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FRICTION OBTAINED DURING TESTS OF A LANDING GEAR
HAVING A STATIC-LOAD RATING OF 20,000 POUNDS

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SUMMARY

An experimental investigation was made at the Langley landing loads track to obtain data on the maximum spin-up coefficients of friction developed by a landing gear having a static-load rating of 20,000 pounds. The forward speeds ranged from 0 to approximately 180 feet per second and the sinking speeds, from 2.7 feet per second to 9.4 feet per second. The results indicated the variation of the maximum spin-up coefficient of friction with forward speed and vertical load. Data obtained during this investigation are also compared with some results previously obtained for nonrolling tires to show the effect of forward speed.

INTRODUCTION

One important factor governing the design of aircraft for the landing condition is the magnitude of the maximum drag load developed while the landing-gear wheels are being spun up immediately after initial touchdown. Much data relative to this problem have been obtained under controlled conditions for a small lightly loaded landing gear at relatively low forward speeds. (See ref. 1.) In addition, a number of flight investigations have been carried out with large aircraft. (See, for example, ref. 2.) However, prediction of the drag loads with an acceptable degree of accuracy over the range of practical operating conditions still remains a problem.

In order to extend the range of controlled test data to larger loadings and higher forward speeds, a series of tests were made at the Langley landing loads track with a jet-bomber landing gear. The purpose of this paper is to present the results of these tests which show the effect of forward speed and vertical load on the maximum coefficient of friction developed during the wheel spin-up process. Also presented are comparisons of these data which were obtained for a rolling tire subjected to drag load with some nonrolling results presented in reference 3.

APPARATUS AND TEST PROCEDURE

The tests were carried out by making simulated landings at the Langley landing loads track. The basic elements of this facility are shown schematically in figure 1. Included is a large main carriage (fig. 2) weighing approximately 100,000 pounds traveling on steel rails which are located on each side of a 2,200-foot-long concrete runway. The runway surface characteristics are similar to actual portland-cement surfaces in current use.

The landing gear (fig. 3) was attached to the drop carriage located within the main carriage. Motion of the drop carriage with respect to the main carriage is restrained so that it travels only in the vertical direction. Simulated landings were made by accelerating the main carriage to the desired forward speed by means of the hydraulic jet catapult (ref. 4) and then releasing the drop carriage which was initially set at some predetermined height based on the vertical velocity desired for the particular test. Just prior to the instant of touchdown, a hydraulic engine applied a lift force equal to the dropping weight to simulate a wing lift of 1 g throughout the landing impact. After the landing impact, the main carriage is stopped by a battery of 20 hydraulic arresting gears.

The landing gear used for these tests was the main gear of a medium jet bomber airplane. The total dropping weight or static load was 20,000 pounds. The gear was equipped with a 44 × 13, type VII, 26-ply-rating tire. The normal tire inflation pressure for the 20,000-pound weight is 140 pounds per square inch and most of the tests were made with that pressure, although a few tests were made at other tire inflation pressures. All tests were made with the strut inclined at an angle of 15° (nose up) to the vertical. The yaw and roll angles were set at 0° throughout the entire investigation.

The main part of the investigation consisted of four series of tests, each series being made over a range of horizontal velocities and at a fixed sinking speed. The horizontal-velocity range was from 0 to approximately 180 feet per second and the vertical velocities were approximately 3 feet per second, $5\frac{1}{2}$ feet per second, $7\frac{1}{2}$ feet per second, and $9\frac{1}{2}$ feet per second. A brief investigation was made at various tire inflation pressures ranging from 35 pounds per square inch to 210 pounds per square inch. The forward speed for the tire-pressure investigation was approximately 160 feet per second, and the sinking speed was about 7 feet per second.

INSTRUMENTATION

Instrumentation was provided to obtain the vertical and drag forces developed between the tire and runway. Also obtained were the vertical displacements and accelerations of both the upper and lower masses of the landing gear as well as the rotational displacement, velocity, and acceleration of the wheel. Figure 4 is a schematic drawing of the test apparatus and shows the locations of the various instruments.

The vertical load between the tire and runway was obtained from the vertical component of the strain-gage-type force-measuring dynamometer. Corrections for the inertia forces introduced by the mass below the dynamometer were derived from acceleration values obtained from the upper and lower mass accelerometers mounted normal to the runway surface in the locations shown in figure 4. The weight of the lower or unsprung portion of the landing gear was 534 pounds and the weight of the upper portion including all structure and fittings below the dynamometer but exclusive of the unsprung portion of the landing gear was 2,770 pounds. The remaining weight necessary to achieve a static load of 20,000 pounds on the landing gear consisted of the dynamometer, drop carriage, and disposable weights mounted in the drop carriage above the dynamometer.

The drag load developed between the tire and runway surface was derived from the equation

$$D = \frac{I\alpha}{r}$$

where

D drag load between the tire and runway surface

I moment of inertia of landing-gear wheel and tire (11.51 slug-ft^2)

α angular acceleration of wheel

r perpendicular distance between axle center line and runway surface

This method for obtaining drag load and the angular accelerometer used for these tests are described in reference 5. Values of r were derived by subtracting the vertical component of the strut stroke from the drop-carriage displacement and then subtracting this value from the unloaded tire radius. Measurements of strut stroke were obtained from a linear slide wire potentiometer. The drop-carriage displacement was measured by a circular slide-wire potentiometer driven by a chain and sprocket arrangement.

Wheel angular velocity was obtained from a voltage generator mounted on the wheel axle. The rotational displacement of the wheel was measured by a cam and breaker assembly which caused a deflection of the oscillograph record for each 36° of rotation. The displacement occurring between initial touchdown of the landing-gear wheel and the first deflection of the record was obtained by integration of the wheel angular velocity.

The horizontal velocity of the main carriage was obtained by noting the time taken to travel a given distance. Distance measurements were obtained by the use of metal tabs spaced at 10-foot intervals along the side of the track. When a tab interrupted a light beam focused on a photo cell mounted on the main carriage, a pulse occurred on the oscillograph-record trace.

Direct measurements of tire-contact length and tire-contact area could not be obtained. However, these values were computed from the experimental tire deflection data by using the method described in reference 3. Since this method was derived by using deflection data obtained from tires experiencing pure vertical load, some question may arise as to its validity for the case of a rolling tire subjected to drag load. Figure 5 shows the variation of vertical load with tire deflection for the landing gear used during these tests. The solid line was obtained during a drop test where the tire was subjected to a pure vertical load. The data points were obtained at the time of the maximum spin-up drag coefficient of friction during the forward-speed tests. It can be seen that the load-deflection characteristics of the rolling tire subjected to drag load and the stationary tire subjected to pure vertical load are similar. Therefore, it appears that the method for obtaining tire-footprint lengths and areas presented in reference 3 and used in this report should yield acceptable answers for the case of a rolling tire subjected to drag load.

RESULTS AND DISCUSSION

The values of the basic quantities measured during this investigation, together with the conditions for each test, are listed in table I. Typical time histories obtained for tests at each of the sinking speeds are shown in figures 6 to 9. These time histories show that, after an initial relatively steep rise, the vertical-load curve levels off and the average value is roughly constant for an appreciable period of time. Since during a number of these tests wheel spin-up occurred within this period, it is possible to observe the effect of changes in forward speed on the maximum spin-up coefficient of friction μ_{max} without introducing additional effects caused by appreciable changes in vertical load.

The variation of μ_{max} with horizontal velocity for an approximately constant vertical load (16,400 pounds to 21,000 pounds) is shown in figure 10. As can be seen, the largest values of μ_{max} occurred at an intermediate value of the forward-speed range. These data indicate that, in the vertical-load range of 16,400 pounds to 21,000 pounds, the largest values of μ_{max} for this landing-gear configuration occur in the horizontal-velocity range between approximately 100 feet per second to 120 feet per second. At the low forward speeds, wheel spin-up occurs soon after touchdown and the low values of μ_{max} obtained for these tests are in a large part attributed to the presence of molten rubber in the tire-footprint area which was produced during the early stages of the spin-up process when the slip ratios and skidding velocities were large. This effect decreases with increased horizontal velocity because the rotational displacement of the tire between the instant of touchdown and the time of μ_{max} increases with forward speed. This effect is shown clearly in figure 11 where the coefficient-of-friction data of figure 10 are plotted against the ratio of tire peripheral displacement occurring up to the time of μ_{max} to the tire-footprint length at the time of μ_{max}. This ratio tends to increase with forward speed for similar vertical loadings. Figure 11 indicates that, for this vertical load and this landing-gear configuration, the tire peripheral displacement after touchdown must be somewhat more than one footprint length in order to minimize the effect of molten rubber produced during the early stages of the spin-up process.

The decreasing trend of μ_{max} with forward speed shown in figure 10 which occurs at velocities greater than 120 feet per second was also indicated in reference 1. It is also in agreement with the braking results of reference 6 which showed that the maximum coefficient of friction obtained during braking for a particular airplane decreased with increasing horizontal velocity. In this connection it should be noted that the conditions which result in maximum coefficient of friction during spin-up and during braking are very similar in that the skidding velocities and slip ratios are very small and the tire is primarily experiencing friction of the static or interlocking type in both cases. Larger vertical loads would cause spin-up to occur with smaller wheel rotational displacements and should move the peak shown in figure 10 toward the higher velocities.

Figure 12 shows the effect of vertical load on μ_{max} for an approximately constant forward speed. The relatively large forward speed, between 150 feet per second and 174 feet per second, with the accompanying large tire peripheral displacement to time of μ_{max}, should tend to reduce the effects of molten rubber developed early in the spin-up process.

However, for most of the data shown in figure 12, the values of the average unit bearing pressure in the tire footprint have a maximum spread of only 20 percent and vary randomly with the vertical load. It is therefore probable that the reduction in μ_{max} which occurs with increases in vertical load was caused by the presence of heated rubber in the tire footprint area. This reduction in μ_{max} could be caused by the decreased spin-up time and the increase in the length of the footprint which accompany an increase in vertical load.

Since drag load is the product of vertical load and coefficient of friction, the results shown in figure 12 suggest that the largest spin-up drag loads obtained during this investigation may have been associated with values of μ_{max} smaller than the maximum values of μ_{max} recorded during these tests. This is shown to be the case in figure 13 where it can be seen that the maximum drag load recorded during this investigation was 20,800 pounds and was obtained at a value of μ_{max} of 0.66 whereas the largest value of μ_{max} obtained during this investigation was 0.87, and the corresponding drag load was a little over 10,000 pounds. The flagged data points in the figure were obtained during tests in which wheel spin-up occurred during the early stages of the impact and while the vertical load was still rising. Since these points indicated very low maximum drag loads and did not follow the trends of the other data, they were not considered in fairing the data of figure 13. In connection with this figure it should be noted that the maximum drag load occurred at an intermediate value of the forward speed range. (See table I.) These results indicate the necessity for knowing the variation of μ_{max} with vertical load and forward speed when seeking maximum design spin-up drag loads.

In order to evaluate the usefulness of slow-speed sliding data for predicting values of μ_{max} for the case of the rolling tire, the friction data obtained during this investigation are compared with the slow-speed sliding data given in reference 3. (See fig. 14.) As in the case of braking, the slow-speed sliding data were obtained at very small skidding velocities (10 inches per minute); however, since the tire was sliding, the slip ratios were equal to 1. The comparison of figure 14 indicates that a large number of the tests gave values of μ_{max} considerably less than those predicted by the average of the slow-speed sliding data. This condition was probably due to the effect of forward speed and the presence of heated rubber in the tire footprint area. The largest values of μ_{max} obtained during these tests, however, lie somewhat above the values indicated by the slow-speed sliding data. This latter condition might result from a reduction in the coefficients of friction obtained during the slow speed sliding tests caused by heating in the tire footprint. Appendix B of reference 1 indicates that the effect of heating in reducing the coefficient of friction is greatest at the higher slip ratios, and, as noted previously, the slip ratio was 1 during the slow-speed sliding tests.

The variation of the average unit bearing pressure in the tire footprint area with vertical tire deflection is derived in reference 3 by using data for tires subject to pure vertical loads. In order to obtain some indication of the applicability of this variation to the case of the rolling tire subjected to drag load, the data obtained during this investigation are compared with the results given in reference 3. This comparison is shown in figure 15. Although the data obtained at tire inflation pressures of 140 pounds per square inch show considerable scatter, the figure indicates reasonable agreement between the results of reference 3 and the forward-speed data obtained at μ_{max} during this investigation.

A limited amount of data gathered at other tire pressures is also compared with the results of reference 3 in figure 15. The trend of this data indicates that, for the underinflated tire, the results of reference 3 underestimate the average unit bearing pressure but give good agreement in the neighborhood of the rated inflation pressure. This trend suggests that the variation of average unit bearing pressure with tire deflection given in reference 3 does not fully account for the tire stiffness when the tire is underinflated.

SUMMARY OF RESULTS

A series of landing tests made over a forward-speed range from 0 to approximately 180 feet per second and a range of sinking speeds from 2.7 to 9.4 feet per second using a landing gear having a static-load rating of 20,000 pounds gave the following results:

1. The maximum coefficient of friction developed during wheel spin-up reached its greatest value at an intermediate value of the forward-speed range covered during these tests. This maximum occurred when the tire peripheral displacement up to wheel spin-up was somewhat greater than the footprint length at wheel spin-up.

2. In the horizontal-velocity range between 150 feet per second and 174 feet per second, the maximum coefficient of friction at spin-up decreased as the vertical ground load increased.

3. The largest spin-up drag load at the ground was associated with a coefficient of friction smaller than the maximum coefficients obtained during this investigation.

4. Some of the maximum spin-up coefficients of friction obtained during this investigation were somewhat larger than the average of those obtained during slow-speed sliding tests.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., October 1, 1958.

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TABLE I

TEST CONDITIONS AND RESULTS

Test	Horizontal velocity, ft/sec	Vertical velocity at touch-down, ft/sec	Initial tire inflation pressure, lb/sq in.	Vertical load at time of μ_{max}, lb	Drag load at time of μ_{max}, lb	μ_{max}	Tire deflection at time of μ_{max}, in.	Wheel angular displacement up to time of μ_{max}, deg
1	32	2.9	140	7,300	5,200	0.71	1.2	4
2	54	2.7	140	10,300	6,000	.58	1.9	40
3	72	3.0	140	12,100	7,100	.59	1.6	43
4	91	3.0	140	12,400	8,600	.70	1.7	86
5	150	2.9	140	12,600	8,700	.69	---	184
6	165	2.8	140	11,500	10,100	.87	1.8	209
7	0	5.5	140	------	------	---	---	---
8	37	5.4	140	10,200	7,400	.72	1.4	7
9	56	5.5	140	16,400	8,600	.52	2.2	29
10	71	5.5	140	17,300	10,100	.58	2.1	40
11	94	5.3	140	16,600	13,200	.80	2.2	47
12	114	5.2	140	18,900	15,000	.79	2.2	94
13	127	5.3	140	20,300	15,400	.76	2.2	101
14	154	5.4	140	15,600	10,800	.69	2.0	191
15	170	5.4	140	18,100	11,900	.66	2.2	194
16	0	7.2	140	------	------	---	---	---
17	23	7.2	140	10,600	8,000	.76	1.5	4
18	54	7.4	140	20,400	10,600	.52	2.4	22
19	72	7.4	140	24,700	10,900	.44	3.3	36
20	98	7.4	140	26,700	12,800	.48	3.2	43
21	129	7.4	140	27,600	17,300	.63	3.3	83
22	150	7.4	140	26,200	15,600	.60	3.1	112
23	174	7.3	140	25,100	15,600	.62	3.2	169
24	0	9.3	140	------	------	---	---	---
25	31	9.2	140	------	9,700	---	2.1	7
26	54	9.2	140	17,300	9,800	.57	2.0	11
27	73	9.2	140	28,400	13,300	.47	3.8	40
28	110	9.4	140	31,600	20,800	.66	3.7	50
29	134	9.4	140	33,400	18,600	.56	4.1	97
30	150	9.0	140	------	14,200	---	4.0	47
31	160	9.4	140	32,800	16,700	.51	4.0	140
32	179	9.1	140	34,000	19,400	.57	4.1	130
33	154	7.1	140	21,000	14,400	.69	2.8	135
34	157	7.2	35	22,100	13,600	.61	6.4	151
35	164	7.0	70	22,800	14,800	.65	4.3	140
36	162	6.8	100	25,000	14,200	.60	3.6	162
37	163	7.0	210	22,300	14,100	.75	2.0	148

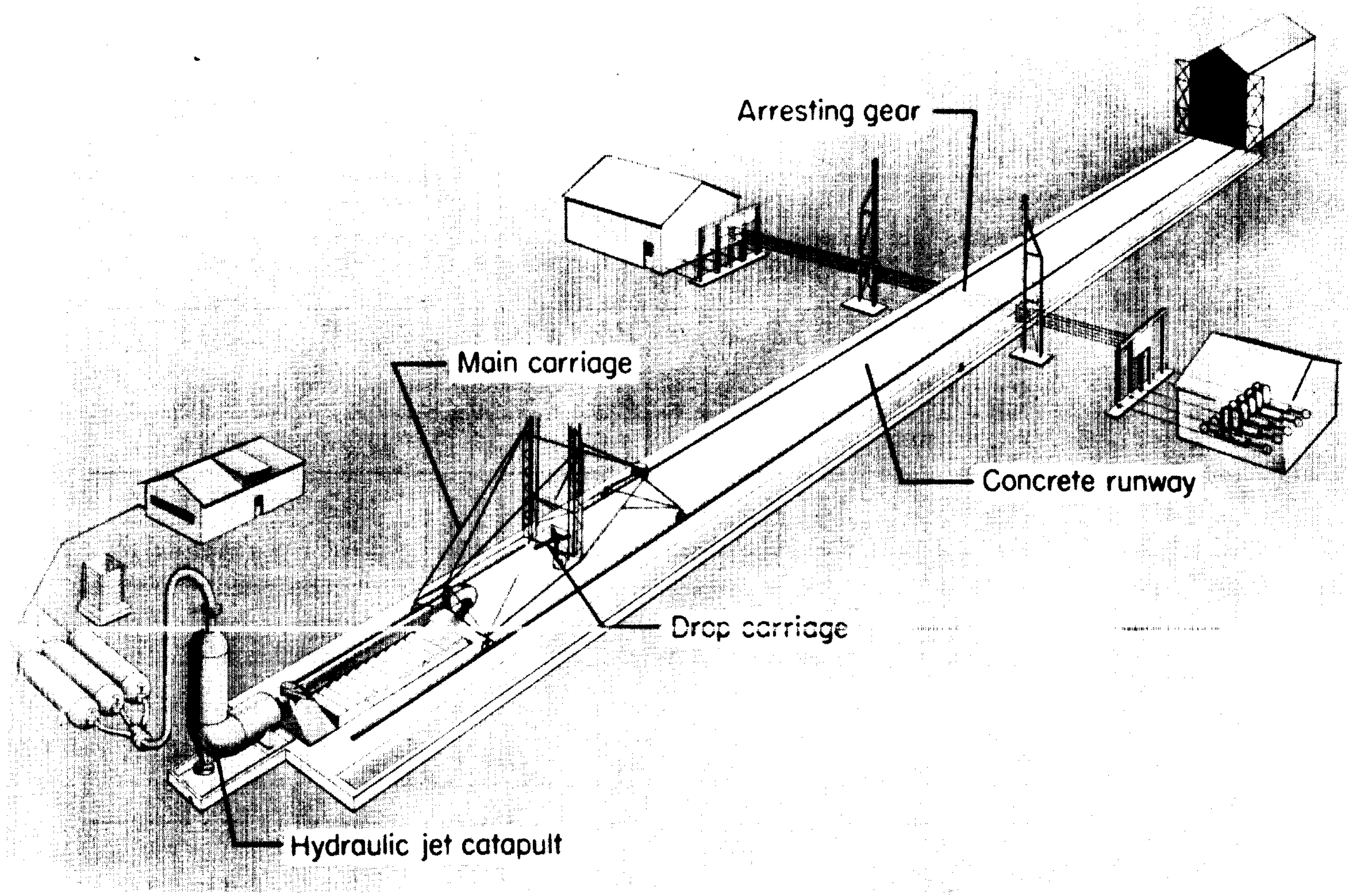

Figure 1.- Schematic drawing of Langley landing loads track. L-58-1693

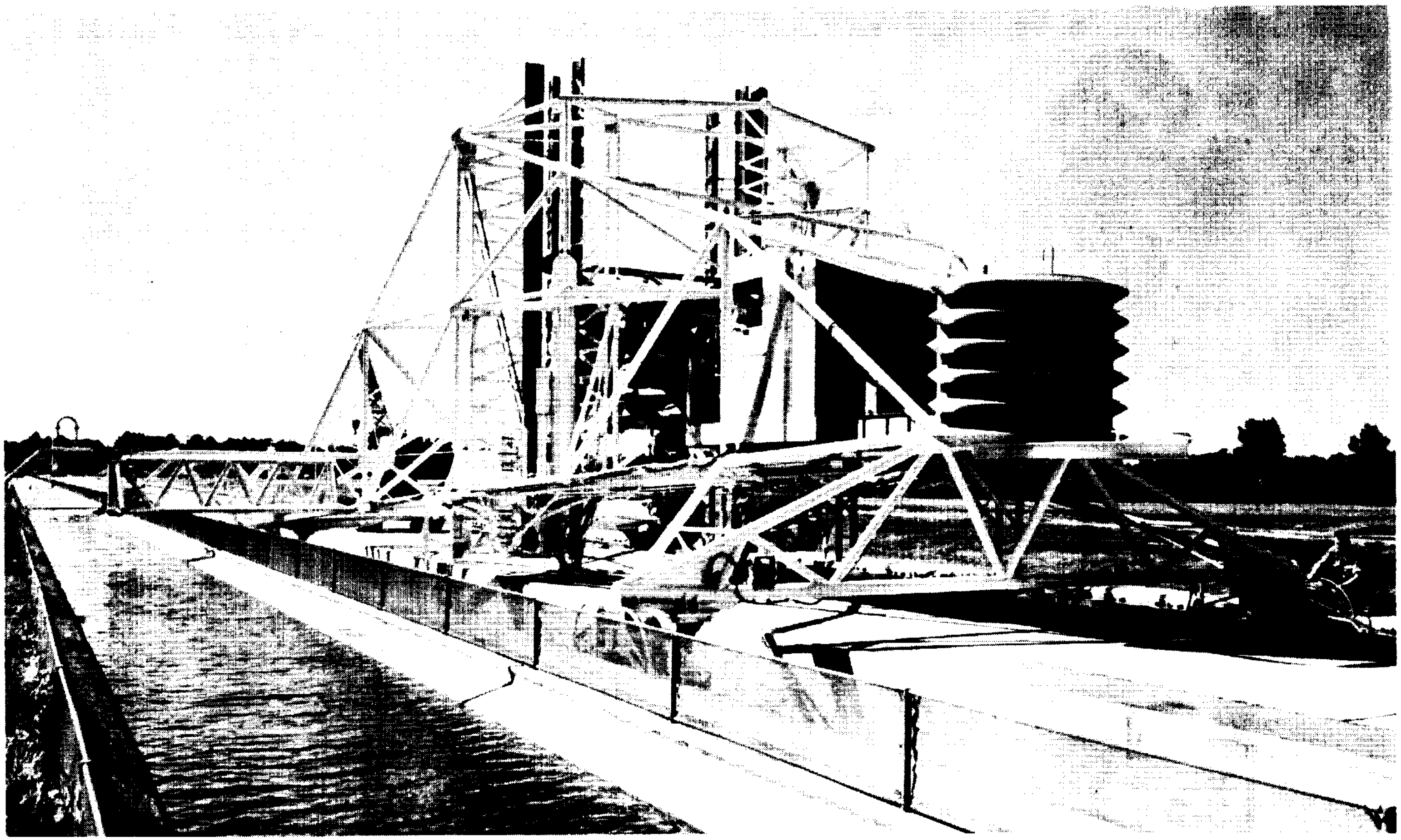

Figure 2.- Langley landing loads track carriage. L-95476

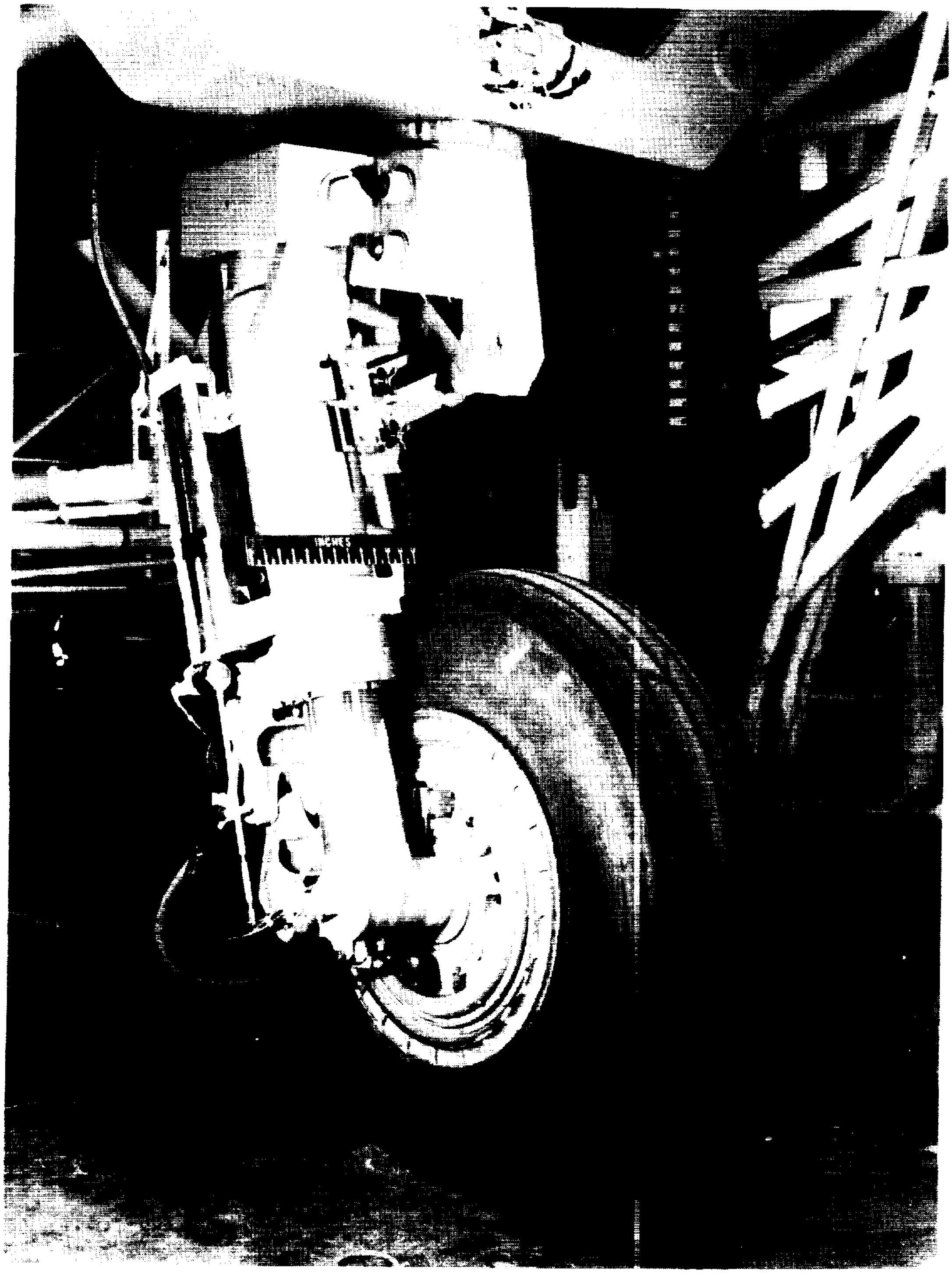

Figure 3.- Landing gear mounted for testing. L-57-1338

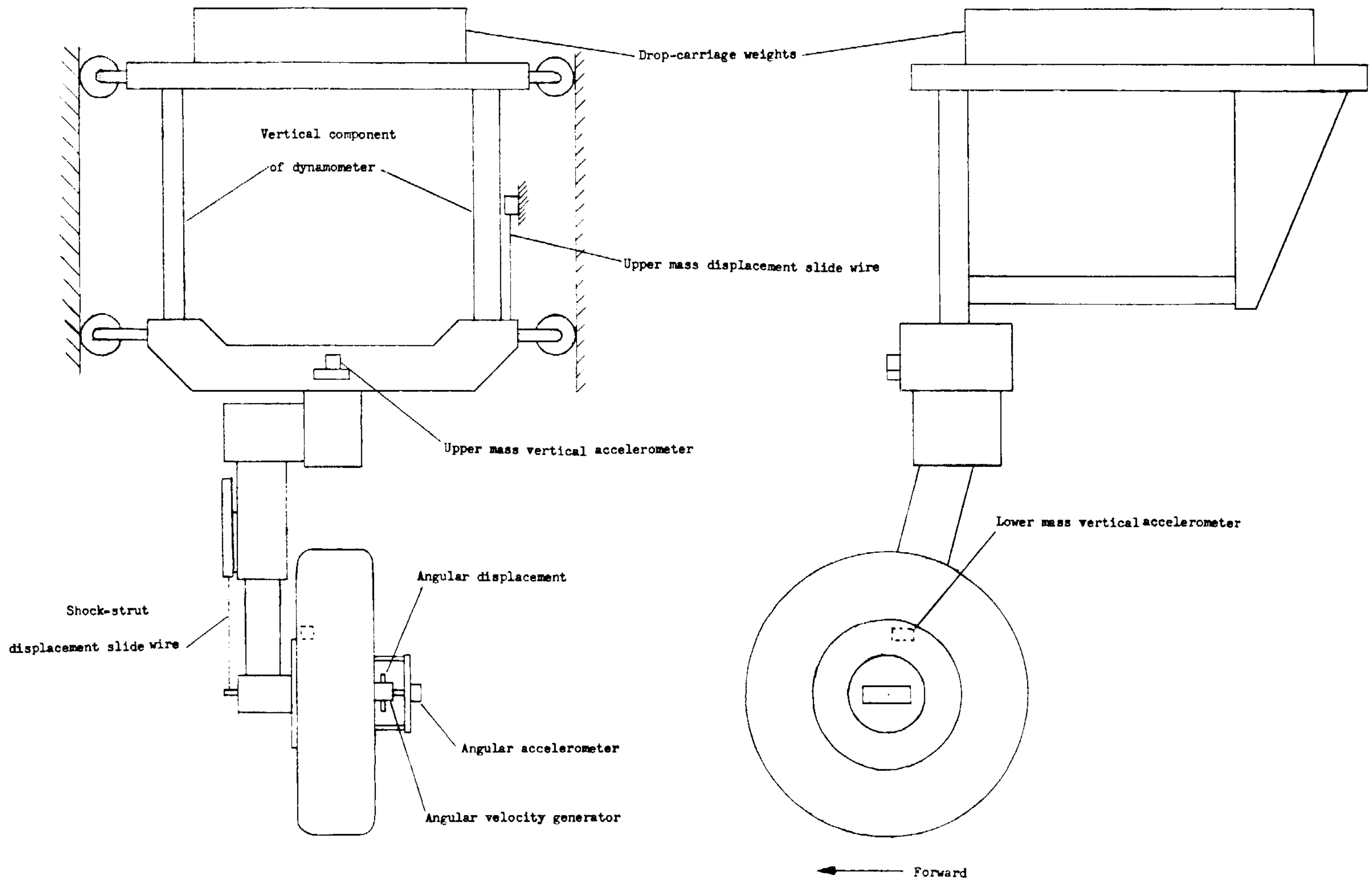

Figure 4.- Schematic view of landing gear and instrumentation.

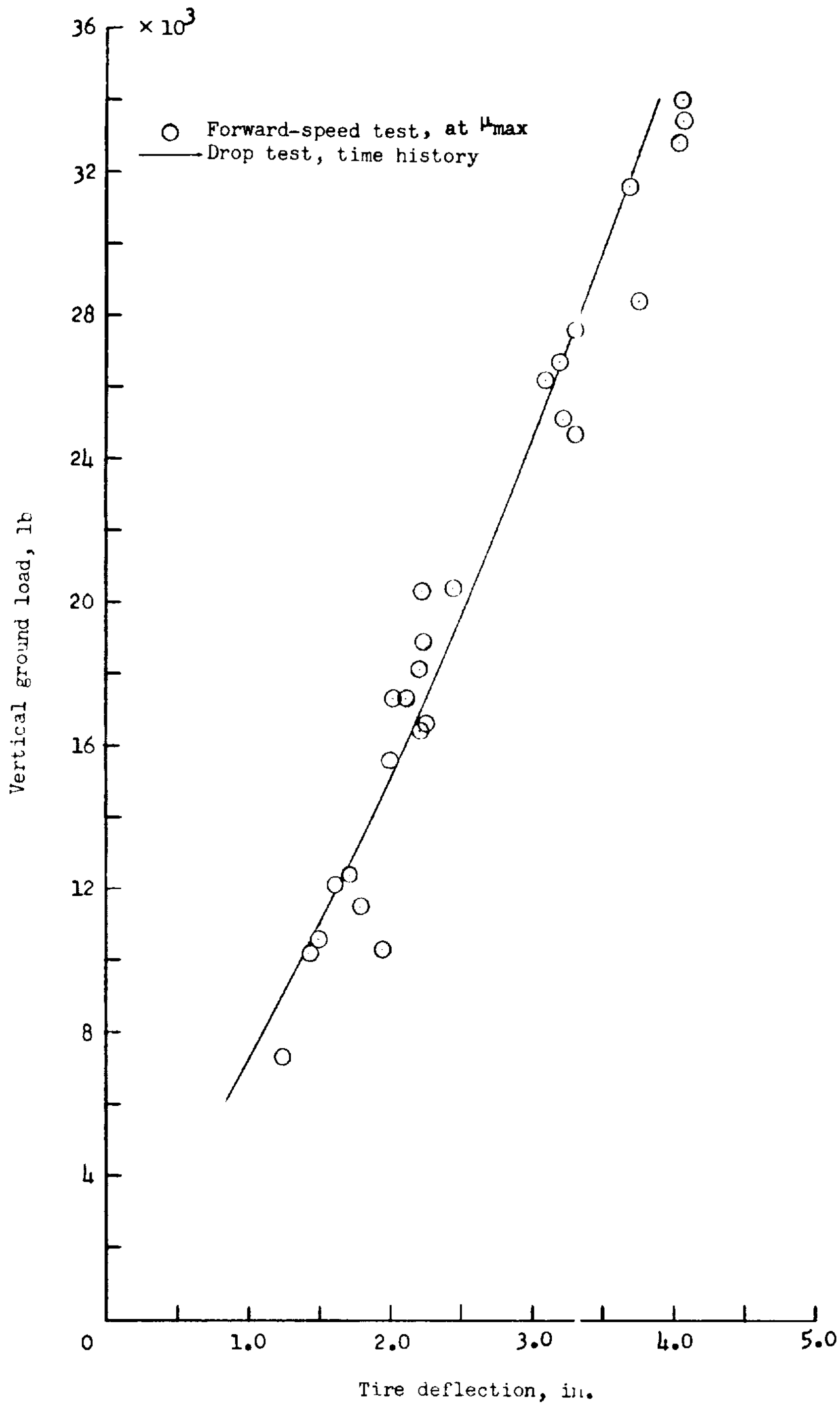

Figure 5.- Vertical-force deflection variation for forward-speed tests and for drop test with zero forward speed.

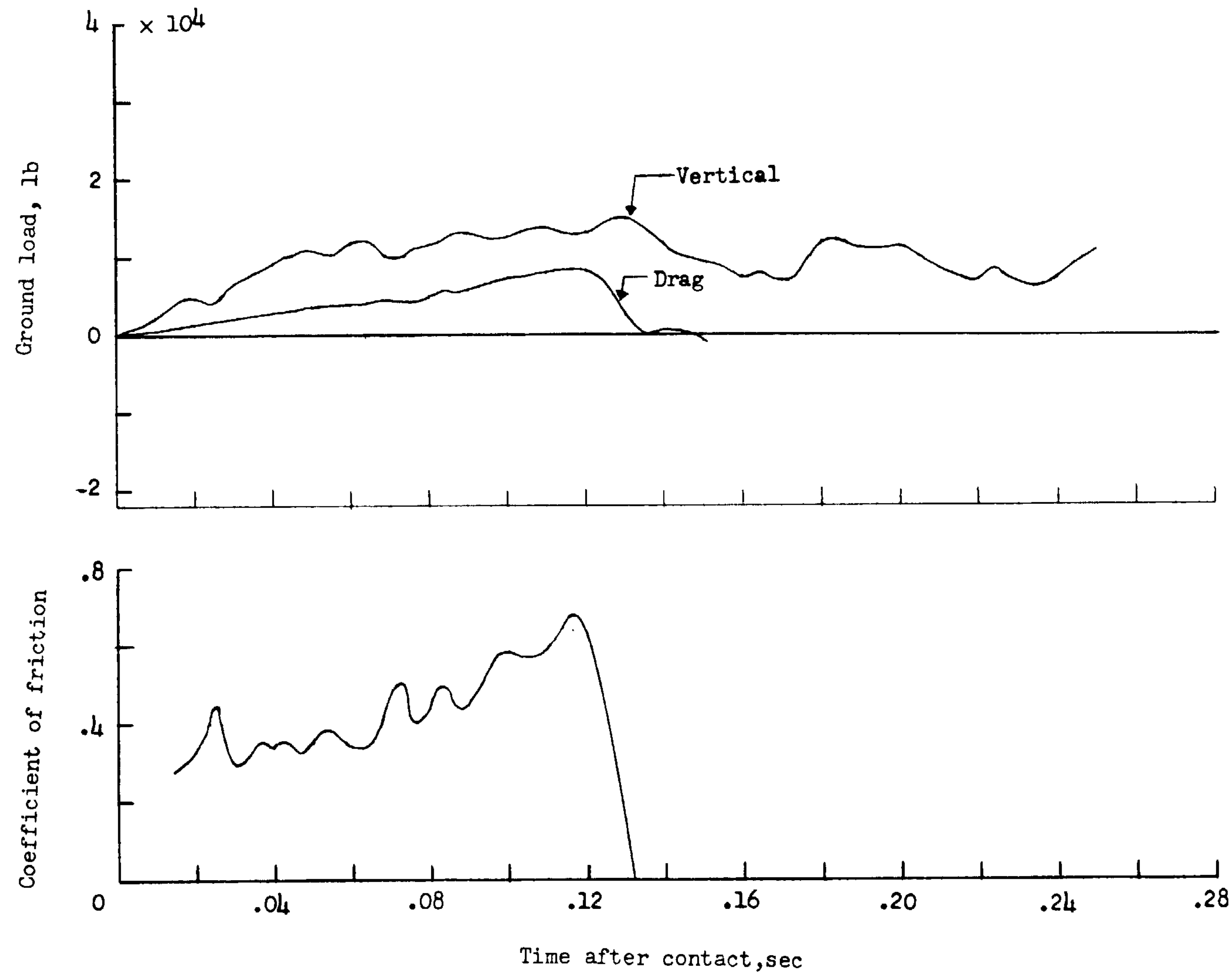

Figure 6.- Time histories of applied ground loads and coefficient of friction for test 5. Horizontal velocity, 150 feet/second; vertical velocity, 2.9 feet/second.

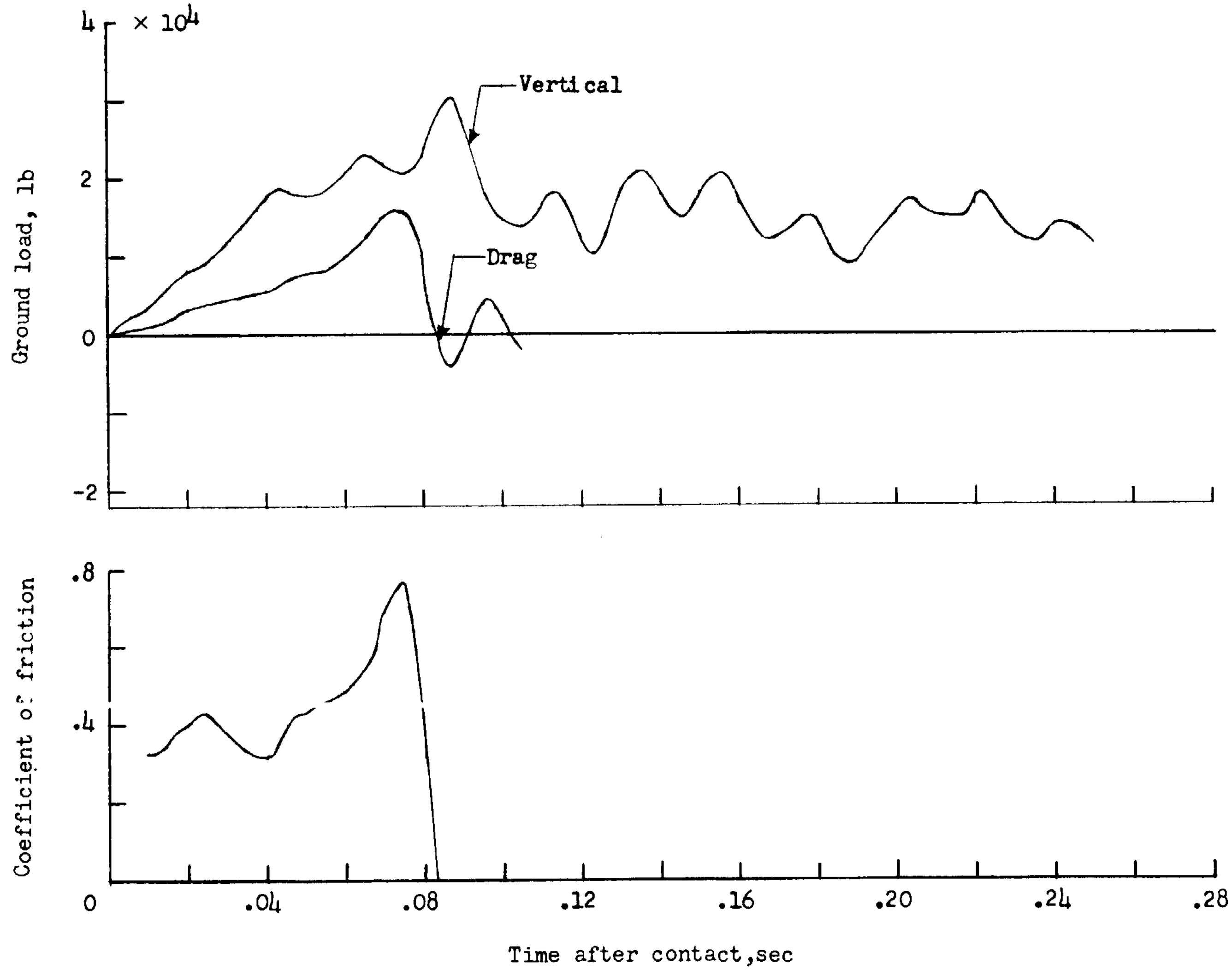

Figure 7.- Time histories of applied ground loads and coefficient of friction for test 13. Horizontal velocity, 127 feet/second; vertical velocity, 5.3 feet/second.

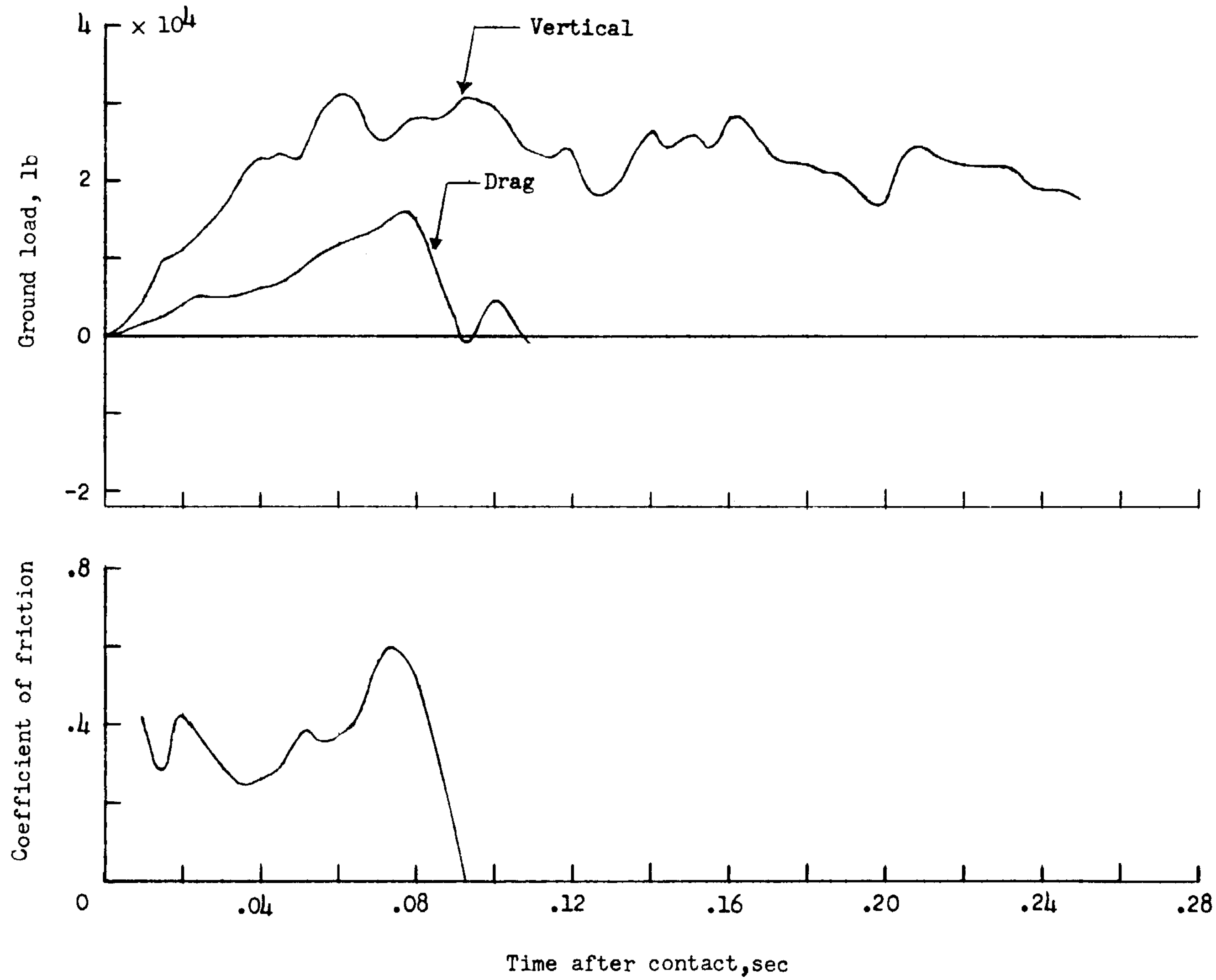

Figure 8.- Time histories of applied ground loads and coefficient of friction for test 22. Horizontal velocity, 150 feet/second; vertical velocity, 7.4 feet/second.

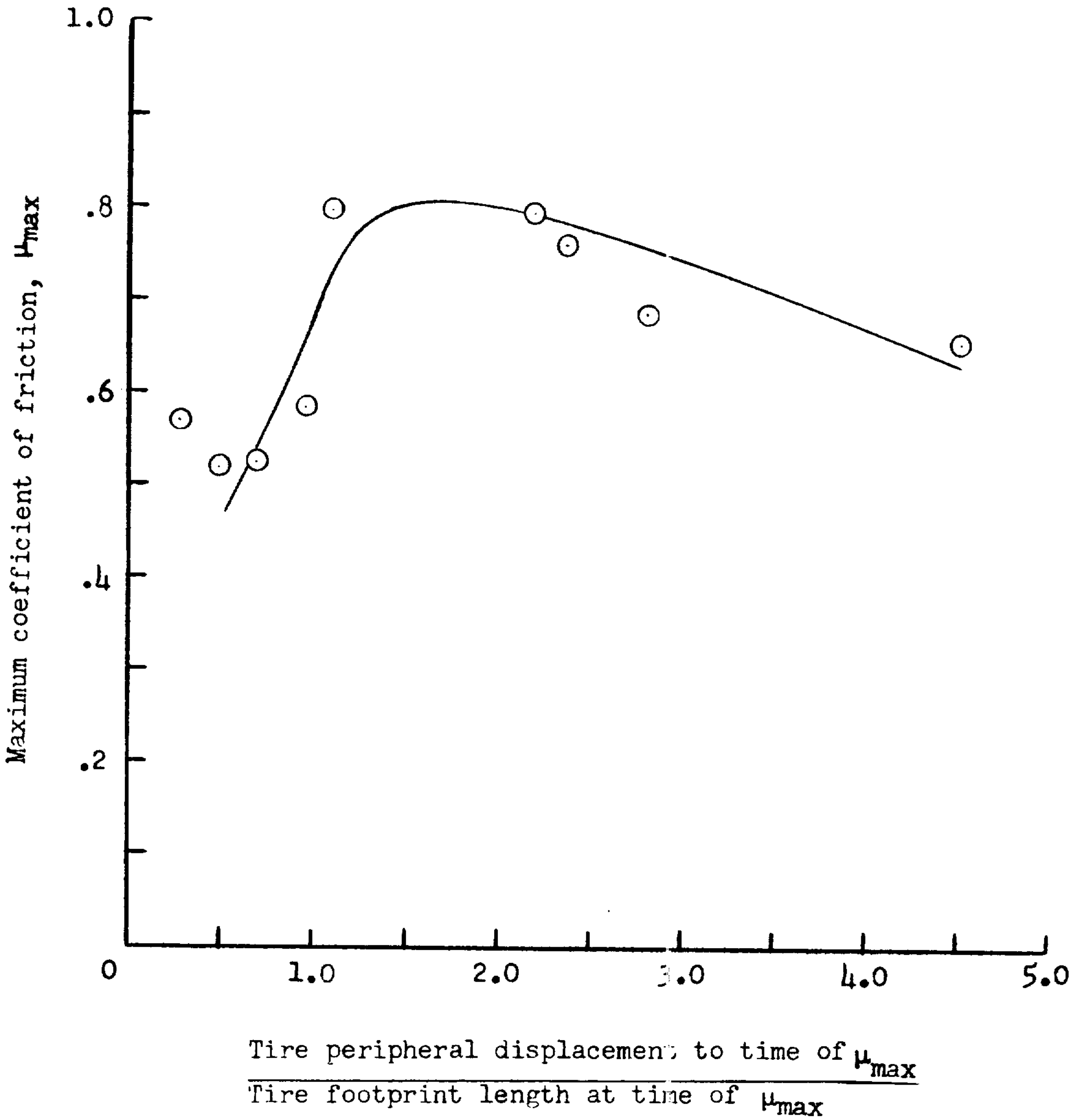

Figure 11.- Variation of maximum coefficient of friction with the ratio obtained at time of μ_{max} of tire peripheral displacement and tire footprint length for vertical ground loads between 16,400 and 21,000 pounds.

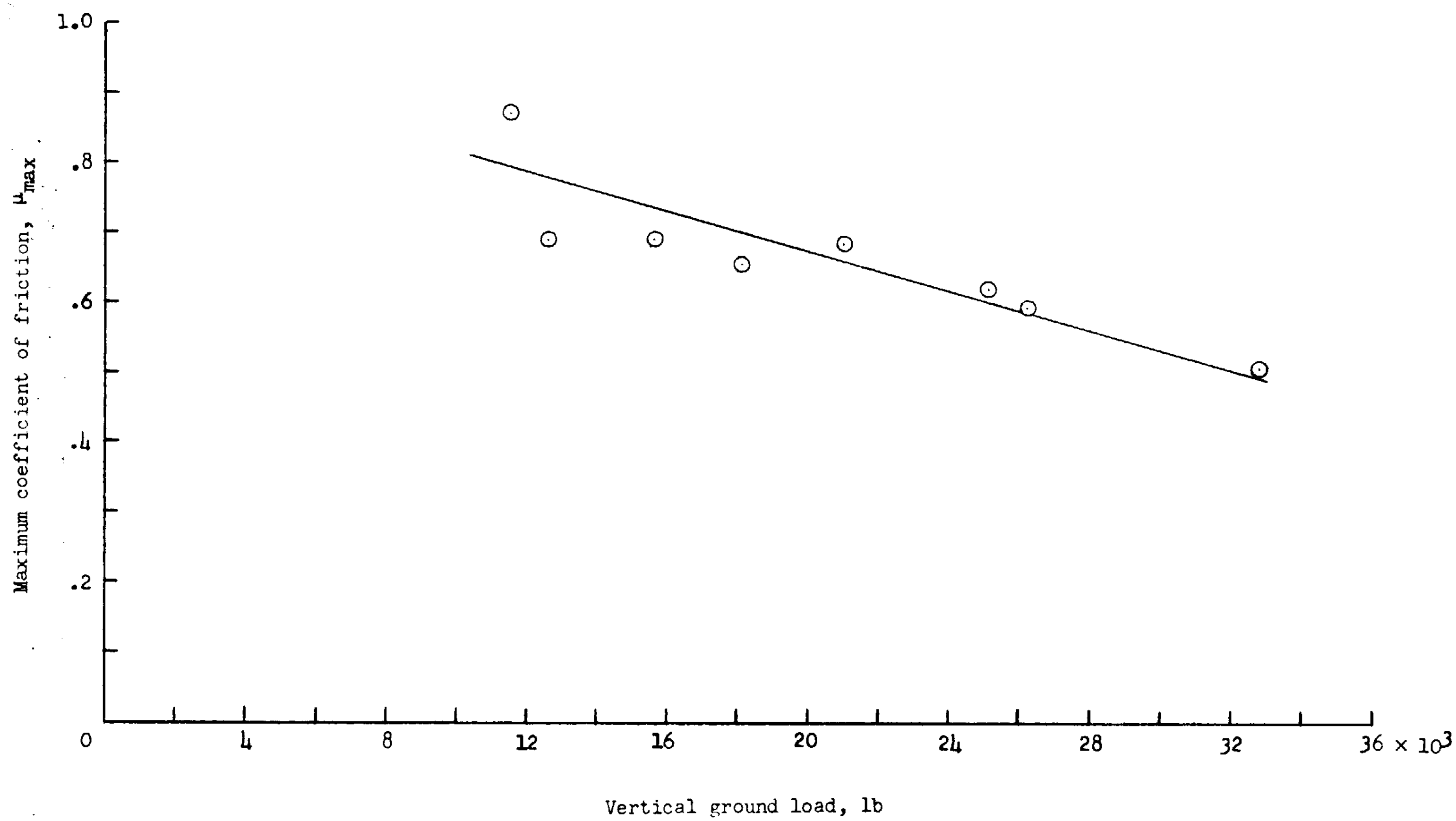

Figure 12.- Variation of maximum coefficient of friction with vertical ground load for forward speeds between 150 feet/second and 174 feet/second.

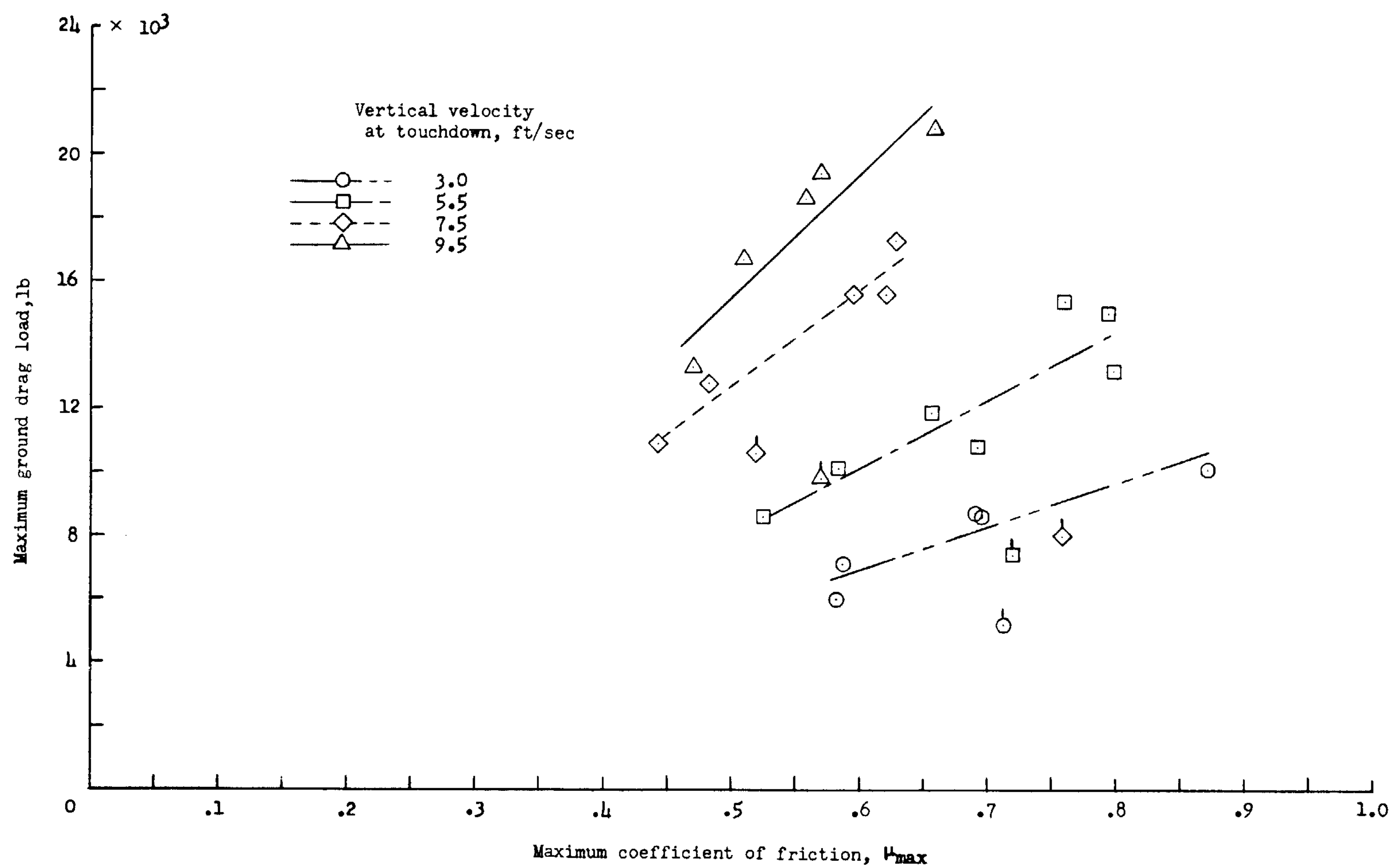

Figure 13.- Variation of maximum ground drag load with maximum coefficient of friction for various vertical velocities. The flagged data points were obtained during tests in which wheel spin-up occurred during the early stages of impact and while the vertical load was still rising.

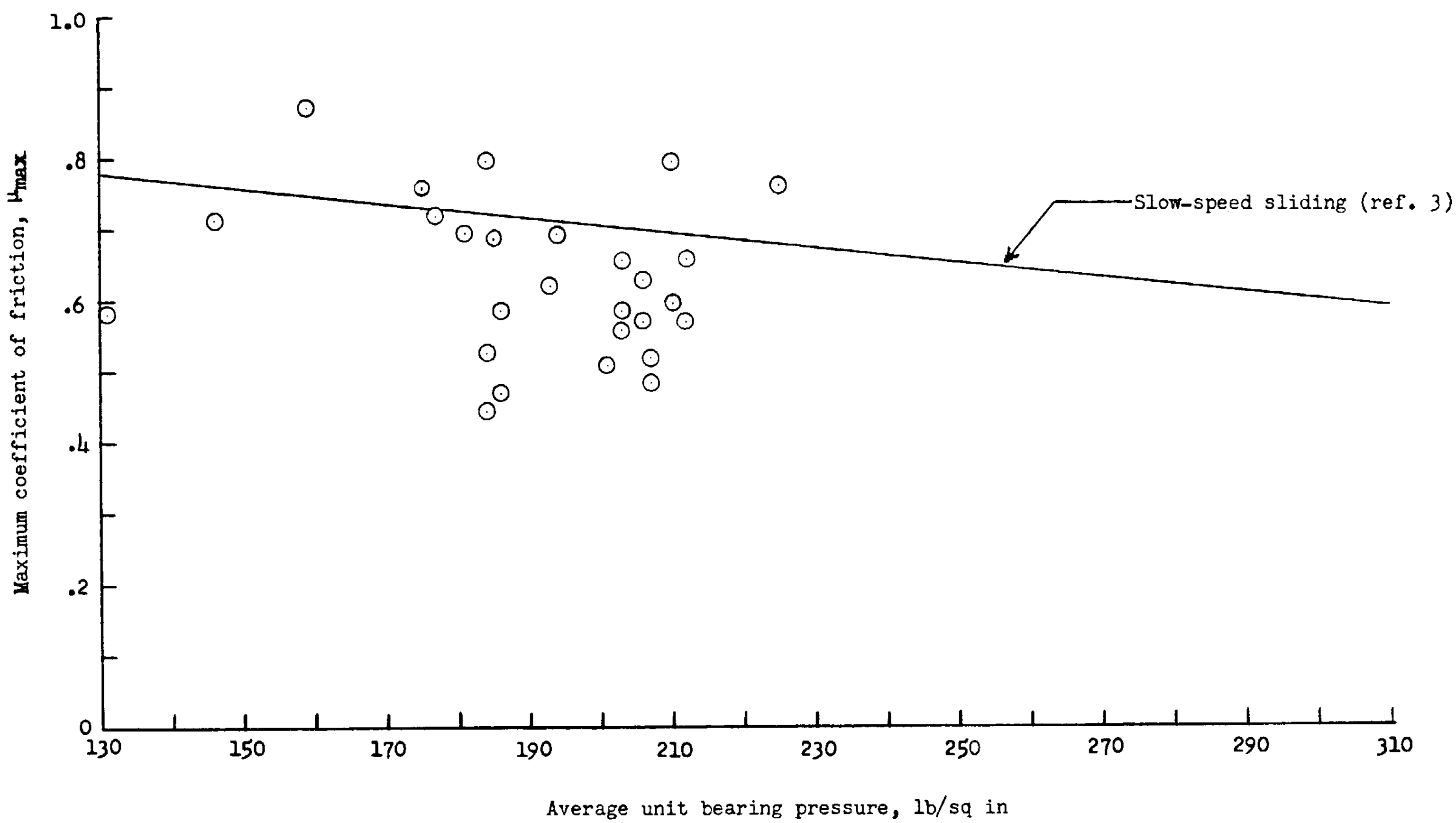

Figure 14.- Variation of maximum coefficient of friction with average unit bearing pressure. Initial tire inflation pressure, 140 pounds per square inch.

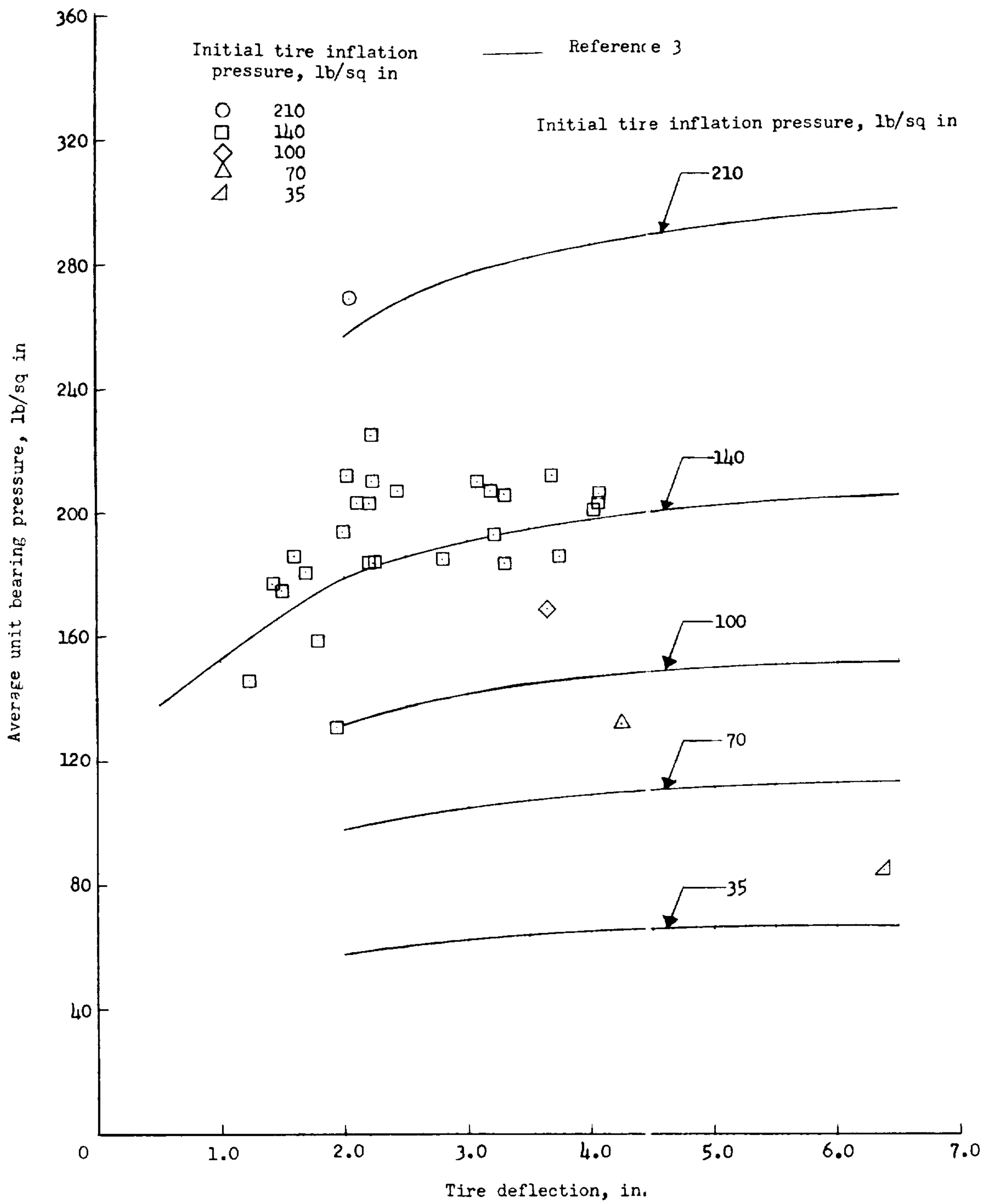

Figure 15.- Variation of average unit bearing pressure with tire deflection for various initial tire inflation pressures.