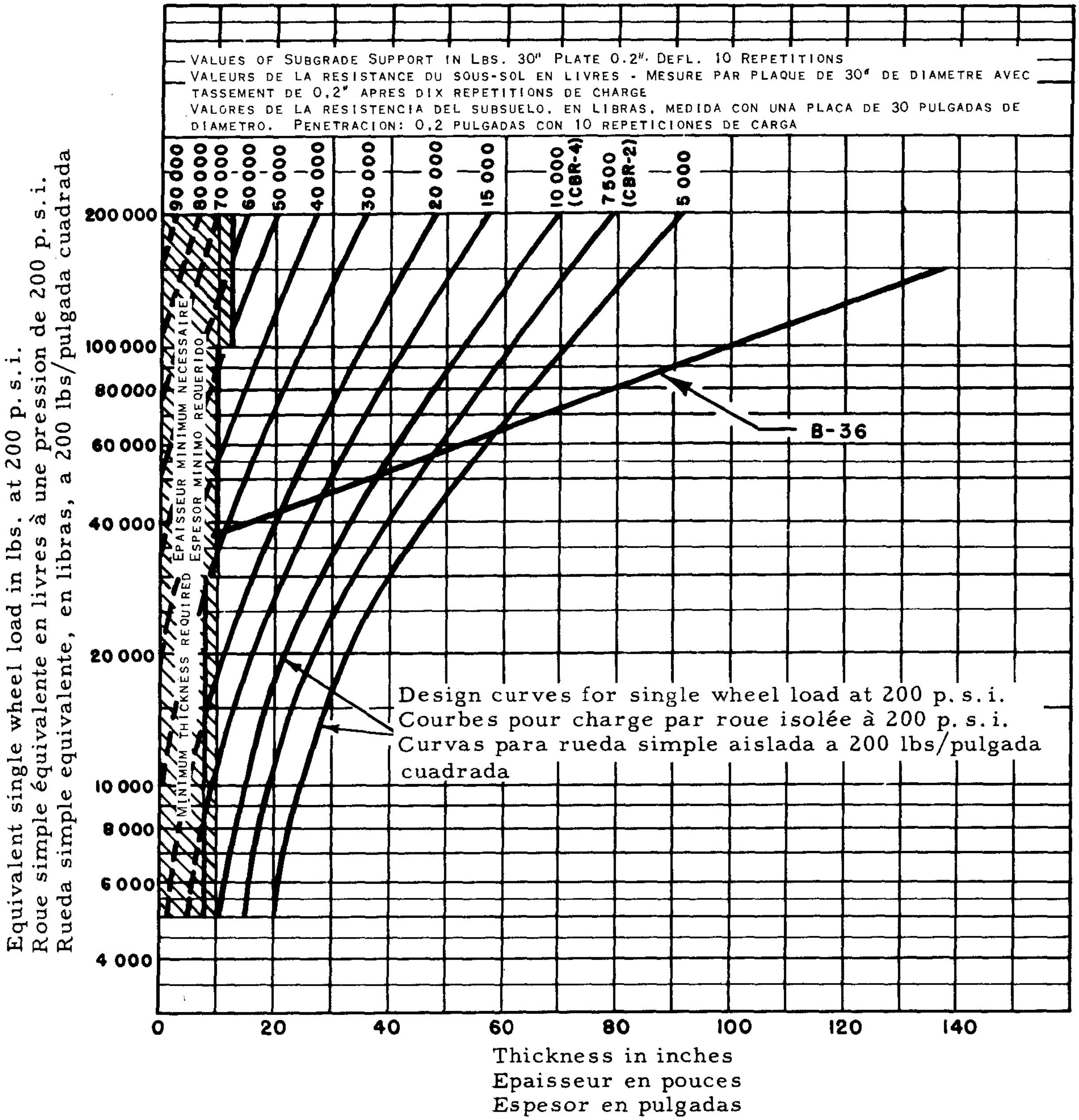

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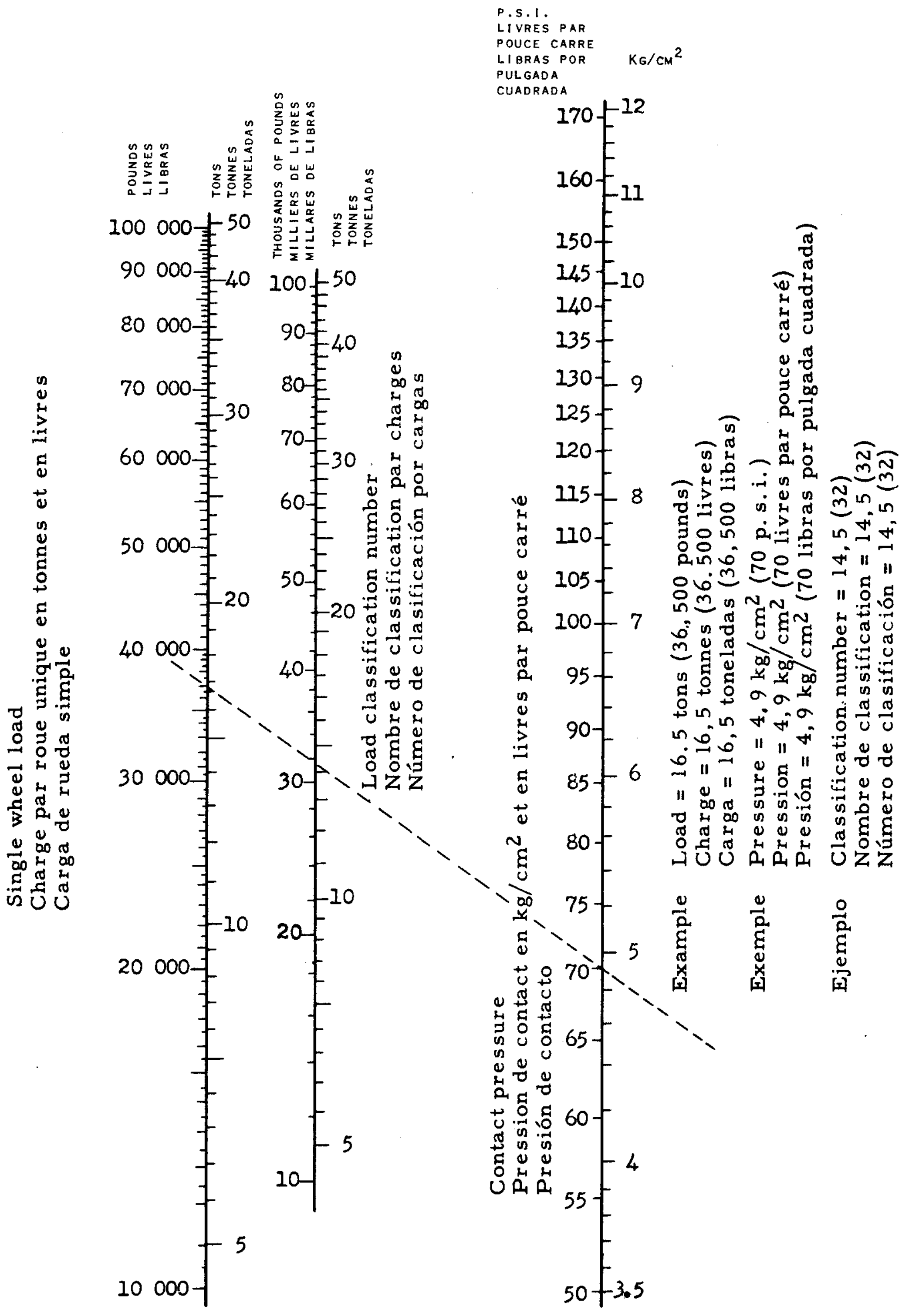
Fig. 16 Load classification of runways and aircraft alignment chart
Abaque pour la détermination de la classification par charges des pistes d'envol et des aéronefs
Abaco para determinar la clasificación por cargas de las pistas y de las aeronaves



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