A CRITICAL STUDY OF SPIN-UP DRAG LOADS ON AIRCRAFT LANDING GEARS

Thesis by

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In Partial Fulfillment of the Requirements
For the Degree of
Aeronautical Engineer

California Institute of Technology
Pasadena, California
1949

ACKNOWLEDGEMENT

The author takes this opportunity to acknowledge the cooperation of the Lockheed Aircraft Corporation and to thank them for the data and information they so generously made available. In particular, the author wishes to thank Mr. J. F. McBrearty and Dr. W. L. Howland of that organization for their kind assistance and guidance. Without the cooperation of these men the project would have been impossible. In addition, the author wishes to thank Dr. E. E. Sechler, Dr. D. E. Hudson, and Mr. M. L. Williams, Jr. of the California Institute of Technology for their valuable criticism of the manuscript.

SUMMARY

This report attempts to analyze in detail the spin-up drag loads imposed upon an aircraft main landing gear. Other factors in the landing gear problem are ignored except insofar as they affect this one type of loading. As an instrument for study, one model of aircraft was chosen for which extensive flight test and drop test data were available.

The main parameters which enter into the spin-up drag load are the landing weight of the aircraft, the rate of descent at contact, the ground speed, the time interval from initial contact to attainment of maximum vertical load, and the coefficient of friction between the tire and the runway surface. Minor parameters which may affect the drag load are the tire pressure, moment of inertia of the rolling stock, oleo pressure, and quantity of oil in the hydraulic shock absorber.

The results of this study indicate that the maximum gear drag load is primarily a function of the time required to reach maximum vertical load, and that further study of this parameter, using drop test data for several types of aircraft, might well lead to some valuable empirical information essential to landing gear design. The value of the coefficient of friction was seen to vary widely in test landings but a maximum value of 0.55 appears to be satisfactory for limit design calculations.

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INTRODUCTION

Recent statistical studies have revealed that the aircraft landing gear is more of a trouble-maker than was previously realized. The Air Force has reported that, neglecting combat damage, trouble with the landing gear was responsible for more aircraft in unflyable condition during the war than all other causes combined except the power plant, to which the landing gear was a close second. During the first four months of 1946, for another example, 10% of all accidents sustained by aircraft of the AAF were caused by landing gear failures. The situation was nicely summarized recently by the Air Force Office of Flying Safety when they reported 60 cases of landing gear collapse in a period of 90 days, of which 30 occurred during the "normal" landing roll.

The entire landing gear problem is clearly outlined by Mr. J. F. McBrearty, Structures Division Engineer at Lockheed Aircraft Corp., in his paper "A Critical Study of Aircraft Landing Gears", Ref. (a). The present research project is a continuation of Mr. McBrearty's study, but it is restricted to only one small phase of the problem: specifically, the spin-up drag loads imposed upon the main landing gear structure during the initial contact and spin-up period. Vertical loads, side loads, taxiing and braking loads and other design conditions have been ignored except insofar as they effect the spin-up drag loads.

Experimentation in this field is of such an expensive nature that comprehensive programs must necessarily be financed by government funds. A small amount of miscellaneous testing has been done by private industry, but the cost of coordinated flight and drop testing by individual companies is for the most part financially prohibitive. As a result, the author has chosen as the basic instrument of his study an airplane which has an excellent service record insofar as the landing gear is concerned, and for which considerable flight test and drop test data were available. It is a twin-engined aircraft having a maximum landing weight of 54,000 pounds and utilizing a retractable tricycle landing gear.

NOTATION

F_d = drag force, positive aft. Pounds.

F_v = vertical force, positive up. Pounds.

T_o = torque exerted by external forces, taken about axle of wheel. Foot-pounds.

I_w = Moment of inertia of wheel about axis of rotation. Slug-feet square.

W = gross weight of airplane at time of landing. Pounds.

m = airplane mass. W/g.

V = ground speed at time of initial contact. Feet per sec.

Δt_v = time interval between first ground contact and attainment of maximum vertical load. Sec.

r_e = effective rolling radius of tire. Feet.

$\dot{\theta}$ = angular velocity of wheel. Radians per sec.

$\ddot{\theta}$ = angular acceleration of wheel. Radians/sec/sec.

a = linear acceleration of airplane C.G. Feet/sec/sec.

μ = coefficient of friction between tire and landing runway.

DERIVATION OF FORMULA

During the landing approach the wheels of a conventional airplane are not spinning. At the instant of initial contact the runway surface begins to exert a horizontal force in the aft direction, thus tending to rotate the wheel. The angular inertia of the wheel resists this tendency, thus transmitting a drag load to the supporting structure. The wheel will spin up to the ground speed of the aircraft in a short period of time, after which there will be no drag load from this cause. The rotational friction of the wheel is of such a small magnitude that it can be neglected.

During this critical spin-up period the tire will experience a combination of spinning and skidding, the latter varying in some unknown manner from 100% to 0% during the time Δt_v. However, data in Ref. (i) indicates that the coefficient of friction between the tire and the runway is almost independent of slippage until this slippage is reduced below 10%, whereupon the coefficient rapidly approaches zero.

Also during this period the vertical load on the wheel will vary, due to the sinking speed of the aircraft, but the manner in which it varies is not readily visualized since the reaction of the hydraulic shock absorber is not known. Therefore, we turn to a time-history of an actual landing and find that the vertical and drag forces increase essentially as a straight-line function of time. Figs. 1 and 2 are presented as typical time-histories of the test airplane, and they bear out the statements made above. Attention is invited to the landing gross weights and rates of descent at contact of the test aircraft in both histories.

The forward speed of the airplane is readily shown to be essentially constant by a mathematical treatment. Utilizing data for flight no. 44, Table I as a typical case and assuming a "transport" or two-point landing:

$W = 45{,}000$ lbs.

$V = 126$ ft/sec.

$\Delta t_v = 0.20$ sec.

$F_{d_{av}} = 3500$ lbs. per wheel

$$F = m\,a$$

$$2\,F_{d_{av}} = (45000/32.2)\,a$$

$$a = -2(3500)(32.2)/45000 = -5.0 \text{ ft/sec/sec.}$$

$$\Delta V = -5.0\,(0.2) = -1.0 \text{ ft/sec.}$$

This figure is based upon a landing gear structure that is infinitely stiff and thus transmits all forces undiminished to the C.G. of the airplane. This is obviously not the case, since the gear and its supporting wing structure are elastic and thus energy is absorbed by their deformation. This means the change in velocity found above is too high. In Flight Test it was found that the change in ground speed during the time Δt_v was so small it could not be measured, thus substantiating our assumption.

Now, with the physical phenomena well described, and utilizing a few simplifying assumptions that are substantiated by the above discussion, one can analyze the forces existent and find an expression for the maximum spin-up drag force that will be imposed upon one wheel during the interval Δt_v.

Assumptions:-

(1) that the vertical force, F_v, increases uniformly over the period Δt_v.

(2) that the drag force, F_d, increases uniformly over the period Δt_v.

(3) that $F_{v_{max}}$ and $F_{d_{max}}$ occur simultaneously at Δt_v.

(4) that the coefficient of friction remains constant until the peripheral velocity of the tire reaches the ground speed of the airplane, which time is Δt_v; and that the coefficient of friction then drops to zero.

(5) that the ground speed of the landing craft, V, is essentially constant during the time interval Δt_v.

From the principle of angular impulse and angular momentum we know that

$$\int_{t_1}^{t_2} T_o \, dt = I_o \, (\dot{\theta}_2 - \dot{\theta}_1)$$

hence in our problem

$$\int_{0}^{\Delta t_v} \frac{F_{d_{max}}}{2} r_e \, dt = I_w \dot{\theta}$$

$$\dot{\theta} = \frac{V}{r_e}$$

$$F_{d_{max}} r_e (\Delta t_v) = 2 I_w \frac{V}{r_e}$$

$$F_{d_{max}}^{2} = \frac{1}{r_e^2} \frac{2 I_w V}{\Delta t_v} F_{d_{max}}$$

$$F_{d_{max}}^{2} = \frac{1}{r_e^2} \frac{2 I_w V}{\Delta t_v} \mu F_{v_{max}}$$

$$F_{d_{max}} = \frac{1}{r_e} \sqrt{\frac{2 I_w V \mu F_{v_{max}}}{\Delta t_v}} \qquad \text{Eq.(1)}$$

In order to justify our equation let us substitute some actual test flight measurements as recorded in Table I. Again choosing Flight no. 44 as typical:

I_w = 33 slug feet^2 (measured)

V = 126 feet/sec.

$F_{v_{max}}$ = 10,000 lbs.

Δt_v = 0.20 sec.

r_e = 2.11 feet

μ = 0.55 (assumed; design criterion)

$$F_{d_{max}} = \frac{1}{r_e}\sqrt{\frac{2\ I_w\ V\ \mu\ F_{v_{max}}}{\Delta t_v}}$$

$$= \frac{1}{2.11}\sqrt{\frac{2\ (33)\ (126)\ (0.55)\ (10,000)}{0.20}}$$

$$= \underline{7170 \text{ lbs.}}$$

Measured $F_{d_{max}} = \underline{7000 \text{ lbs.}}$

thus confirming our fundamental equation with flight test data. A somewhat similar formula is developed by Dr. M. A. Biot in Ref. (d), utilizing a different approach. The equation is not new, having first been presented without development by N.A.C.A. Technical Note 863 as early as 1942.

The ANC Groundloads Bulletin presents a totally different formula, purely empirical in nature and based upon a sinusoidal build-up of vertical load. It appears to be satisfactory for use in the design stages but is less suited to our present purpose.

FLIGHT TEST RESULTS

A comprehensive flight test program with the test airplane has been completed and is reported in Ref. (f). Pertinent data necessary for this study has been recorded in Table I, appended herewith. Instrumentation and methods utilized are included in the reference, but for this paper a brief resumé will be sufficient since we are primarily interested in results rather than methods.

Vertical and drag loads were determined by strain gauge measurements, the gauges being located on the vertical strut and drag strut of the right gear, and the output of the gauges being recorded directly on an oscillograph. Forces were later resolved into horizontal and vertical components. The time interval Δt_v can be read directly from the oscillograph record. Accelerations were measured by specially designed accelerometers placed at various locations in the aircraft. Wheel RPM measurements were obtained with D.C. generators geared directly to the wheels.

Ground speed and rate of descent of the airplane C.G. were obtained by the usual photo-grid method. In addition, the rate of descent of the right wheel during the few seconds preceding contact were obtained by the water-jet method. This consists of photographing the gap between the wheel and the ground with a gun camera mounted on the opposite main gear axle. A ground reference line is provided by a small jet of water squirted from a nozzle attached to the right gear. Rates of descent by both methods are tabulated on Table I wherever data was available. Attention is invited to the striking difference in results between the two methods. A study of the time histories of the landings in question indicates that some errors may be attributed to landing on one wheel first, but this is not true in all cases. It is apparent that neither method is completely satisfactory or reliable, nor has any method come to the attention of the industry that can be trusted for accuracy. This, then, is one feature of testing technique that must be improved before much more progress can be made.

The design sinking speed for both commercial and military aircraft is 12 feet per second, except in the case of carrier-based planes where a higher figure must be used. This represents, in practice, an unflared landing at 720 feet per minute, a rate of descent so radical that it is difficult for test pilots to intentionally duplicate. In addition, a complete airplane is often drop-tested to this sinking speed without failure, and usually without any detectable damage. Investigation by the N.A.C.A. reveals that the "average" landing will be made with the rate of descent ranging from 1 to 3 feet per second, and that an unflared blind landing will average about 5 feet per second. The point to be made here is that the design criterion for sinking speed is certainly adequate, and that many service failures attributed to "hard landings" may in reality be considerably less severe than the 12 feet per second unflared landing for which the landing gear is designed and demonstrated to be adequate.

The latest ANC Groundloads Bulletin (March 1948) specifies a coefficient of friction of 0.55 to be used in design calculations for the maximum spin-up drag loads. This figure is an arbitrary one based upon experience alone, and is assumed to be the largest value that will be experienced when landing under limit design conditions. As a matter of interest Fig. 3 is appended to show how this design criterion has varied since 1930.

In an attempt to learn something about the coefficient of friction in these landing tests, the formula derived earlier was solved for μ in all cases where sufficient data was available, and the results are plotted on Fig. 4. Hereafter the coefficient thus obtained will be called the "effective" coefficient of friction; it is that coefficient experienced by the landing gear structure rather than the true coefficient defined by the ratio of drag load to vertical load at the point of contact of the tire, a value which is physically impossible to obtain in flight testing.

The scatter of points on Fig. 4 is somewhat disconcerting but it does show one fact: the design criterion of ANC-2a is a good estimate since all but three points lie below this level. There also appears to be a tendency for μ to decrease with an increase in gross weight, but this is not definite. Figs. 5 and 6 are graphs of the same data plotted against rate-of-descent and against ground speed at contact. Again the scatter of points does not permit fairing a curve nor drawing any general clues as to the variation of μ with these parameters.

Additional cross-plots were attempted with the same negative results. At this point in the investigation it becomes apparent that there are so many parameters controlling the effective coefficient of friction that one cannot pin it down with flight test data. Instead we must turn to drop testing methods in which we can control the variables and hope to determine at least the tendencies of the coefficient.

DROP TEST RESULTS

An extensive drop test program for the landing gear of our test airplane is reported in Ref. (g). Only such data as is applicable to this investigation has been appended as Tables II and III. In these tests an actual gear was rigged in a drop test tower and dropped from various heights and under various loads. The "landing" surface was either a concrete or a steel slab mounted on a floating platform. Vertical, drag, and side forces experienced by this platform were measured by strain gauges and recorded by an oscillograph. Effective ground speeds were simulated by pre-rotating the wheel in a reverse direction prior to dropping. Structural members of the gear were also instrumented but these readings are of little interest in this investigation since we can get true vertical and drag loads, and hence true values of the coefficient of friction, directly from the platform measurements.

As a starting point the coefficient of friction was plotted against platform vertical and drag loads. The results, Fig. 7, were similar to flight test results but with somewhat less scatter. This plot is based upon data of Table I in which the wheel was pre-rotated to 700 RPM, giving an effective ground speed of 80 MPH for all drops.

An examination of Figs. 1 and 2 reveals that the vertical load experienced by one gear structure is something less than one-half the landing weight of the aircraft. This is due to the lift of the wings during the spin-up period. Other investigators have shown that essentially full wing lift acts on the airplane during the landing impact regardless of the severity of the landing. Therefore, the vertical load will be a function of the weight of the airplane, of the oleo design, and of time. Fig. 8(a) shows with fair accuracy the time to reach peak vertical loads on the airplane. It would be interesting to plot similar curves for different types of aircraft, were the data available. Such a study might lead to a fairly accurate empirical formula for estimating Δt_v for any airplane under a given design vertical loading. It should be noted here that Ref. (g) states as one of its conclusions that "the maximum gear drag load was found to be a function of the time required to spin up the wheels."

Fig. 8(b) is a plot of maximum drag versus maximum vertical loads. In this graph the scatter appears to be less but that is merely due to the manner of presentation. We still have an envelope rather than a curve. The relationship between drag and vertical loads is extremely important. Reviewing the elementary assumptions made while deriving equation (1), it becomes apparent that if the engineer can design a shock strut that is considerably "softer" in the initial part of the stroke, thereby reducing the vertical load during the spin-up period, the maximum drag load can be substantially reduced.

Fig. 9 is a further breakdown of results based upon the data of Table III. In these tests the drop weight, tire pressure, strut pressure, and oleo oil volume were held constant. The variables were the effective ground speed and the vertical velocity at impact. The coefficient of friction has been plotted against each of the variables. Here for the first time we get some points which appear to fall in a definite curve. Due to the scarcity of test points in Fig. 9(a) we cannot really justify the curves shown: they are intended primarily to connect drops made under similar conditions and thus show the tendencies of the coefficient under the action of the two variables.

Unfortunately these drop tests were conducted mainly to prove the adequacy of the landing gear and research was a secondary consideration. The magnitude of the forces produced in the drop tests were usually much greater than those encountered in flight test, so that comparisons were impossible. However, with even a few drops available, Fig. 9 shows definite tendencies and should be further verified by subsequent testing. It must be noted here that the ground speeds and rates of descent as shown on this figure are approximate. Test points were chosen in which these parameters were similar, but drops in which they were constant are not available. Under the circumstances it is felt that these curves should be considered qualitatively rather than quantitatively.

As a side light on the status of current research along these lines Fig. 10 has been included. This curve was furnished by the B. F. Goodrich Co. and shows the coefficient of friction decreasing with an increase in ground speed, as determined by A-20 airplane taxi tests. The slopes found in Fig. 9(b) are opposite in nature. The only similarity between the two is the fact that the coefficients found were of the same general magnitude.

As a final attempt to examine the coefficient of friction and its relationship with spin-up drag loads, time-histories were again utilized. Fig. 11 is a typical time-history of platform vertical and drag loads during three drop tests. The shape of the curves is similar to those found in flight testing, but the magnitudes of the loads are greater and Δt_v is generally a little smaller, a result to be expected after viewing Fig. 8. In this instance the curves for three different "landing" surfaces are shown: dry concrete, dry steel, and wet steel. Note that the vertical forces are all similar, but that the drag forces are of different magnitudes and frequencies. Table III lists the only tests made for these surfaces under similar drop conditions. However, Tables IV and V show typical values for the coefficient of friction of rubber tires on various surfaces of interest to the aeronautical engineer. These figures were presented by various tire and rubber companies and are the result of static tests under controlled conditions. Since the coefficient of friction varies under the effect of such factors as tread condition, surface cleanliness, moisture content, surface texture, etc. these figures can only be taken as representative values.

From oscillograph records of the numerous drop tests one can readily make plots such as Fig. 11. From these the instantaneous ratio of drag to vertical loads gives the instantaneous coefficient of friction, and plots such as Fig. 12 are the obvious result. Here again the number of parameters involved makes analysis difficult, so that the same data was plotted to larger scales and with fewer variables.

Fig. 13 shows a time-history of the coefficient of friction, permitting the airplane weight to vary but holding the ground speed and rate of descent constant. This curve indicates a definite drop in the coefficient at 60,000 pounds, yet practically no change between 30,000 and 45,000 pounds. This odd and inconclusive result suggested a second check, Fig. 14, using the same weights and the same ground speed, but at a higher rate of descent. The result was the same. Hence, coupling this with the indication of Fig. 4 we must conclude that there appears to be a lowering of the coefficient of friction with an increase in the landing weight of the airplane, but the exact amount of such change is not yet known.

The next two graphs are similar cross-plots, made in an effort to verify the effect of vertical velocity at contact. Both plots indicate that the effect is negligible, a result that is not in accord with the indications of Fig. 9. Since the curves of Figs. 15 and 16 are time-histories, each based upon a single drop where conditions are known to be constant, it is felt that this is a more conclusive method of analysis. Both of the latter curves indicate rather erratic values immediately after contact. One might immediately assume instrument errors or inertia effects as a possible explanation. However, a feature that should not be overlooked is the vulcanizing effect which may take place at the point of contact when landing at high ground speeds. How such vulcanizing will effect the coefficient of friction is still a matter of conjecture. In addition, one must realize that after numerous drops the test tire will be worn in spots. Also, during slippage small pieces of rubber will be worn off; these may form small balls between the tire and the landing surface, thus lowering the coefficient of friction. These phenomena are true in both flight testing and drop testing and constitute at least a partial explanation for the scatter found in all of these tests.

OTHER ASPECTS OF THE PROBLEM

The preceding discussion deals with only one small phase of an important and very complex problem. No mention has been made of the relationship between spin-up drag loads and other factors: for example the dynamic spring-back loads, and the twisting moment produced in the wing structure of a multi-engined aircraft by the drag force on the landing gear. This latter, coupled with the accelerations of the engine mass which is supported by a nacelle directly above and forward of the main gear, comprises a very serious wing torsion problem. The vibration problem of the landing gear is extremely difficult; it does not lend itself to a classical solution due to the elasticity of the supporting structure. Furthermore, the present investigation has been limited to results obtained on only one aircraft. The field is still new and comparatively uninvestigated.

No discussion on spin-up drag loads would be complete without some mention of pre-rotation prior to landing. Theoretically, if the wheels of the airplane can be spun up to such a speed that the tangential velocity equals the ground speed at contact there will be no drag load. This is theoretically sound and experimentally true, but it has some practical drawbacks.

There have been several methods of pre-rotation tried. On the test airplane, experiments were made using tire flaps, a device brought out by one of the larger tire companies, but only 47% pre-rotation was obtainable by this method. It was found that to obtain a substantial reduction in gear drag load the amount of pre-rotation must be held within approximately 10% of the full 100% value of desired RPM. In service, of course, the actual ground speed at contact will vary with wind conditions, landing weight of the aircraft, and pilot technique. Since excessive pre-rotation will cause forward drag loads, it becomes apparent that at least a certain degree of pre-rotation control by the pilot would be desirable. A further disadvantage of tire flaps is that when operating under service conditions any mud on the runway would build up behind the flaps, making them inoperative.

A greater degree of success has been had by using a Dever's ring-wound type wheel motor, an electric installation built right into the wheel and utilizing 24-volt d.c. power. Gear drag loads were substantially less on these tests, but here again speed control by the pilot was not made available. Furthermore, one cannot depend upon an electric installation being 100% reliable, so that the landing gear structure must still be designed to forces existent at zero pre-rotation.

The Goodyear Aircraft Corporation has furnished a curve, Fig. 17, showing the effect of pre-rotation on drag loads, as determined by controlled tests in the Laboratory. The Lockheed Aircraft Corporation has found in actual tests that this ideal curve is not actually realized in flight test: that very little reduction in drag load is noticeable up to 50% pre-rotation, but that above this percentage the drag load decreases rapidly. As transport and bomber type aircraft become larger, and their landing gears become heavier and more complicated, it may become mandatory to use some form of pre-rotation. The results will be fruitful when someone does present a reliable solution to this problem, and considerable attention is being directed along this line of attack.

Another design which shows some promise of improving the life of the landing gear is a hydraulic damper similar in principle to an oleo shock absorber but built into the drag strut of the main landing gear. This was first tried on the Lockheed "Constellation" and is now optional equipment for that aircraft. The manufacturer reports that installation of the damper drag links will reduce the maximum forward drag load by 59%, the maximum spin-up drag load by 11%, and will reduce the gear oscillation essentially to one cycle. The latter feature, of course, will greatly lengthen the fatigue life of the landing gear and its supporting structure.

The "landing gear strength envelope" was first introduced in 1946 by Ref. (j) as a method of showing graphically the overall strength of a landing gear structure. Fig. 18, which is reproduced here with the consent of the authors, shows by superposition the relative vertical and drag strengths for the main gears of five airplanes in use today. Each of the curves A, B, C, D, and E represents a different airplane. Each diagram shows graphically the maximum combinations of vertical and drag loads which the landing gear can sustain without failure. The strength envelopes presented are made non-dimensional by dividing actual strength by airplane gross weight, and are comparative since the general function of the airplanes shown is nearly the same for all. From his study of service and accident reports, Mr. J. F. McBrearty reports in Ref. (a) that

> "...failures seldom occur because of vertical or side loads but rather because of loads in the drag direction either forward or aft. The most predominant source of failures appear to be in the drag bracing itself, or its attachments or in some element of the structural system transmitting drag forces throughout the structure."

With this fact in mind, an inspection of Fig. 18 makes it immediately apparent that engineers have been putting too much emphasis on vertical strength and insufficient attention has been given to the drag loads. Our earlier curves show that the spring-back drag forces are nearly as great as spin-up loads. Other experimenters have in several landings found the drag loads to exceed the vertical loads. It now becomes apparent that Fig. 18 points the way for immediate improvement in landing gear characteristics. Landing gear strength envelopes should be cut down somewhat in the vertical direction, thereby saving weight, and they should be increased in both fore and aft drag directions to increase the life and reliability of the gear. Such changes in the envelope are possible by close detail design.

This outline, though not complete, is sufficient to indicate the fields that are now being explored and to indicate the possible trends of landing gear design in the near future.

CONCLUSIONS

1. The value of 0.55 for the coefficient of friction as specified in ANC-2a to be used for computing spin-up drag forces is a reasonable estimate of the maximum value that may be expected, although occasionally a higher value may be experienced.

2. There appears to be a tendency for the coefficient of friction to decrease with an increase in landing weight.

3. The vertical velocity at contact has no appreciable effect upon the coefficient of friction.

4. Results of this investigation indicate an increase in the coefficient of friction with an increase in ground speed at contact, a result not in accord with previous investigators.

5. The time to reach maximum vertical load was found to decrease for an increase in vertical load. This parameter should be investigated further, using similar data for other types of aircraft, since it is of major importance in determining the maximum spin-up drag load.

6. A reliable means of accurately measuring the rate of descent at contact is urgently needed by the industry.

7. Shock strut design is a promising field of endeavor. If a shock absorber can be made considerably "softer" in the initial part of the stroke, thereby reducing the vertical load during the spin-up period, the maximum drag load can be substantially reduced.

8. Landing gear strength envelopes are an excellent method for illustrating graphically the ultimate strength of a gear under any combination of vertical and drag loads, and they also point the way for immediate improvement in landing gear design.

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TABLE I

FLIGHT TEST DATA

Test No.	$F_{d_{max}}$ R. Gear lbs.x10^{-3}	$F_{v_{max}}$ R.Gear lbs.x10^{-3}	r_e ft.	Δt_v sec.	V ft/sec	μ —
34	8	14	2.08	0.23	131	0.526
35	6	9	2.16	0.21	123	0.485
36	12	20	2.00	0.19	123	0.675
37	8	16	2.05	0.15	117	0.326
39	6	8	2.11	0.24	154	0.474
40	9	20	2.01	0.16	116	0.380
41	6	9	2.12	0.21	113	0.506
42	5.5	8	2.11	0.22	129	0.435
43	7.5	12	2.12	0.19	129	0.470
44	7	10	2.11	0.20	126	0.524
45	6.5	9.5	2.12	0.21	129	0.493
46	8.5	11.5	2.04	0.20	155	0.510
47	7.5	15	2.16	0.30	123	0.645
48	6.5	11	2.15	0.12	117	0.276
49	7	12	2.11	0.19	122	0.428
50	7	11	2.12	0.20	126	0.481
54	5.5	9	2.18	0.21	152	0.334
55	6.5	9	2.15	0.20	139	0.472
56	5.2	11.5	2.17	0.28	153	0.306
57	5	9.5	2.16	0.20	153	0.244
58	5	8.5	2.13	0.15	154	0.197
59	7.7	11	2.12	0.22	138	0.586
60	5.5	9	2.15	0.14	142	0.232
61	7.5	17	2.04	0.14	166	0.176
62	4.5	7.5	2.20	0.28	138	0.400

Computation:

$$\mu = \frac{F_{d_{max}}^{\;2} \; (r_e)^2 \; \Delta t_v}{2\;(33)\;(V)\;\; F_{v_{max}}}$$

$$I_w = 33 \text{ slug ft.}^2$$

TABLE I

FLIGHT TEST DATA (Cont'd)

Test No.	μ	Rate of Descent		Aircraft Weight	Tire Press.
		R. Gear	Airplane		
	—	Ft/sec.	Ft/sec.	lbs.	lb/in.^{2}
34	0.526			45,000	62
35	0.485			↓	↓
36	0.675			↓	↓
37	0.326			↓	↓
39	0.474			↓	↓
40	0.380		6.20	↓	↓
41	0.506	1.67	3.47	↓	45
42	0.425	1.45	2.93	↓	80
43	0.470	4.27	2.98	↓	62
44	0.524	3.47	3.88	↓	↓
45	0.493	1.85	2.05	↓	↓
46	0.510	2.90		↓	↓
47	0.645	2.10		↓	↓
48	0.276	2.75		↓	80
49	0.428	3.33		↓	62
50	0.481	2.50		↓	62
54	0.334	2.47		58,300	80
55	0.472	1.55		↓	↓
56	0.306	2.28		↓	↓
57	0.244	2.10		↓	↓
58	0.197	2.08		↓	↓
59	0.586			↓	↓
60	0.232	1.50		↓	↓
61	0.176	3.20		↓	↓
62	0.400	1.38		↓	↓

Notes: (1) Rate of descent for R. Gear is measured by water-jet method.

(2) Rate of descent for airplane is measured by photo-grid method.

(3) r_e = rolling radius of tire determined from Goodrich Tire Deflection Curve, using peak vertical load for each test.

TABLE II

Drop Test Data

Constant Ground Speed

Drop. No.	Platform $F_{d_{max}}$	Platform $F_{v_{max}}$	μ	Δt_v	Wheel Speed	Rate of Descent	Drop Weight
Units →	lbs.x10^{-3}	lbs.x10^{-3}	—	sec.	R.P.M.	F.P.S.	lbs.x10^{-3}
104	6.0	16.7	0.360	0.210	700	1.0	8.7
105	9.7	25.8	0.376	0.128		4.8	
106	13.4	37.8	0.364	0.095		5.4	
110	11.6	25.1	0.472	0.174		1.9	15
111	16.9	36.8	0.460	0.115		5.9	
112	26.2	58.8	0.445	0.087		9.5	
117	7.4	15.4	0.480	0.210		2.4	
118	14.6	29.7	0.491	0.124		6.2	
119	21.3	49.6	0.430	0.090		9.5	
120	29.5	55.3	0.534	0.078		11.9	
124	13.1	32.4	0.405	0.160		1.0	22.5
125	17.4	44.0	0.396	0.110		5.5	
126	19.6	56.7	0.346	0.095		7.6	
127	22.4	68.5	0.328	0.080		9.4	
131	11.2	22.0	0.510	0.170		2.3	
132	15.8	36.1	0.438	0.110		5.9	
133	20.3	57.5	0.353	0.085		9.3	

Dry Concrete

Tire Press — 60 p.s.i.

Effective Ground Speed — 80 M.P.H.

TABLE III

Drop Test Data

Variable Ground Speed

Drop No.	Wheel Speed	Effective Gr. Spd.	Platform $F_{d_{max}}$	Platform $F_{v_{max}}$	μ	Rate of Descent	Surface Material
Units →	R.P.M.	M.P.H.	$lbs x 10^{-3}$	$lbs x 10^{-3}$	—	F.P.S.	—
136	140	19	10.5	50.7	0.207	9.9	Dry Concrete
137	260	33	14.6	52.1	0.280	10.2	↓
138	420	51	17.4	54.9	0.317	10.1	
139	560	66	19.8	56.5	0.350	10.2	
140	70	10	6.4	32.1	0.200	5.9	
141	140	19	7.2	33.7	0.214	5.8	
142	280	35	11.7	35.6	0.329	6.0	
143	420	51	13.9	37.8	0.368	5.7	
144	560	66	15.8	37.5	0.421	5.6	
145	70	10	8.1	49.5	0.167	9.9	
146	700	80	7.6	13.2	0.575	2.7	
150	700	80	19.6	49.6	0.395	9.7	
193	420	51	9.2	22.9	0.401	2.5	
194	560	66	10.7	22.2	0.482	2.3	
196	280	35	9.8	21.2	0.462	2.5	
*197	700	80	18.6	33.8	0.550	5.5	Dry Steel
*163	↓	↓	3.3	31.3	0.105	5.8	Wet Steel
*201			13.1	33.6	0.390	5.2	Dry Concrete
*202			15.6	37.3	0.419	5.4	"

*Drop Conditions Nearly Identical.

Drop Weight — 22,500#

Tire Press — 60 p.s.i.

Strut Press — 322 p.s.i.

Oleo Oil — 15 qts.

TABLE IV

Coefficient of Friction For Rubber Tires On Various Landing Strip Materials

Material	Wet	Dry
Asphalt	0.7	0.8
Macadam	0.4	0.7
Metal - smooth	0.1	0.6
Metal - embossed	0.3	0.6
Wood	0.15 - 0.3	0.6
Grass	0.04 - 0.10	0.10 - 0.5
Earth - clay	0.1 - 0.3	0.6
Earth - gravel	0.6	0.6
Dry lake bed	0.15	0.6

Note: these are typical values.

Courtesy B. F. Goodrich Co.

TABLE V

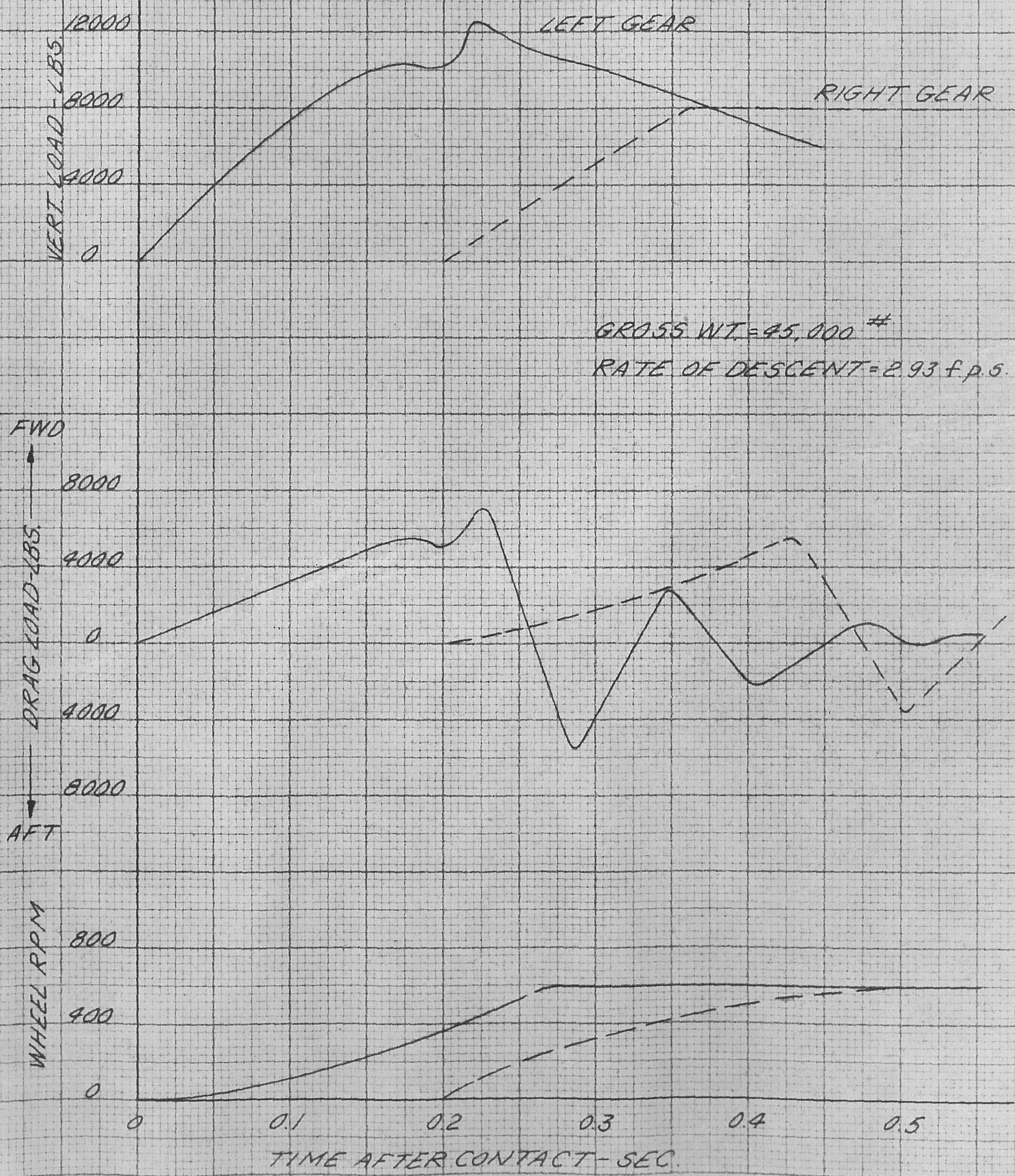
Representative Values of Coefficient of Friction of Natural Rubber Pneumatic Tires on Highways - Established by Controlled Tests in 1941 - 1942.

Source of Data	Type of Highway	Condition Surface	Type Tread	Speed MPH	μ
National Bureau Stds.	Concrete	Dry	New (Rib)	20	.625
National Bureau Stds.	Concrete	Wet	New (Rib)	20	.505
National Bureau Stds.	Asphalt	Dry	New (Rib)	20	.645
National Bureau Stds.	Asphalt	Wet	New (Rib)	20	.505
National Bureau Stds.	Macadam	Dry	New (Rib)	20	.600
National Bureau Stds.	Macadam	Wet	New (Rib)	20	.398
National Bureau Stds.	Mud on Concrete	Wet	New (Rib)	20	.548
National Bureau Stds.	Oil on Concrete	Wet	New (Rib)	20	.228
Iowa State College	Broomed Concrete	Dry	New	10 40	.810 .625
Iowa State College	"	Dry	Smooth	10 40	.830 .785
Iowa State College	"	Wet	New	10 40	.705 .535
Iowa State College	"	Wet	Smooth	10 40	.700 .525
Iowa State College	Packed Snow	Wet	New	25	.220
Iowa State College	Wet Ice	Wet	New	5	.070

Courtesy Goodyear Aircraft Corp.

FIG. I-TIME HISTORY OF MEASURED LANDING LOADS

FLIGHT TEST RESULTS



GROSS WT. = 45,000 #
RATE OF DESCENT = 2.93 f.p.s.

FIG. 2- TIME HISTORY OF MEASURED LANDING LOADS

FLIGHT TEST RESULTS

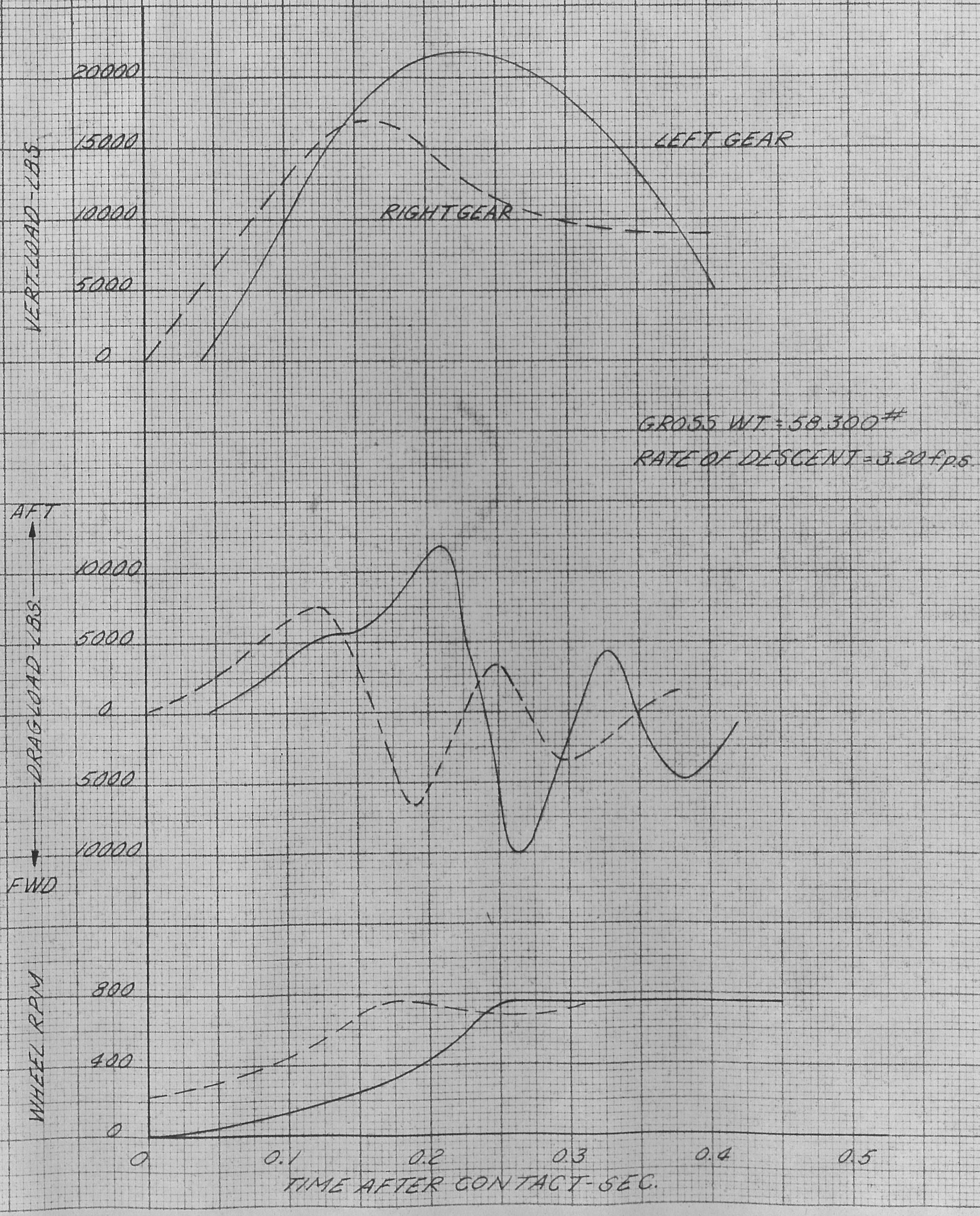
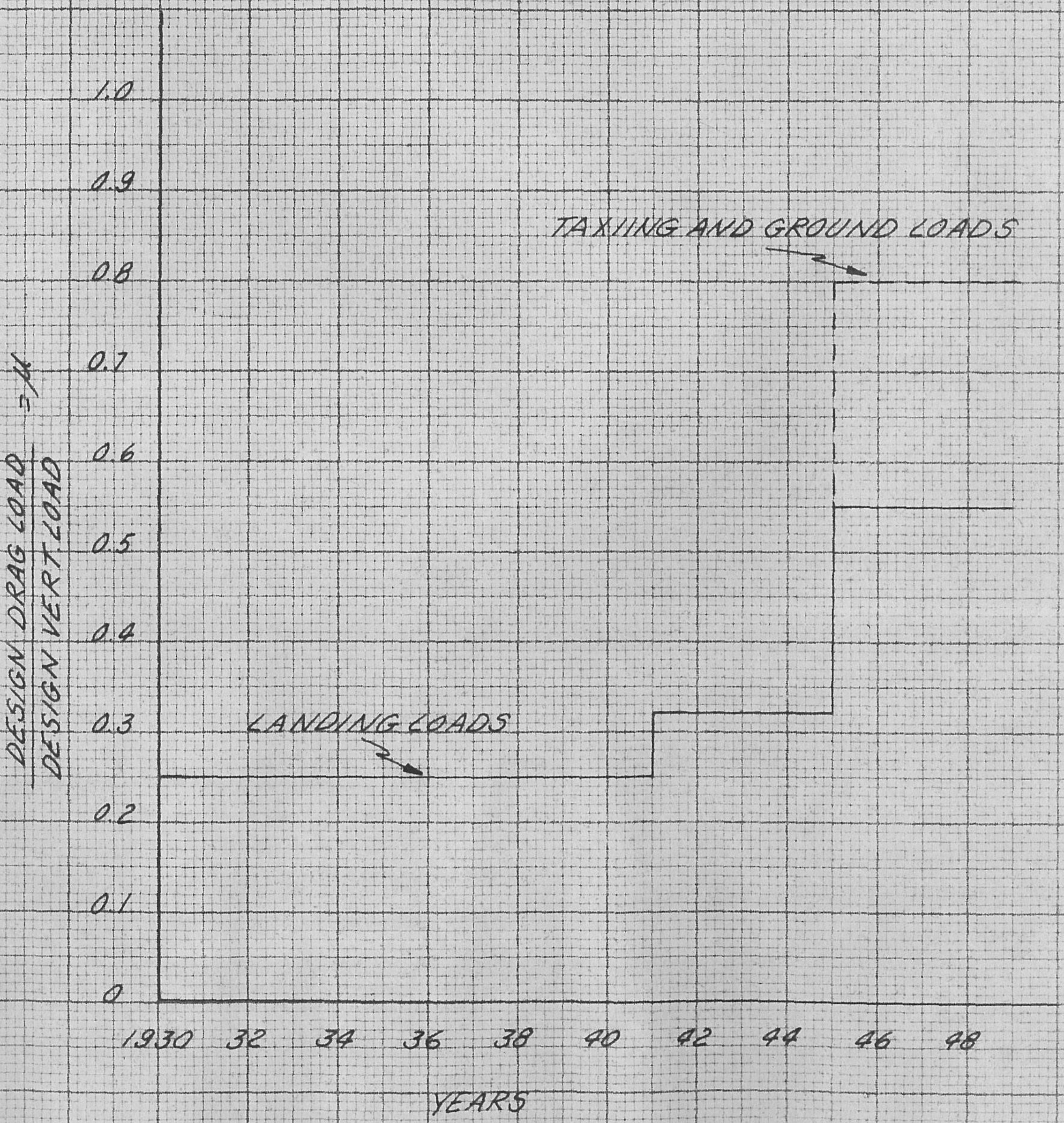


FIG 3 - DESIGN CRITERIA FOR SPIN-UP DRAG LOADS



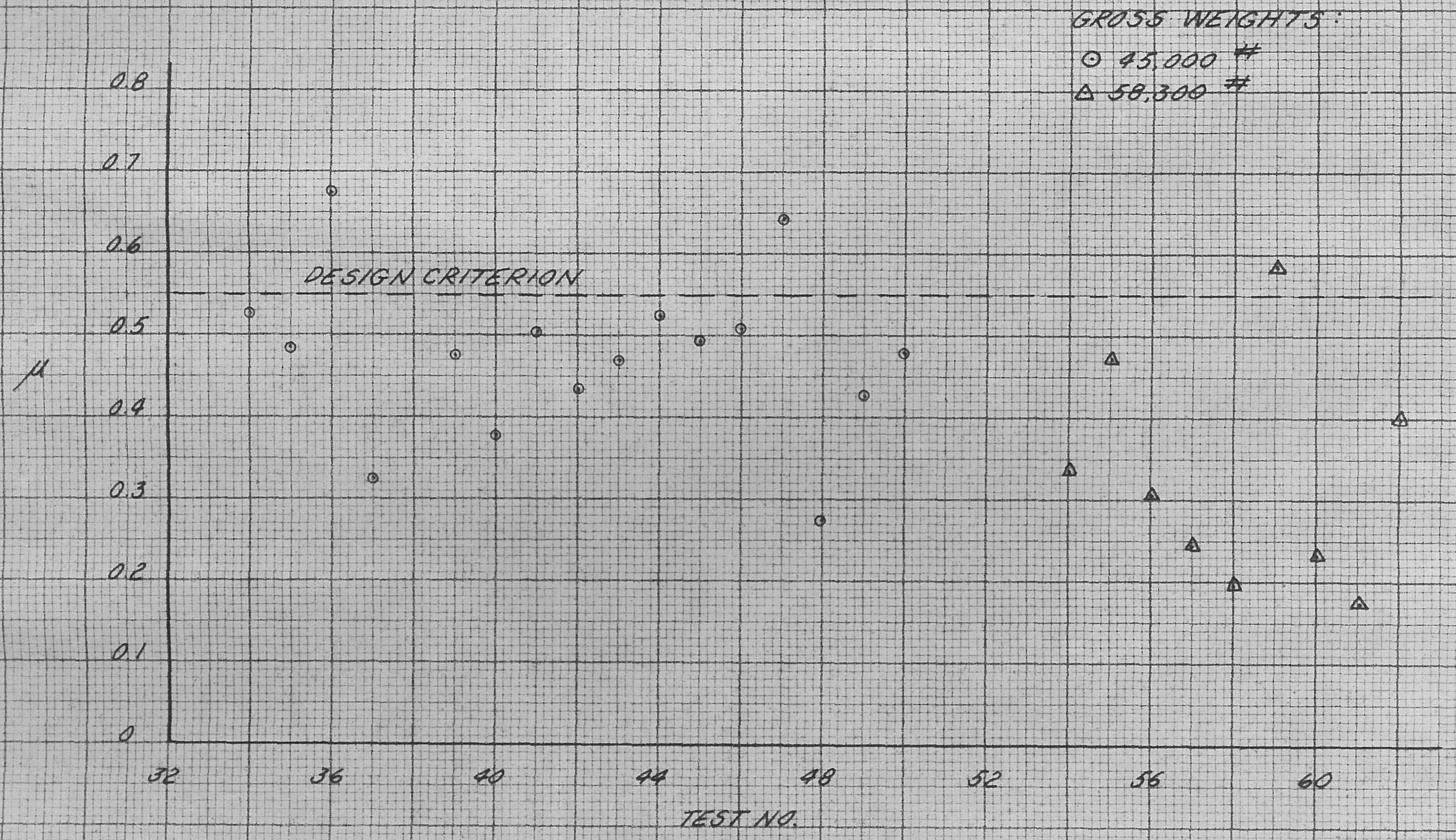


FIG. 4 - EFFECTIVE COEFFICIENT OF FRICTION

FLIGHT TEST RESULTS

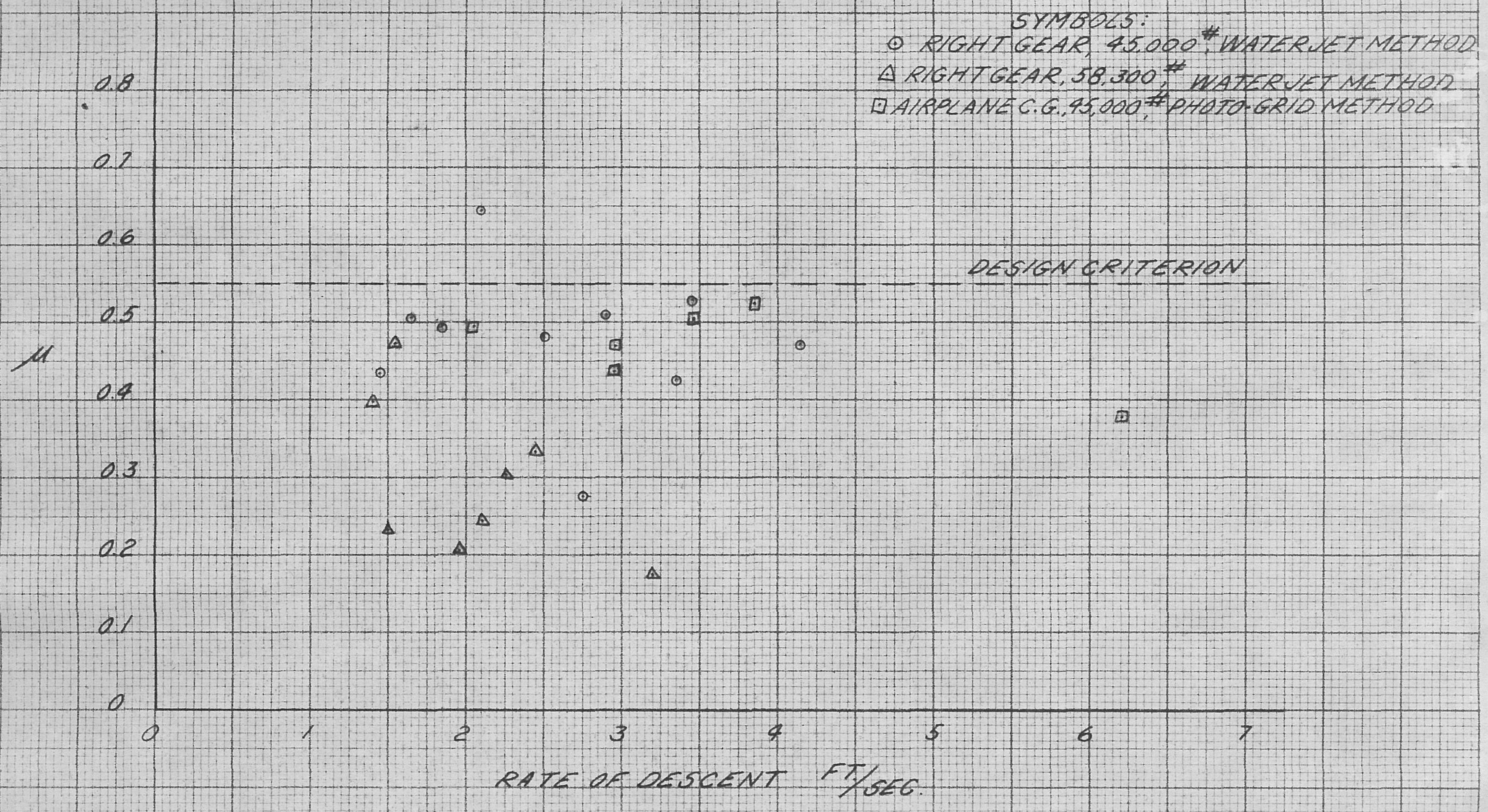


FIG. 5 - EFFECTIVE COEFFICIENT OF FRICTION VS. RATE OF DESCENT
FLIGHT TEST RESULTS

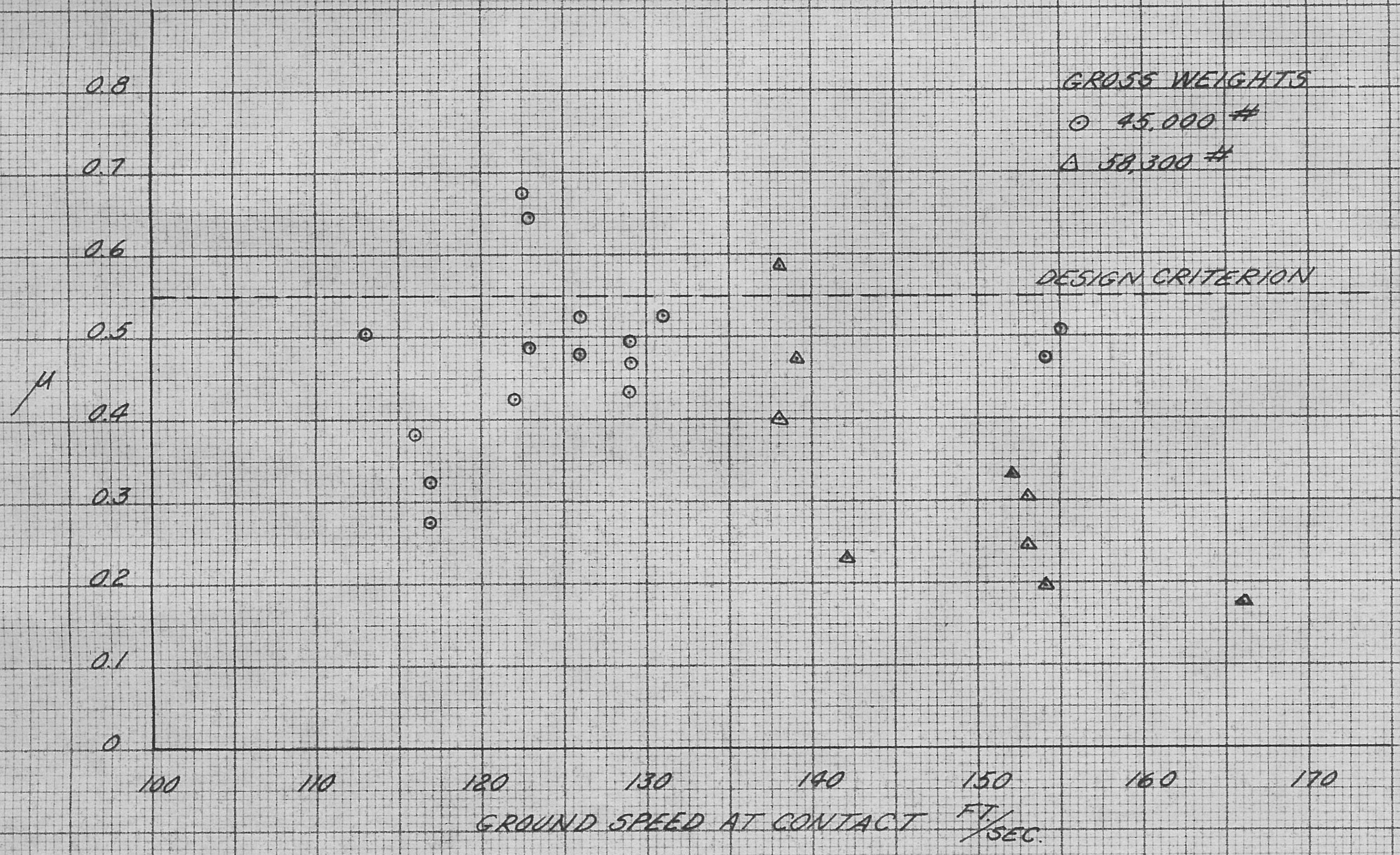


FIG. 6 - EFFECTIVE COEFFICIENT OF FRICTION VS. GROUND SPEED

FLIGHT TEST RESULTS

FIG. 7 - VARIATION OF μ WITH VERTICAL AND DRAG LOADS

DROP TEST RESULTS

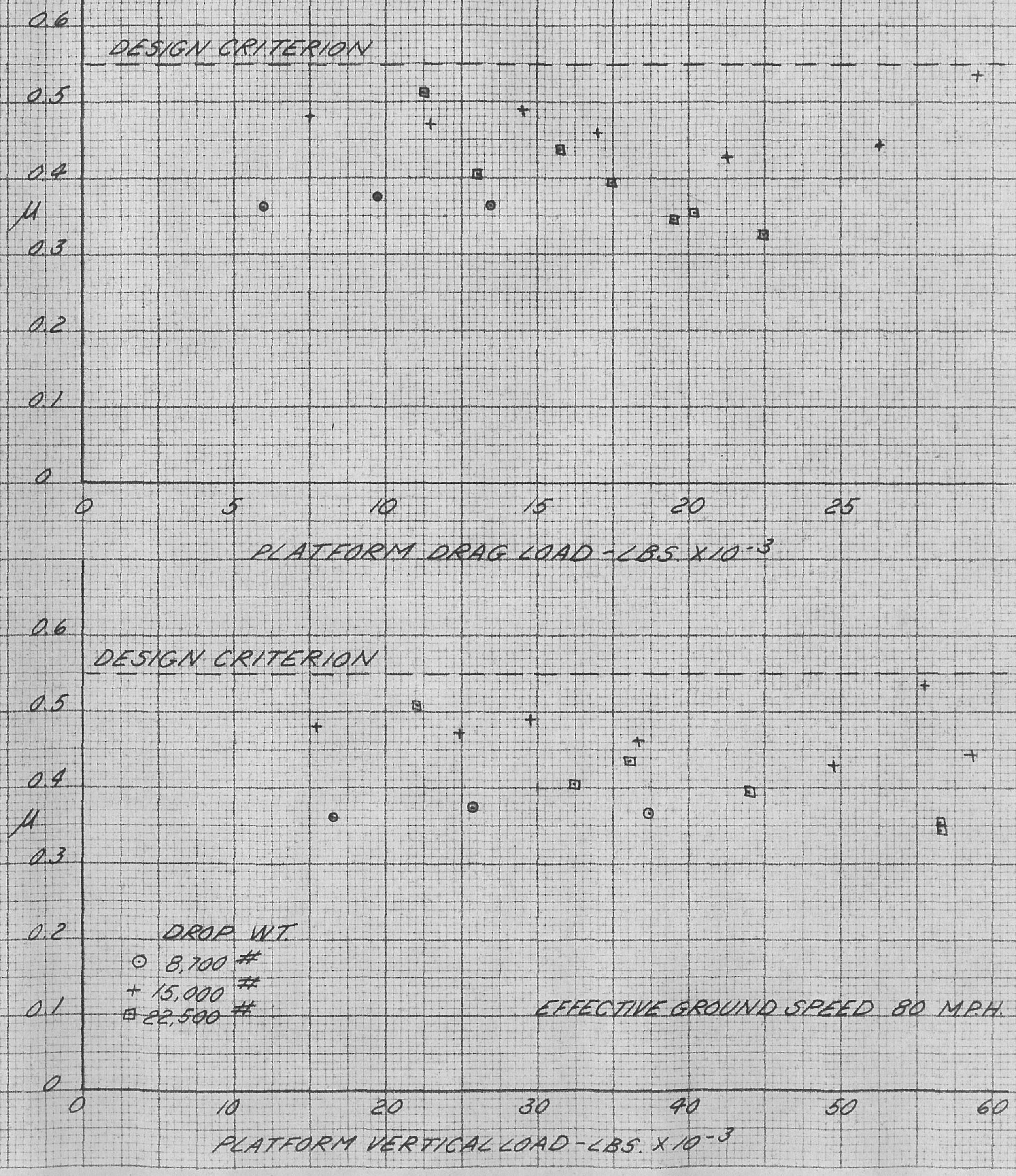


FIG. 8-VARIATION OF DRAG LOAD AND Δt_v WITH VERTICAL LOAD

DROP TEST RESULTS

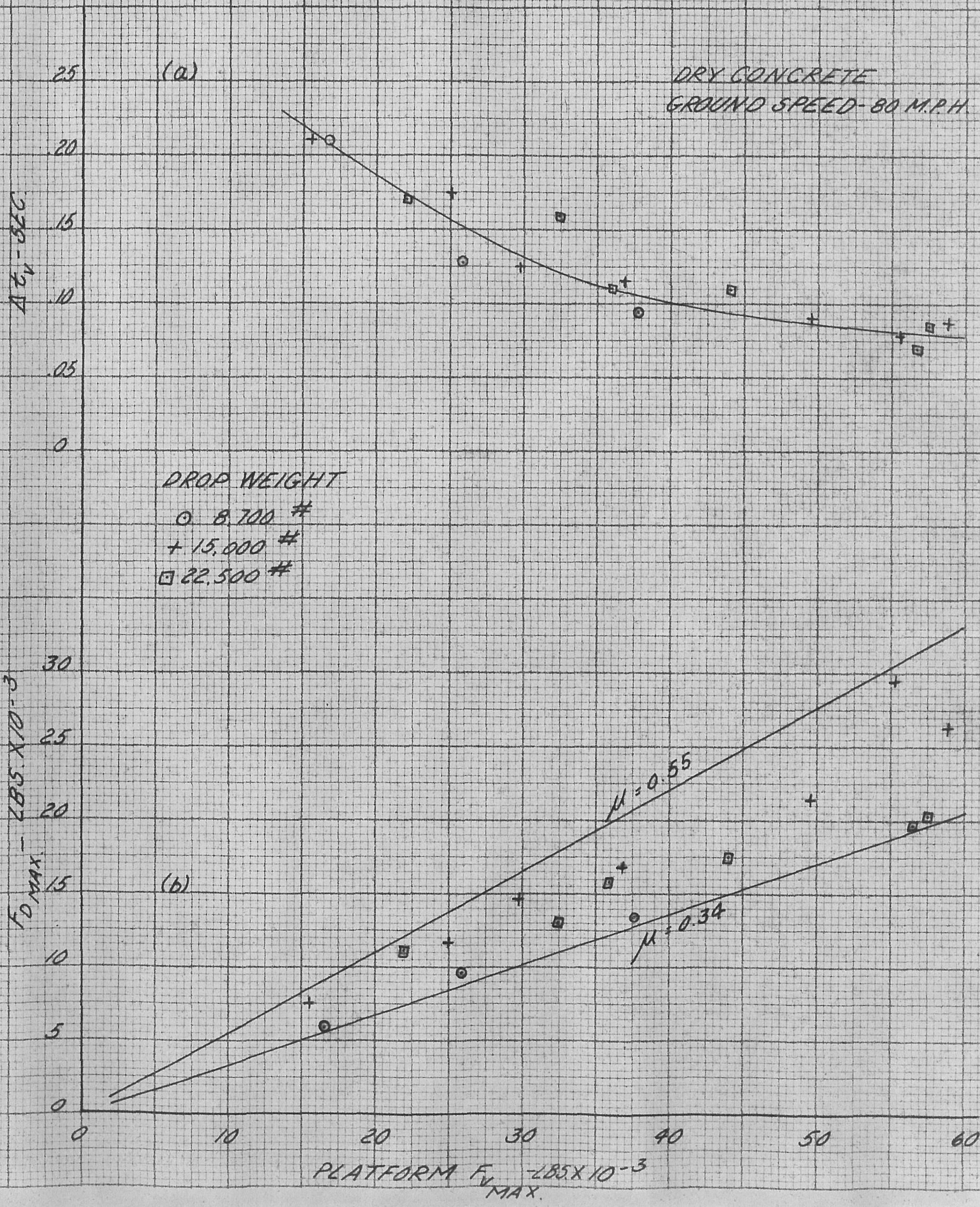


FIG. 9 - VARIATION OF μ WITH RATE OF DESCENT AND GROUND SPEED

DROP TEST RESULTS

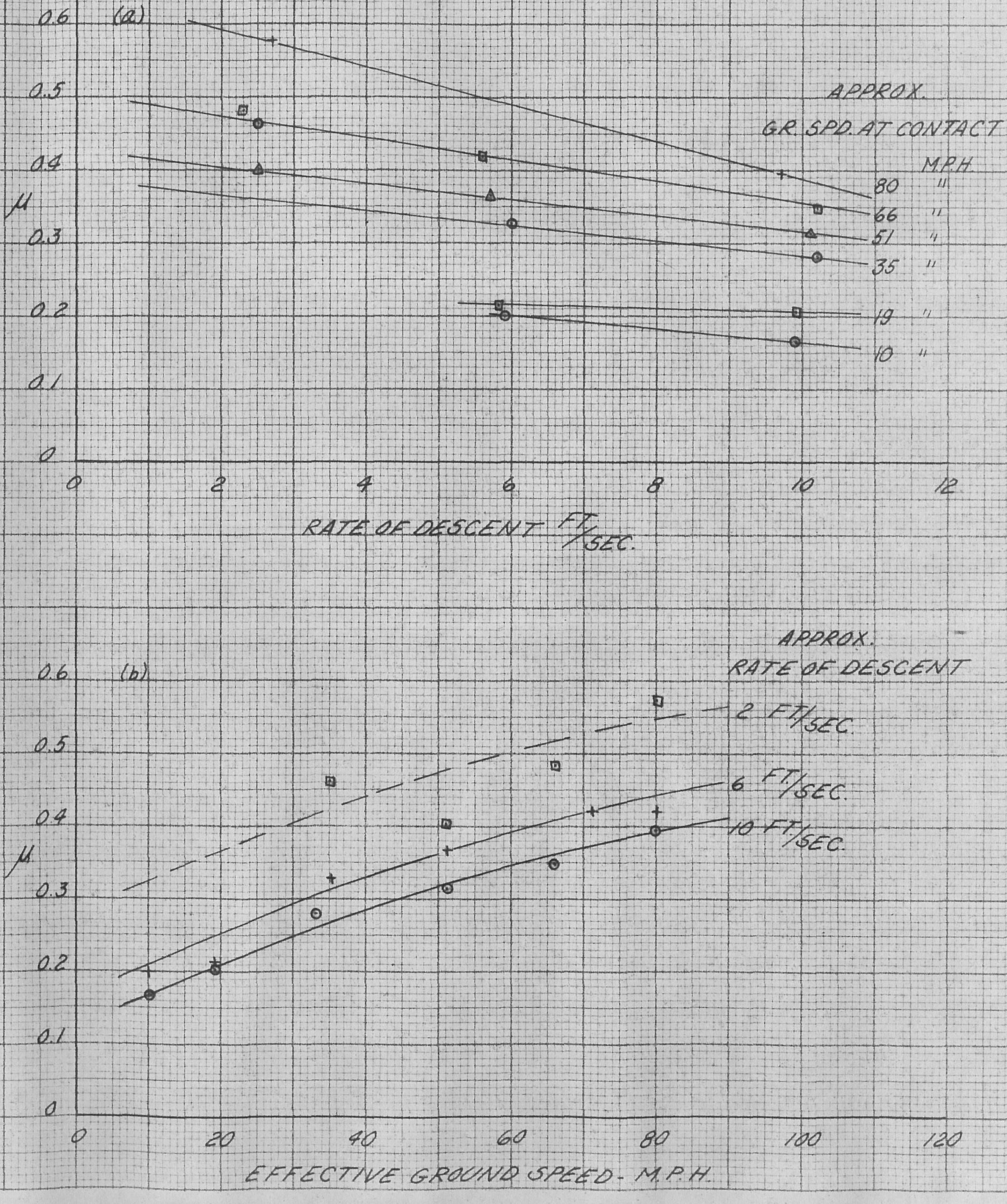
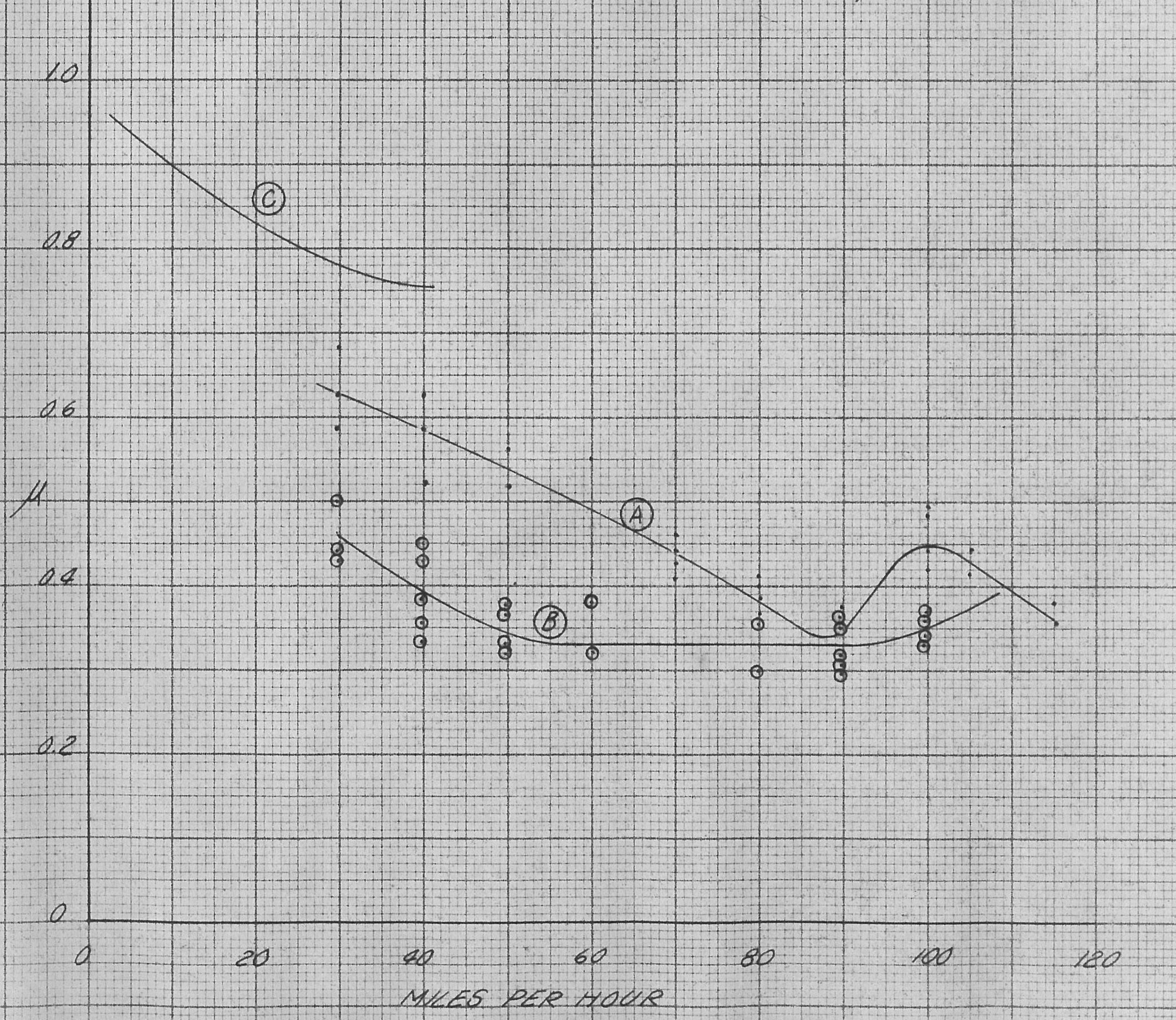


FIG. 10 - COEFFICIENT OF FORWARD SLIDING
FRICTION VS. SPEED

DETERMINED FROM A-20 AIRPLANE TAXI TESTS WITH 44" S.C. TIRE AND STATIC LOADS PER WHEEL AS INDICATED. DRY CONCRETE

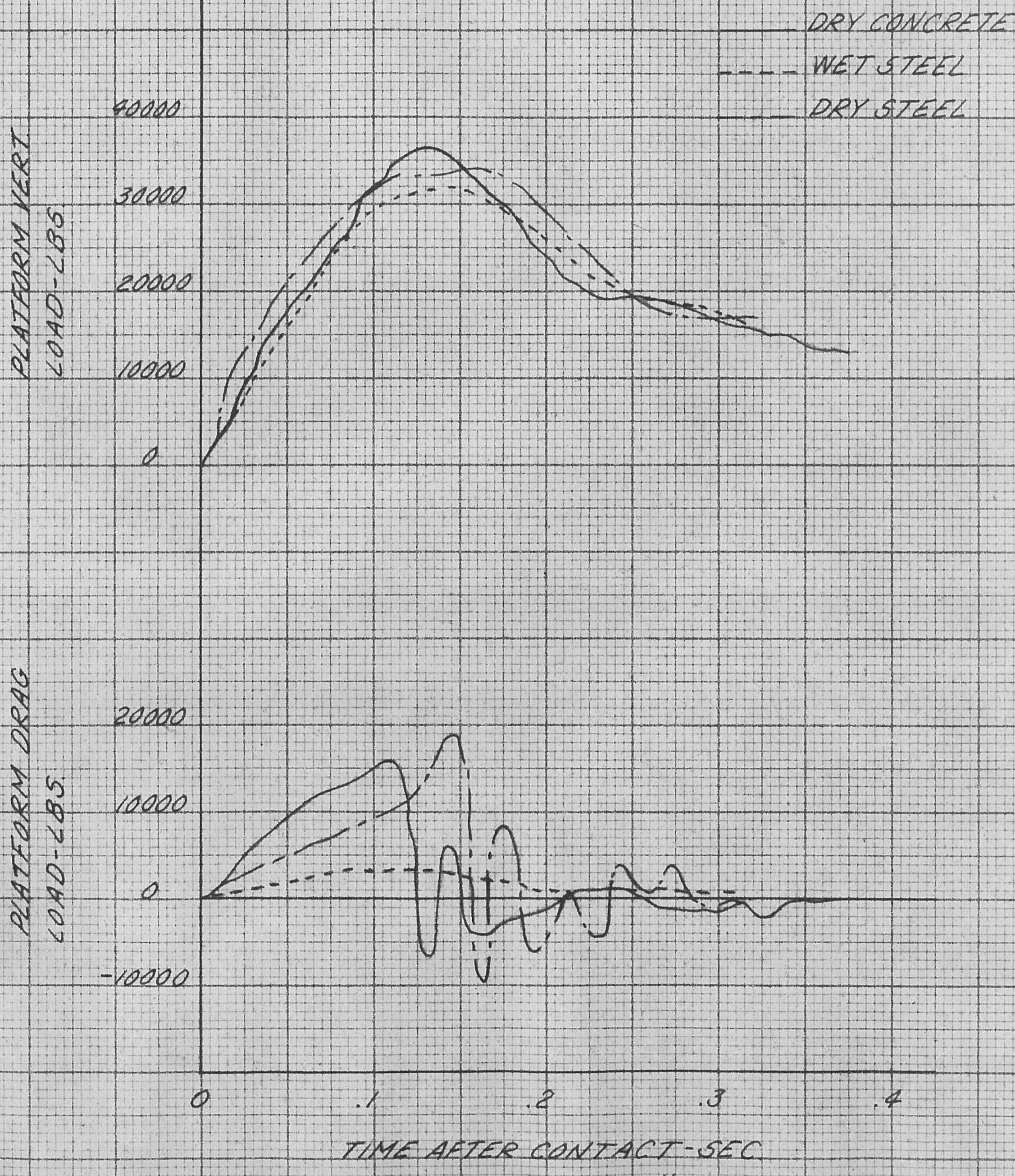
Ⓐ 6765# LOAD PER TIRE
Ⓑ 9305# " " "
Ⓒ PASSENGER CAR TIRE ON DRY ROUGH CONCRETE, FROM REF. (i)



COURTESY B.F. GOODRICH CO.

FIG. 11- PLATFORM VERTICAL AND DRAG LOADS, ILLUSTRATING EFFECT OF LANDING SURFACE

DROP TEST RESULTS



AIRPLANE WT. — 45,000 #
EFFECTIVE GROUND SPEED — 85 M.P.H.
RATE OF DESCENT — 6 F.P.S.

FIG. 12- COEFFICIENT OF FRICTION VS. TIME
DROP TEST RESULTS
DRY CONCRETE

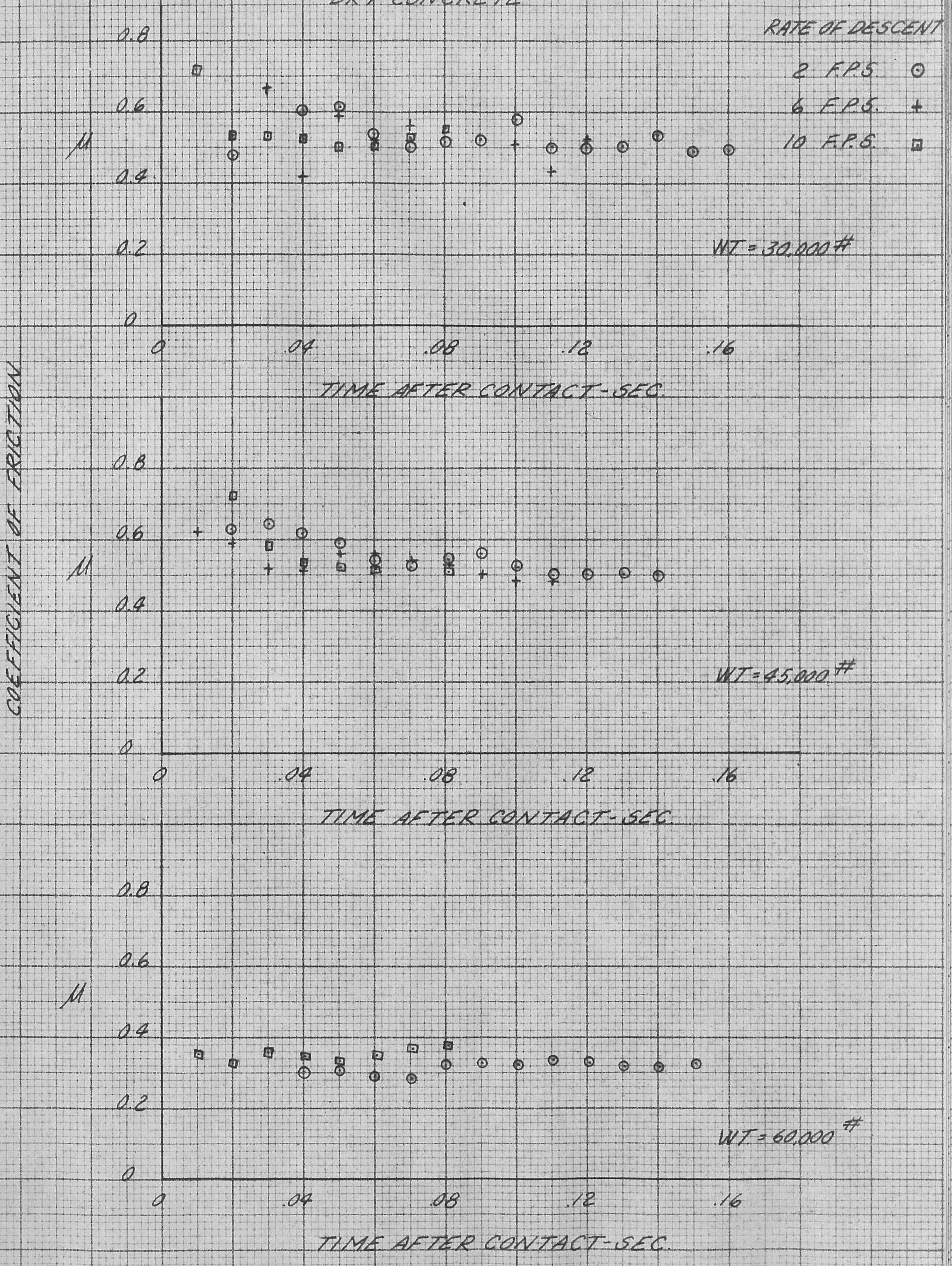
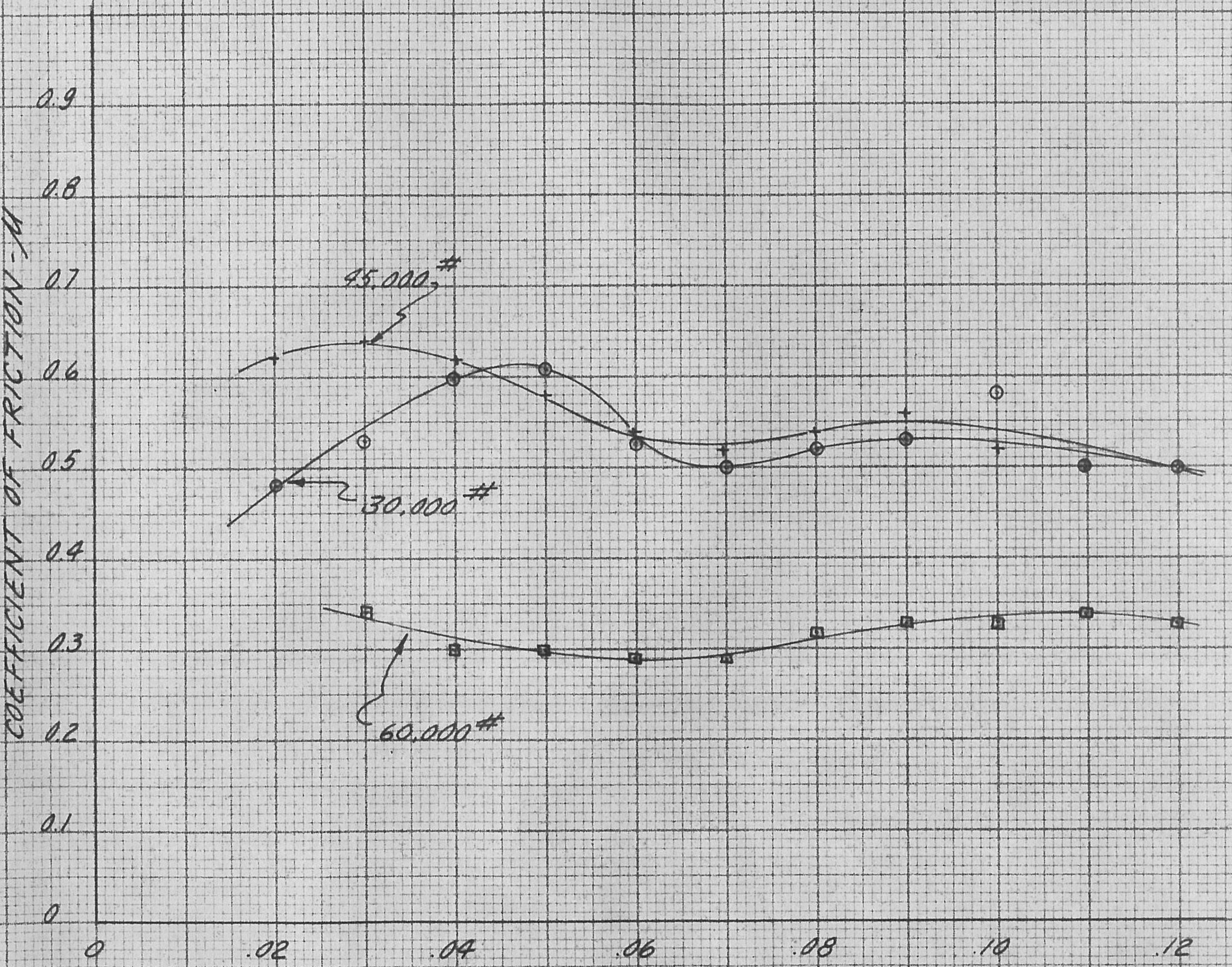


FIG. 13 - COEFFICIENT OF FRICTION VS. TIME FOR VARIOUS AIRPLANE WEIGHTS

DROP TEST RESULTS

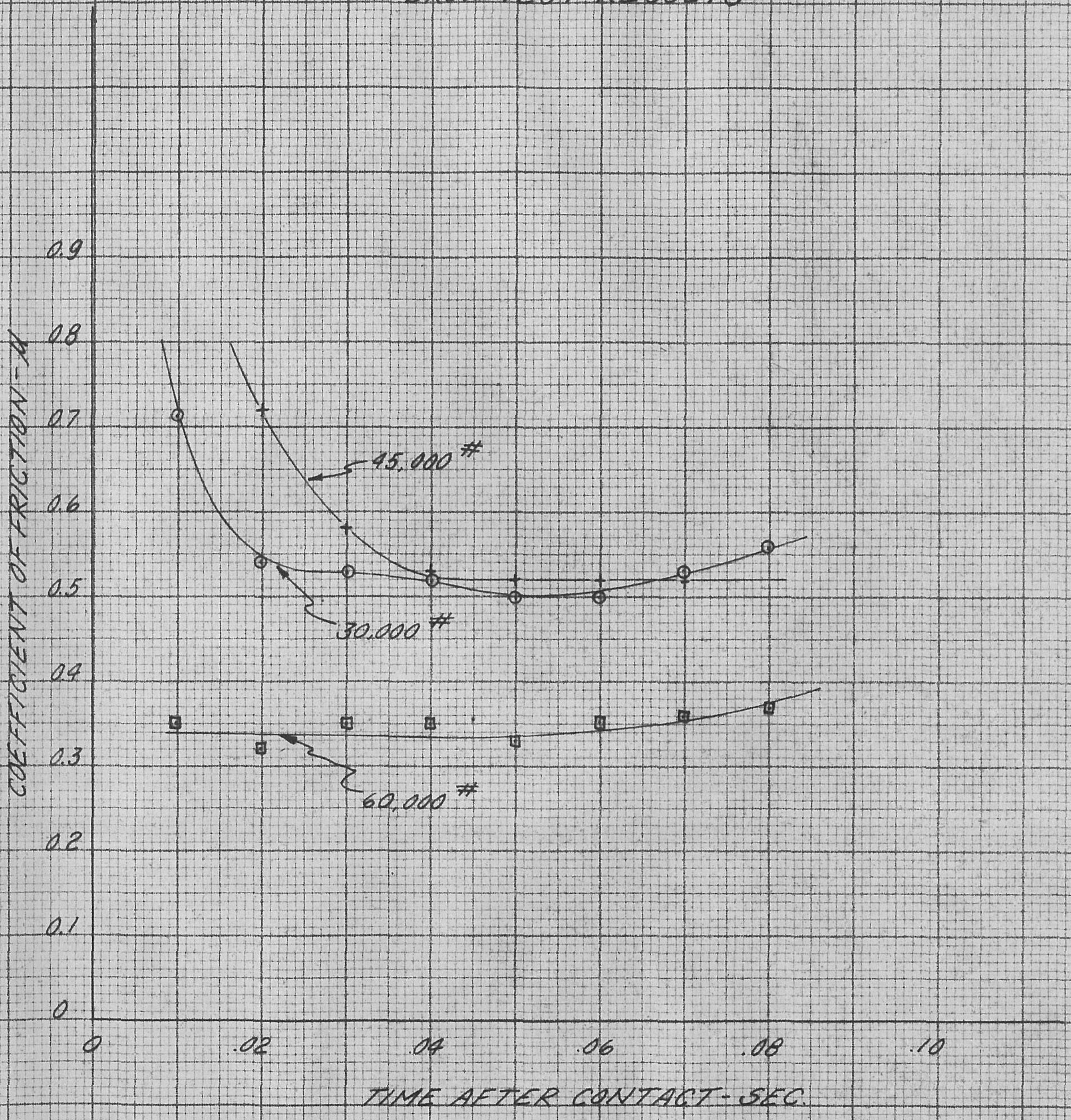


TIME AFTER CONTACT - SEC.

EFFECTIVE GROUND SPEED - 85 M.P.H.
RATE OF DESCENT - 2 F.P.S.
2/3 WING LIFT

FIG. 14 - COEFFICIENT OF FRICTION VS. TIME FOR VARIOUS AIRPLANE WEIGHTS

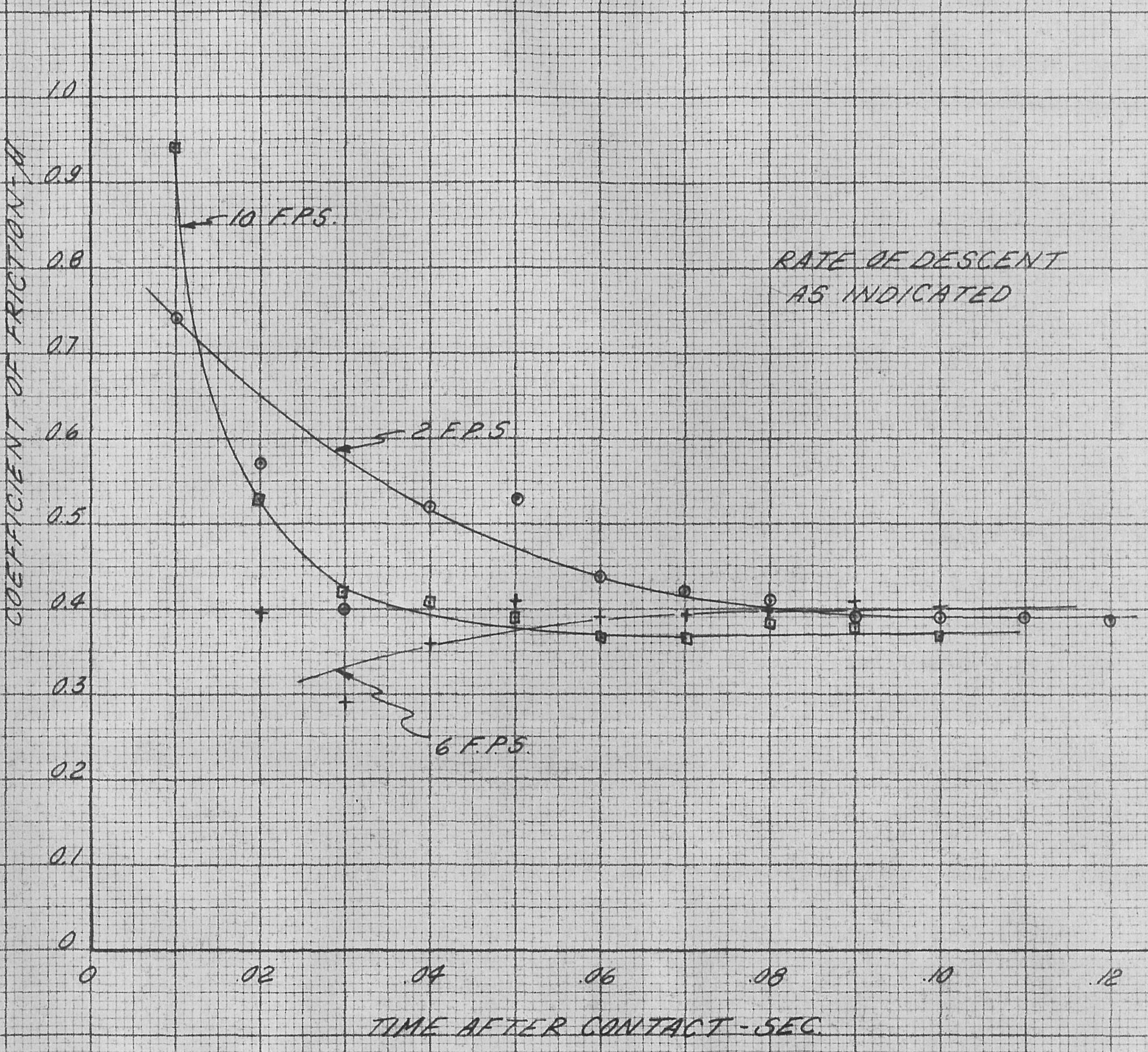
DROP TEST RESULTS



EFFECTIVE GROUND SPEED - 85 M.P.H.
RATE OF DESCENT - 10 F.P.S.
$\frac{2}{3}$ WING LIFT

FIG. 15 - COEFFICIENT OF FRICTION VS. TIME FOR VARIOUS RATES OF DESCENT

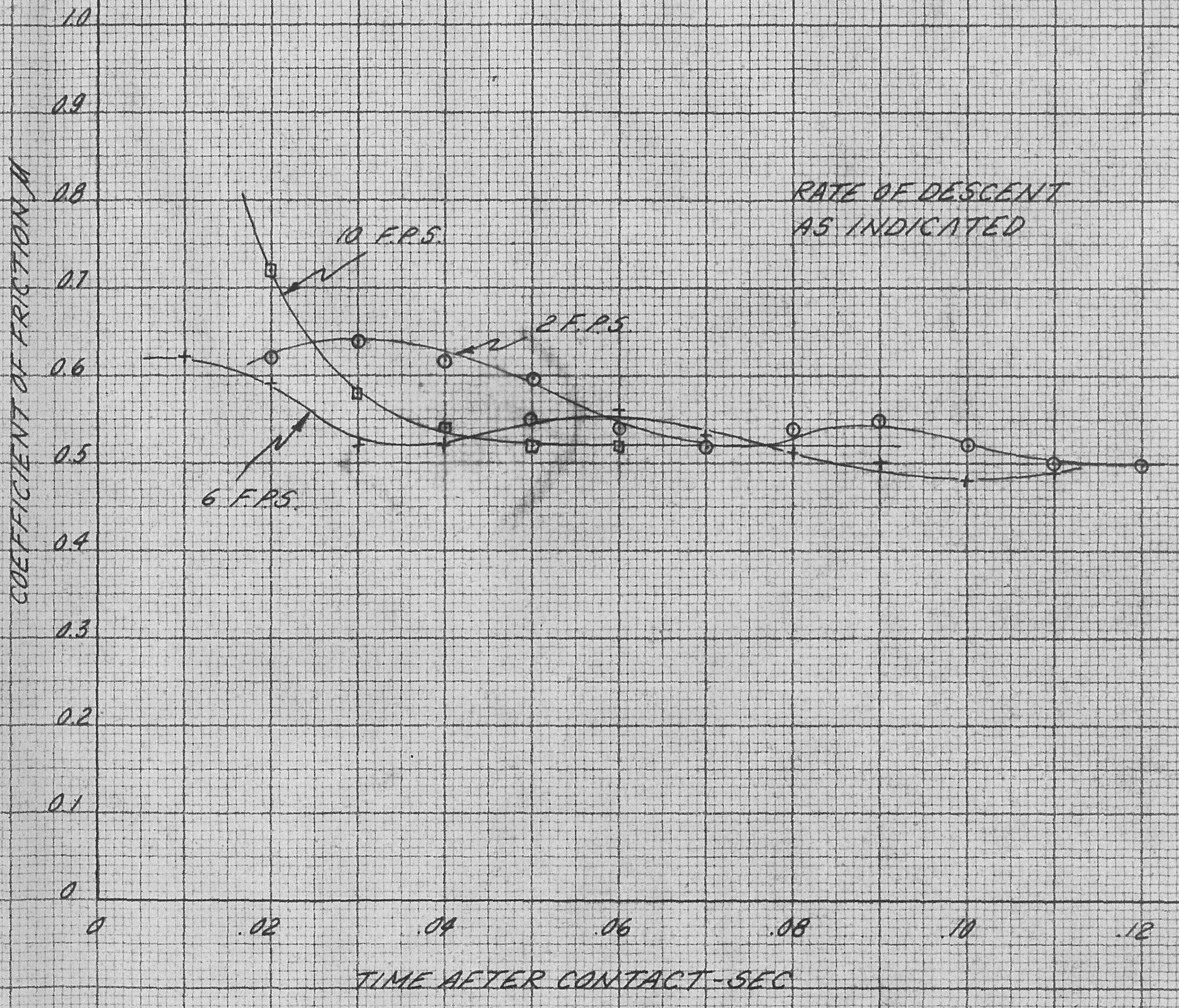
DROP TEST RESULTS



AIRPLANE WEIGHT - 17,400 #
EFFECTIVE GROUND SPEED - 85 M.P.H.
2/3 WING LIFT

FIG. 16 - COEFFICIENT OF FRICTION VS. TIME FOR VARIOUS RATES OF DESCENT

DROP TEST RESULTS



AIRPLANE WEIGHT — 45,000 #
EFFECTIVE GROUND SPEED - 85 M.P.H.
2/3 WING LIFT

FIG. 17- EFFECT OF PREROTATION
CONTROLLED TEST RESULTS

[REF: GOODYEAR REPORT NO. R-93-5]

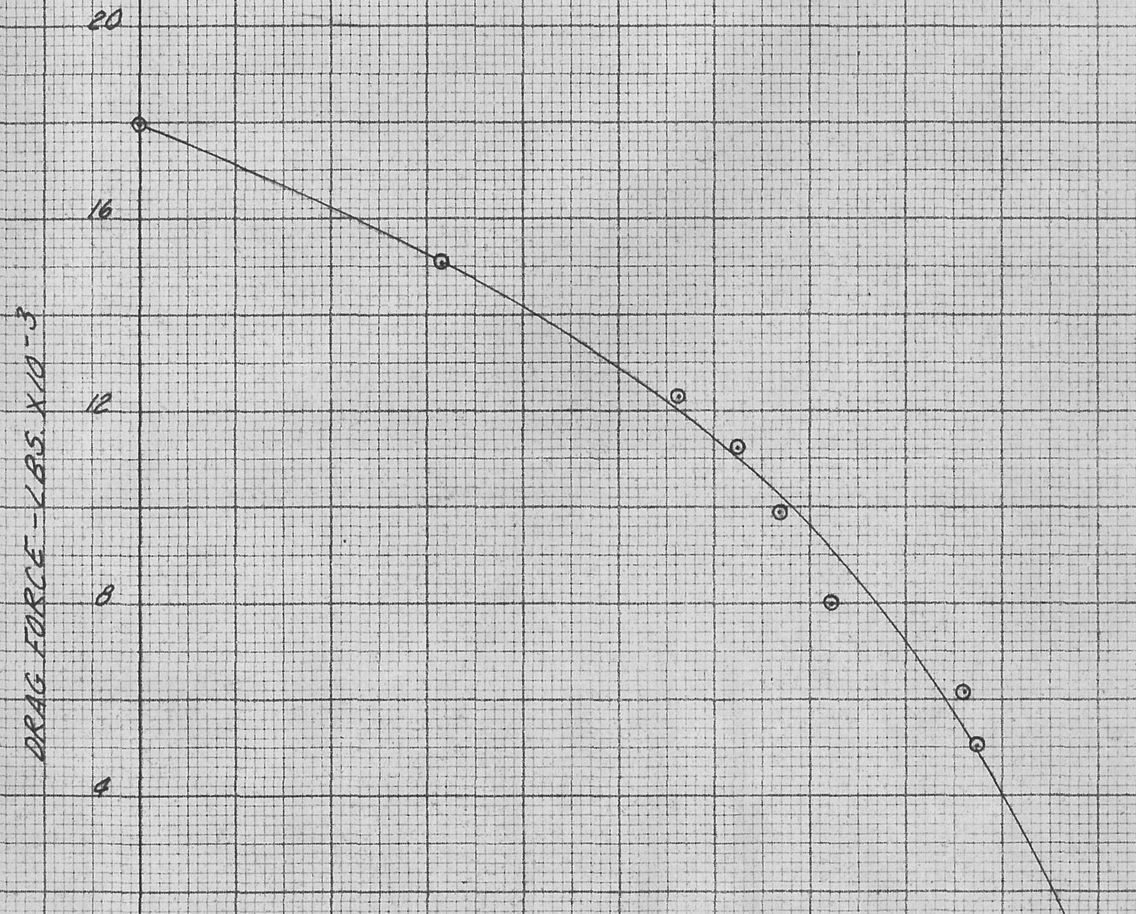


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FIG. 18 - COMPARATIVE STRENGTH ENVELOPES FOR SEVERAL MAIN LANDING GEARS

[ACTUAL STRENGTH DIVIDED BY AIRPLANE WEIGHT]