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AEROSPACE RECOMMENDED PRACTICE

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WHEELS AND BRAKES, SUPPLEMENTARY CRITERIA FOR DESIGN ENDURANCE CIVIL TRANSPORT AIRCRAFT

1. SCOPE

To recommend supplementary design criteria to enhance the endurance, reliability, and dependability of transport aircraft wheels and brakes.

2. REFERENCE SPECIFICATIONS

2.1 Federal Aviation Regulations: Available from Federal Aviation Regulations, Supervisor of Documents, U.S. Government Printing Office, Washington, DC 20402.

FAR Part 25 - Airworthiness Standards: Transport Category Airplanes - Para. 25.731 Wheel and Para. 25.735 Brakes

FAR Part 37 - Technical Standard Order Authorizations, Para. 37.172 Aircraft Wheels and Brakes - TSO-C26, Latest Revision

2.2 Government Publications: Available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120.

MIL-W-5013, Latest Revision - Wheel and Brake Assemblies; Aircraft

2.3 SAE Publications: Available from the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.

ARP 813A - Maintainability Recommendations for Aircraft Wheels and Brakes

3. DISCUSSIONS

The minimum performance standards for the design of civil transport wheels and brakes are defined in reference (a) above. Although not directly applicable, the design requirements and tests in reference (b) are also used, in modified form, to develop commercial assemblies. Ratings of the wheel and the brake are defined in reference (c). Reference (d) should be used as a design guide.

These and preceding specifications have resulted in many successful production assemblies. However, new designs sometimes require a period of development and debugging during initial service. This does not mean that the brake and wheel would not satisfactorily and safely stop the aircraft. It means that during the early stages of operation, a cooperative service development program between airline and brake and wheel manufacturer had to be undertaken to increase the endurance of some parts to a satisfactory service and economical level. Nuisance troubles, such as cracked linings, oil seepage, cracked housings, warped discs, and fatigue failures of secondary parts occurred. Hence, it was apparent that existing development and qualification tests should be supplemented with additional tests which preferably simulate service conditions. In many cases, duplication of these service conditions is not economically feasible, and therefore, other test criteria must be used.

3. DISCUSSIONS (Continued)

The following pages suggest criteria for design endurance levels for wheels and brakes and testing to demonstrate a high degree of assurance for service performance. The types of service are designated by landing frequency since this parameter is fundamental.

The criteria recognizes that airline landings and takeoffs are usually made at weights less than design weights; also, that initial brake application speeds are approximately 80-100% stall speed, although touchdown may be as great as 120-125% stall speed. It also recognizes that some service landings and takeoffs may involve abnormal energies which exceed the daily norm, but which are substantially below the level of the accelerate - stop condition required in the TSO.

The suggested endurance criteria in Tables I and II are based on airline service experience in conjunction with airframe and wheel and brake manufacturers' recommendations. Since increased endurance is normally associated with increased weight, Figs. A, B and C are included in this report to illustrate weight trends.

4. TYPICAL WHEEL ENDURANCE REQUIREMENTS

The performance standards in FAR Part 37 require a minimum roll test of 1,000 miles at maximum static load. This is a short endurance test for aircraft which will be flown about 3,000 hours per year. If the landing rate for the aircraft, for example, is two hours of flight per landing, the actual roll distance will be about (300/2) 4 = 6,000 miles per year. Landing and takeoff, including taxiing, distances for large jet aircraft can average about 4 to 6 miles, but the flying time is about three hours per landing. Thus, the actual roll distance for large jet commercial transports can be about 4,500 miles per year. Short haul jets can average 3,800 landings per year. This results in 15,200 miles per year at four miles per takeoff and landing.

However, the 15,000 mile figure will be reduced by the ratio of service wheels to service plus spare wheels. When spares are assumed to be about 100% of service wheels for short haul jets, the annual average wheel service will be 50% x 15,200 = 7,600 miles per year. Thus, if the wheel is expected to last five years, it could roll as much as 38,000 miles in that time. This mileage will not be at a static load equivalent load equivalent to the design gross or landing weights because the operating weights during takeoff and landing are generally less than the design values.

It is impractical to conduct a 38,000 mile roll test for many reasons. It therefore appears that good detail design, good wheel processing, plus a practical spectrum roll test of reasonable duration at maximum static load and greater, is the most rational method of developing a satisfactory wheel for commercial transports.

Suggested airline service and dynamometer service life roll test mileages for main and nose wheels are given in Table I for aircraft of different landing frequencies.

The effect of longer service life and/or increase in the wheel rating on wheel weight is estimated in Figs. A and B.

Fig. A: This figure portrays the variation in the wheel assembly weight for cast and forged aluminum wheels as the desired wheel roll distance is increased. For example, to increase the roll life of a 40 x 12 size forged aluminum wheel from 1,000 miles to 10,000 miles requires an approximate weight increase of 11.5%.

Fig. B: Wheel rating versus wheel weight shows a 3.7 lb. increase in wheel weight per 1,000 lb. rating for forged aluminum wheels in the 4,000-8,000 mile roll test classification.

It is possible that the increased roll life and associated increase in reliability could outweigh a potential payload penalty in terms of reduced maintenance, fewer spares, and improved passenger service due to fewer unscheduled removals of wheels and brakes.

5. TYPICAL BRAKE ENDURANCE REQUIREMENTS

Specification FAR Part 37 requires a minimum of 100 stops at design landing energy. In addition, one stop must be made at the rejected takeoff stop energy. These are extreme values and represent peaks of energy applications. They are not representative of daily operational conditions.

The airline brake, in daily service, will encounter hundreds of stops at much lower energy and deceleration rates. The energy level is lower due to lower operating weight, aerodynamic drag, auxiliary drag devices such as thrust reversers, prop jet propeller drag, headwinds, delayed braking, etc.

The energy can be abnormally high at times due to higher than normal touchdown speeds, hard braking, unsymmetrical braking due to flat tire or inoperative brake, or unsymmetrical braking due to lateral thrust differences when one or more engines are inoperative.

The energy can also be at a semi-emergency level less frequently due to an interrupted takeoff. This is a takeoff which is aborted before the V1 speed is reached because of technical or operational problems. The energy can also be increased by intermittent braking during taxi operations. Some piston engine aircraft must be taxied at relatively high engine RPM on one or more engines to maintain electrical power for radio communications, cabin lighting, instruments, etc. The airplane's speed would be excessive unless the acceleration is controlled by light constant or intermittent braking. Similarly, the use of two jet engines at high thrust on a four-engine airplane, during taxiing can require intermittent braking to avoid excessive taxi speed. The cumulative effect of the resultant energy on brakes, wheels and tires, after parking, is apparent.

Most airline landings are accomplished on brake assemblies that have been overhauled. These assemblies usually incorporate new or used friction parts, used housings, etc. The endurance of all parts should, therefore, be high. Moreover, the endurance of the friction parts (at the lower service energy levels) must satisfy an extended overhaul schedule that greatly exceeds the landings specified in FAR Part 37. This endurance must not represent 100% lining wear to assure that the brakes are airworthy up to the time of overhaul.

It has been demonstrated that there exists a wide variation in brake life when a given brake is employed at the various airlines. Historically, as much as a 2:1 life variation has been in evidence. Additionally, different friction materials exhibit unlike wear rates at various kinetic energy levels. It, therefore, seems prudent to run tests at different energy levels in order to properly establish the shape of a wear versus kinetic energy curve and thus cover most contingencies. Table II proposes what would be considered to be a typical and adequate test spectrum to be employed in determining the brake life characteristics. It is recommended that the energy levels be defined as a certain percentage of the design normal landing kinetic energy as defined in the basic procurement specification. This eliminates the need for the brake manufacturer to calculate the kinetic energy level which often requires information to which he doesn't have access.

The aforementioned variation in given brake life is the result of many factors. Section 8 of this document presents the more significant factors which determine brake life in operational service and it is this type of analysis that was used in determining the energy levels and deceleration rates that are recommended as being typical and presented in Table II.

6. TYPICAL WHEEL ENDURANCE TEST

The wheel endurance roll tests suggested in Table I should be performed on a dynamometer, and should be independent of the brake development tests. Conventional roll test procedures should be used.

7. TYPICAL BRAKE ENDURANCE TEST

Table II suggests a series of dynamic brake stops to be performed to assist in establishing the endurance or life of the brake between overhauls. Test procedure noted in Table II should serve as a guideline. The thickness and weight of all wearing friction materials and/or assemblies must be carefully measured and recorded prior to and following each series of stops in order to calculate wear rates at each energy level. The brake assembly and friction wear parts should remain serviceable throughout the test and be capable of further endurance to the limit of its design goal. Sufficient information should be recorded to establish performance characteristics for each energy series. This should include brake pressure, brake torque, dynamometer speed, brake heat sink temperature and axle brake mounting flange or axle wall temperature.

8. ENDURANCE AND DEPENDABILITY CRITERIA

Airline service environments normally determine the operational reliability, dependability, and economic criteria of aircraft wheel and brake assemblies. Compliance with these criteria can only be assessed prior to the equipment's installation on the aircraft by accurately determining the expected spectrum of service and operational environments and conducting simulated laboratory tests. Spectrum type tests can be usually be established for wheel assemblies whereas they cannot be as easily established for brake assemblies without advance knowledge of the pilot procedures which control the operating environment.

As an example, an aircraft is retarded on the ground by three major forces which react against its forward motion.

1. The aerodynamic drag, including flaps, airbrakes, and parachutes (if used)
2. Engine Referse Thrust
3. Wheel-Brake Assemblies

These three retarding systems can be used in various combinations with widely different effects on the brake assembly's life and subsequent dependability.

The brake assembly's endurance is commonly defined as the number of brake landings achieved on the aircraft between brake removals for overhaul. With predetermined thicknesses of wearing friction elements, the number of landings obtained between overhaul is directly affected by the braking energy and torque environments during airline use. A second and equal concern is that the dependability and reliability of a brake assembly for any one landing or takeoff is directly affected by what environment it has experienced prior to the event. The following analysis illustrates the effect of operational environments on the endurance and dependability of the brake assembly.

A 7,000 foot runway is shown in Fig. D with four equally spaced turn-offs. For all examples, the aircraft is assumed to be at the same normal service landing weight and the stopping segments start at the same touchdown velocity. The summation of retarding efforts (aerodynamic drag + reverse thrust + braking force) is the same for the examples. However, the combination of the three major retarding forces for each example results in different allotments of braking effort. These differences are noted as a percentage of the total retardation to stop the aircraft. The average aircraft deceleration and the brakes-on velocity are also noted for each of the examples.

In the foregoing distribution of stopping distance shown in Fig. D, note that the mean number of landing stops can be identical as noted for Curves "A" and "B". However, the standard deviation (the measure of the spread or dispersion of events about the mean) will be quite different for each curve. The effect of the magnitude and frequency of landing stops should be considered for the projected distribution to properly establish design criteria for brake life.

Fig. E shows the projected brake life resulting from the various combinations of aircraft deceleration and allotted aircraft energy to the brake system.

Fig. F shows the projected heat sink temperature from aircraft braking and the cooling time required to restore the heat sink's dependability.

8. ENDURANCE AND DEPENDABILITY CRITERIA (Continued)

Table III summarizes the operational factors which must be compared to assess endurance, economics, and dependability. An aircraft stopping in 2,500 feet is arbitrarily assumed for the basis of comparison, as it fits the defined statistical mean of airline landings shown in Fig. C.

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TABLE I

WHEEL ROLL LIFE CRITERIA - DYNAMOMETER TEST

Average Landing Frequency Flight-Hrs./Ldg.	Nominal Airline Takeoff Weight % of Design Gross Takeoff Weight	Airplane Type & Range	Recommended Airline Miles for Design	*Recommended Dynamometer Service Life Test for Main and Nose Wheels in Miles
.54	95	Propjet } Short	50,000	12,500
.76	95	Jet } Short	50,000	12,500
1.68	87	Propjet & Jet Intermediate	50,000	12,500
2.4	86	Jet Long - Domestic	50,000	12,500
4.25	86	Jet Long-Intercontinental	25,000	6,250

*Perform Dynamometer Service Life Roll Test to Chart Conditions Below

Type of Roll	Load	Degrees of Yaw	% of Total Mileage Main Whl.	% of Total Mileage Nose Whl.
Straight	$S_L \times Y_1$	0°	90%	65%
Straight	$D_L \times Y_2$	0°	--	25%
Yaw - Inboard	$S_L \times Y_3$	X° 1	5%	5%
Yaw - Outboard	$S_L \times Y_4$	X° 2	5%	5%

(1) Overload factors Y and degrees X to be established by airframe and wheel manufactures, based on analysis of aircraft's ground operational loads.
(2) Overload factors Y must be 1 (one) or greater.
(3) S_L - Maximum static rating as defined by FAR Part 25.
(4) D_L - Dynamic load per wheel assigned by airframe manufacturer, and should equal or exceed the maximum radial reaction to which the wheel is subjected as a result of aircraft deceleration rates.

TABLE II

BRAKE LIFE CHARACTERISTICS TEST SPECTRUM

Number of Stops*	Energy Level - Percent of Normal Energy	Deceleration ft/sec/sec	Inertia Equivalent - Percent of Normal Energy IE
50	80	12	90
50	70	10	90
50	60	8	90
50	40	6	90

*Each stop is to be preceded by a cold brake simulated taxi stop spectrum and followed by a hot brake simulated taxi stop spectrum as noted below.

Cold Taxi Stop Spectrum

4 snubs from 35 mph to 20 mph
1 stop from 35 mph to 0

Hot Taxi Stop Spectrum

4 snubs from 30 mph to 20 mph
1 stop from 30 mph to 0

Deceleration for taxi snubs and stops to be 4 ft/sec^2. The difference in initial brake application velocity is an adjustment made to compensate for testing at a constant inertia equivalent whereas the airplane is heavier during taxi out (cold taxis) than at taxi in (hot taxis). Because of this difference in airplane weight, the energy input to the brake will be greater during the taxi out phase than the taxi in phase, assuming the same brake application velocity.

Column	1	2	3	4	5	6	7	8	9
Example	Stopping Distance Feet	Aircraft Deceler. ft/sec^2	%Retardation Alloted to Brake Assy.	Brake Life Between Overhaul Landings	Brake Endurance Index	Economic Index	Peak H.S. Temperature °F	H.S. Temp. After 30 in. °F	Dependability Index after 30 minutes
					Based on 1000 landings				Based on 450°F
1	1250	12	75	220	.22	4.5	1200	550	.82
2	3000	5	53	1300	1.30	.77	800	450	1.00
3	4750	3	34	3000	3.00	.33	600	370	1.22

DATA EXPLANATION

Column 1 — Data source — Figure D

Column 2 — Data source — Figure D

Column 3 — Data source — Figure D

Column 4 — Data source — Figure E, using the percent of braking effort and deceleration from Figure D.

Column 5 — Brake endurance index was determined by comparing the design life (assumed to be 1000 landings) with the observed data.

Column 6 — Economic index was determined by taking the reciprocal of Column 5, assuming the brake overhaul cost is constant

Column 7 — Data source — Figure F, the heat sink temperature was estimated.

Column 8 — Data source — Figure F, cooling rates were estimated.

Column 9 — Dependability index was determined by comparing the heat sink temperature after 30 minutes with an arbitrary base of 450° F. In the case of Example 2, the dependability is shown to be restored. This example is only true where 30 minutes is defined as the turn-around interval in service. Where the turn-around interval is different, the dependability index would have to be re-established.

Typical
Variation of Wheel Assembly Weight vs. Wheel Roll Life

Approximate Roll Mileage = 2 X Rolling Radius X N/20,200

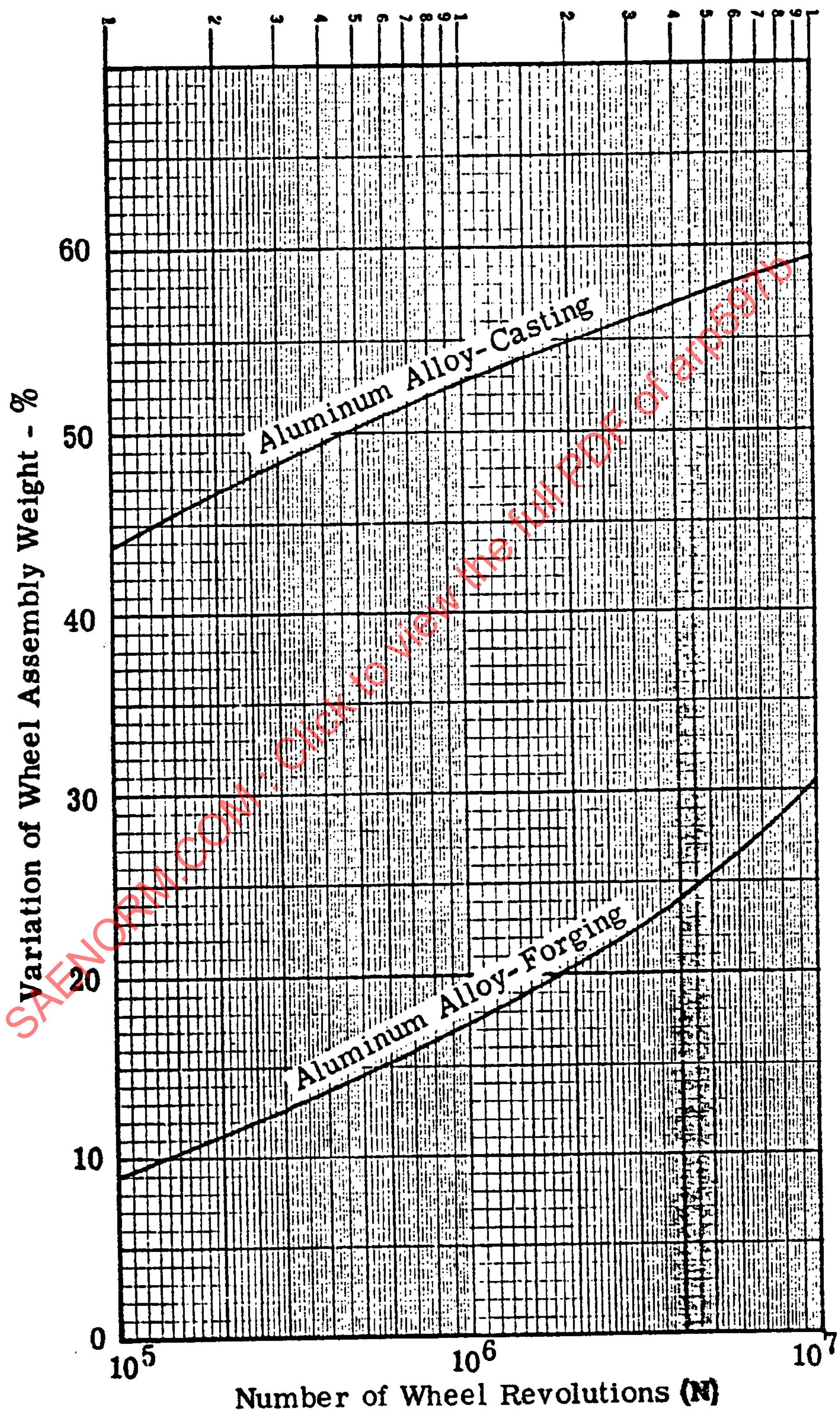

FIGURE A

Typical
Wheel Load Rating vs. Wheel Assembly Weight

Long Life Forged Aluminum
(4000-8000 Mile Dynamometer Roll)

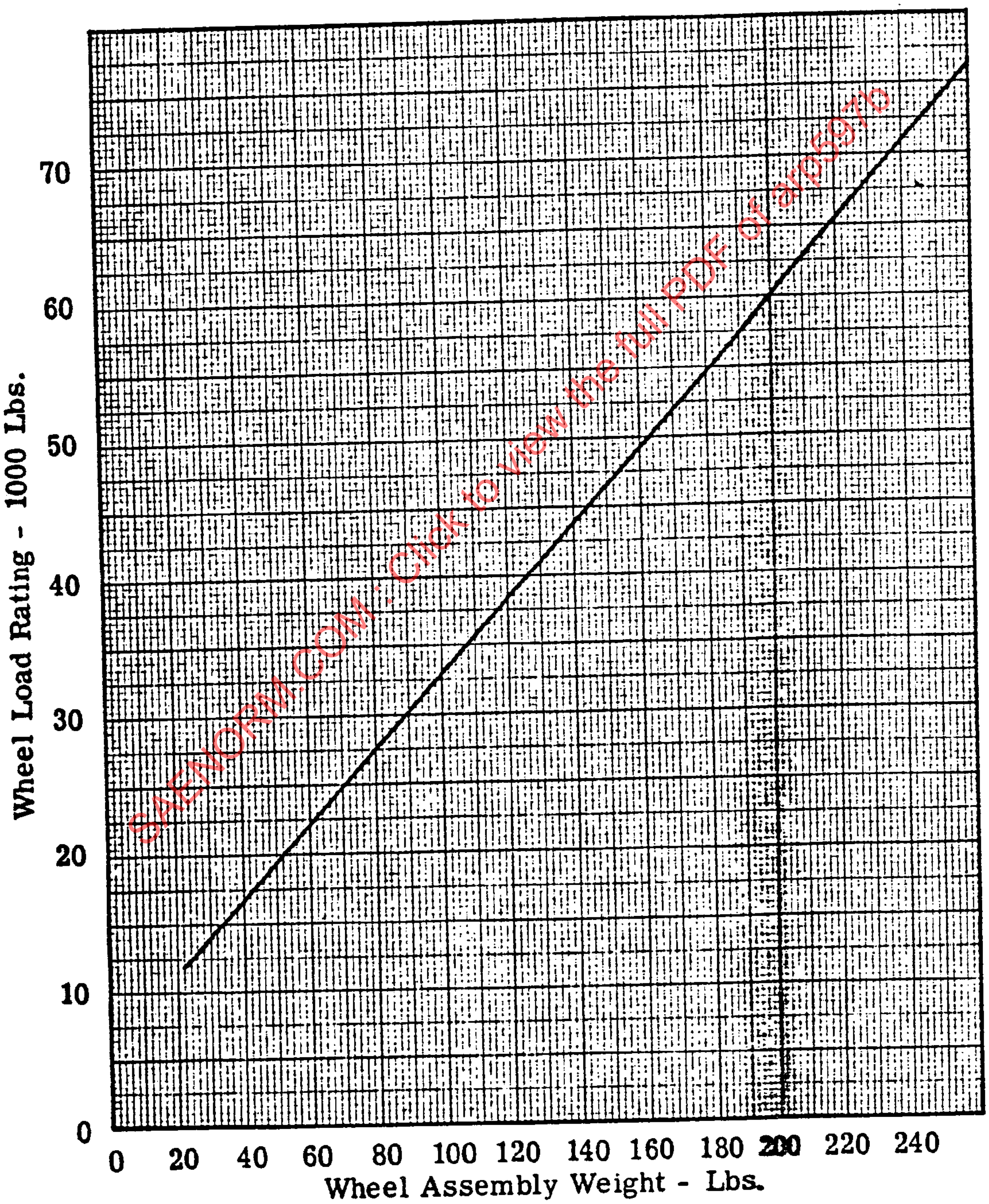

FIGURE B