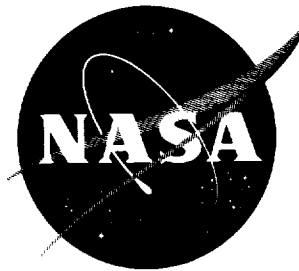


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TECHNICAL NOTE

D-552

STUDIES OF THE RETARDATION FORCE DEVELOPED ON AN
AIRCRAFT TIRE ROLLING IN SLUSH OR WATER

By Walter B. Horne, Upshur T. Joyner,
and Trafford J. W. Leland

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

A series of unbraked (freely rolling) taxi tests were conducted at the Langley landing-loads track with a 32 x 8.8, type VII, 22-ply-rating ribbed-tread aircraft tire to obtain data on tire retardation forces developed during rolling in both slush and water. The forward speeds of the tests ranged from 59 to 104 knots. Tire inflation pressures of 350 and 115 pounds per square inch were used.

Results indicated a parabolic increase of retardation force with increasing forward velocity for both slush- and water-covered runway surfaces. The retardation force was found to increase approximately linearly with increasing water depth. Drag coefficients appropriate to the equations used are presented. Calculations made to determine the effect of slush on the take-off distance of a jet transport are in agreement with data obtained from an actual take-off in slush for this airplane.

This is an interim report which deals with the effect of slush on the acceleration and the ground-run distance of airplanes during take-off.

INTRODUCTION

The introduction of jet-powered transport aircraft into commercial usage in this country has focused attention on the problem of take-off and landing on runways covered with slush or water. This problem has been tolerated on propeller-type aircraft because its effect on aircraft performance did not usually result in unsafe operation. However, the much higher take-off and landing velocities required of the new jets along with their lower acceleration characteristics makes this problem and its effect on aircraft performance much more acute. This operating problem affects aircraft performance in several ways. First, the retardation forces developed by the aircraft wheels when taking off from slush- or water-covered runways increase the take-off distance required by the airplane and under certain conditions would prevent the airplane from

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obtaining the required take-off velocity. Second, the high-velocity spray of slush or water originating from the airplane wheels can be damaging to the surfaces of the airplane that are under spray impingement. Third, under certain conditions of vertical load, tire-inflation pressure, and forward speed, airplane tires operating on slush- or water-covered runways reach a condition called aquaplaning during which the hydrodynamic lift force developed between the tire footprint and the fluid-covered runway surface equals or exceeds the vertical reaction of the airplane mass acting on the tire. During aquaplaning the tire loses contact with the runway surface and thus loses its directional stability and braking effectiveness. Fourth, at subaquaplaning velocities the friction coefficients developed between aircraft tires and the ground during braking on slush- or water-covered runways are considerably reduced from the values obtained on dry runways. The tire tread pattern may influence this effect to a certain extent.

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A general investigation under controlled conditions has been underway at the Langley landing-loads track (ref. 1) to determine the effect of forward velocity; type of runway surface; tire tread material, pattern, and wear; water and slush on the runway; and so forth on the braked and unbraked characteristics of aircraft tires. This investigation is continuing, but, because of great current interest in the effects of slush- or water-covered runways on jet-transport take-off performance, this report is being issued to present the results obtained thus far for a freely rolling (unbraked) wheel operating on a slush- or water-covered concrete runway.

Also presented herein are methods for calculating (1) the retardation force developed on an unbraked tire due to slush or water and (2) the additional take-off distance required for an airplane operating on a slush- or water-covered runway over that required on a dry runway.

The calculated and actual take-off distances required for a four-engine jet transport operating in 0.6 inch of slush are compared.

SYMBOLS

a	aircraft horizontal acceleration on dry runway
a_n	aircraft horizontal acceleration on wet runway
a_r	horizontal deceleration of aircraft due to slush or water
b	chord length of tire cross section at slush or water surface

C_D	drag coefficient
C_z	tire constant; 0.02 for type I tires and 0.03 for types III and VII tires (obtained from ref. 2)
d	diameter of unloaded tire
d_1	fluid depth on runway
$f(w)$	function of tire width
$F_{x,g}$	ground drag load
$F_{x,g,f}$	retardation force acting on airplane tire due to slush or water
$F_{x,g,m}$	retardation force developed on a single main-wheel tire
$F_{x,g,n}$	retardation force developed on single nose-wheel tire
$F_{x,g,\epsilon}$	total aircraft retardation force due to slush or water
$F_{z,g}$	net vertical load acting on tire (static vertical load minus wing lift force)
I	moment of inertia of rotating mass (wheel, brake rotors, tire, and tube)
N_m	number of leading main-wheel tires
N_n	number of nose-wheel tires
p	tire inflation pressure
p_r	rated tire inflation pressure (one-fourth tire bursting pressure)
r_o	unloaded tire radius
Δs	incremental take-off distance of aircraft
V_H	aircraft forward velocity
W	airplane gross weight

w	maximum tire width
x_{cp}	vertical-load center-of-pressure shift
α	wheel angular acceleration
δ	vertical tire deflection
ρ	mass density of fluid (slush or water)

APPARATUS

Test Vehicle

The tests were carried out by making test runs at the Langley landing-loads track. The main carriage (fig. 1) of this facility weighs approximately 100,000 pounds and travels on steel rails which are located on each side of a 2,200-foot-long concrete runway. The runway surface characteristics are similar to those of actual portland-cement concrete surfaces in current use for airport runways.

Tire

The tire used in this investigation was a 32 x 8.8, type VII (extra high pressure), 22-ply-rating ribbed-tread aircraft tire which was mounted on the main landing-gear wheel of a century-series jet-fighter airplane. This wheel was in turn mounted within an instrumented test fixture (fig. 2) suspended below the main carriage. The weight of the rotating mass - that is, the wheel, brake rotors, tire, and tube - was 203 pounds. The moment of inertia of the rotating mass was 2.73 slugs-feet². Tire inflation pressures of 115 and 350 pounds per square inch were used.

Slush and Water Troughs

A cross section of the test runway surfaces is shown in figure 3. The space between the edge of the asphalt runway and the concrete dike shown in this figure forms the slush and water troughs used in the investigation. The location of the troughs on the runway is shown in figure 4. These troughs are similar to the water trough described in reference 3. Artificial slush was prepared in the slush trough by adding snow ice to 1/2 inch of water that had been previously placed in the trough. This snow ice quickly melted in the trough to a consistency that was similar both in appearance and specific gravity to natural slush. The snow ice

used was the fine residue left from chipping block ice. The occasional larger particles rarely exceeded $1/4$ inch in diameter. Immediately before a run several samples of slush were taken by means of a 6- by 6- by 6-inch box made from $\frac{1}{32}$ -inch stainless steel, fitted with a transparent top, and having one end open. The edges of the open end were sharpened to allow the box to be pushed gently through the slush without compressing the sample. When the bottom of the box was completely covered with slush as noted through the transparent top, the open end was closed with a hard rubber cover, trapping the slush and water inside. The box was then weighed, and this weight was compared with the weight of an equal volume of water to give the specific gravity of the slush sample. This same procedure could be used to measure equivalent slush depth.

In figure 5(a) is shown the snow ice being deposited in the slush trough. The sled shown in figure 5(b) contained an adjustable plate that could trim the slush to the desired test depth. The appearance of the slush trough immediately after a test run is shown in figure 5(c).

INSTRUMENTATION

Instrumentation was provided to obtain the vertical and drag forces developed between the tire and the runway. Also obtained were the vertical and drag accelerations of the wheel axle as well as the wheel angular acceleration, velocity, and displacement. Side load was not measured during these tests. All forces were measured by strain-gage dynamometer beams. Because of space limitations within the test fixture, some of the instruments were mounted on an auxiliary axle which was driven at axle speed from the main axle by a toothed timing belt. Figure 6 is a schematic diagram of the test fixture and shows the location of the various instruments.

The vertical load between the tire and the runway was obtained by adding the measured vertical load from each vertical-load beam; the sum of the two drag-beam measurements gave the drag load. Corrections for the inertia forces introduced by the mass of the wheel, tire, and axle assembly (due to runway surface irregularities) were derived from acceleration values obtained from the vertical and drag accelerometers mounted at one end of the axle. The inertia corrections amounted to no more than 10 to 15 percent of the measured values of the vertical and drag load. The weight of the wheel, tire, and axle assembly was 780 pounds.

The horizontal velocity of the main carriage was measured by noting the time taken to travel a given incremental distance. Distance measurements were obtained by the use of metal tabs at 10-foot intervals along the side of the track. When a tab interrupted the light beam in a light-source—photocell combination mounted on the main carriage, a pulse occurred on an oscillograph-record trace.

TEST PROCEDURE

Before each simulated taxi run, the slush and water depths were measured. It should be mentioned that the water depth was extremely difficult to control due to wind effects. A wind blowing along the length of the track tended to slope the water toward the far end of the water trough. All runs were made with the wheel unbraked (freely rolling). The vertical load on the tire while traversing the slush and water troughs was approximately 9,000 pounds.

The investigation consisted of a series of runs conducted at different forward velocities at tire inflation pressures of 350 and 115 pounds per square inch. The forward velocities varied from 59 to 104 knots. The slush depth was held constant at approximately 2 inches, whereas the water depth varied between approximately 0.3 and 1.5 inches.

TEST RESULTS

Time histories of a typical run on slush- and water-covered runway surfaces are shown in figure 7. In this particular run the tire aquaplaned. This fact is substantiated by the wheel-angular-velocity curve which shows the wheel losing approximately two-thirds of its dry runway angular velocity while on the slush-covered runway. Tire planing is also indicated by the displacement curves shown in figure 7. The differences between the carriage displacement and computed vertical tire deflection curves are a direct measure of the vertical axle displacement caused by the hydrodynamic lift forces acting between the tire and the ground. The explanation of the spin-down during aquaplaning of the tire is indicated by the variation of the vertical-load center-of-pressure curve shown in this figure. The hydrodynamic lift force acting on the tire in the slush and water troughs moves the vertical-load center of pressure forward of the axle a distance x_{cp} (fig. 8) which for these particular test conditions is sufficient to make the product $F_{z,g}(x_{cp})$ greater than $F_{x,g}(r_0 - \delta)$ and, hence, tire spin-down occurs.

The variation of retardation force with forward speed for the slush- and water-covered runway surfaces is shown in figures 9 and 10, respectively. The curves passed through the data are based on the plausible assumption of a parabolic distribution. The trend of the data shown in figure 11 indicates that the retardation force developed by a tire rolling on a water-covered runway can be considered to increase approximately linearly with increasing water depth.

METHOD FOR CALCULATION OF SLUSH OR WATER RETARDATION FORCE

AND ADDITIONAL TAKE-OFF DISTANCE

Retardation Force Developed on a Single

Unbraked Aircraft Tire

This method is based on the assumption that the retardation force developed by an unbraked tire rolling on a slush- or water-covered runway surface varies directly with the square of the forward velocity and the first power of the tire frontal area exposed to the slush or water and the slush or water mass density. It is also assumed that tire aquaplaning effects on the retardation force may be disregarded. Thus, the retardation force developed by a tire rolling on slush- or water-covered runways may be expressed by

$$F_{x,g,f} = \frac{1}{2} C_D \rho d_1 f(w) V_H^2 \quad (1)$$

For these calculations, $f(w)$ was chosen as the chord length of the tire cross section at the slush or water surface which can be expressed approximately (fig. 12) as

$$f(w) = b = 2w \left[\frac{\delta + d_1}{w} - \left(\frac{\delta + d_1}{w} \right)^2 \right]^{1/2} \quad (2)$$

If equation (2) is substituted into equation (1), the retardation force on the tire due to the fluid expressed in terms of tire and fluid conditions becomes

$$F_{x,g,f} = C_D \rho d_1 w V_H^2 \left[\frac{\delta + d_1}{w} - \left(\frac{\delta + d_1}{w} \right)^2 \right]^{1/2} \quad (3)$$

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It was found that a value of C_D of 0.75 was required for the calculations of equation (3) to match the experimental data shown in figure 9 for a 2-inch slush depth. Similarly, for the 1.3- to 1.5-inch water-depth data shown in figure 10, it was found that a value of C_D between 0.70 and 0.75 was required. It is encouraging to note the similarity of the C_D values obtained from the slush and water tests.

At the present time no experimental data are available to check the calculations of this method for the condition of a tire rolling in snow. However, since it is not expected that the tire will completely remove the snow from the runway in the path of the tire as is apparently the case for slush and water (fig. 5(c)), the results should be conservative - that is, overestimation of the snow retardation force.

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Retardation Forces Acting on Aircraft During Take-Off

Results from the track investigation on a single wheel rolling on a slush-covered runway indicate that all of the slush in the path of the wheel was usually thrown from the runway with the exception of an icy film less than 0.1 inch thick next to the runway. This phenomenon occurred at all test velocities, including velocities in excess of that required for tire planing. It is assumed, therefore, that the retardation forces developed on rear wheels of a landing-gear arrangement, such as a dual-tandem bogie landing gear, are negligible and that only the leading wheels of the landing gear need be considered. Accordingly, full slush drag effects on both nose-wheel tires and on the front four tires of the two main gear bogies were assumed in the calculations. The four rear tires of the two main gear bogies are assumed to be free of drag due to slush.

The retardation forces developed on each nose and leading main wheel during the take-off may be calculated from equation (3) by using a value of C_D of 0.75 for slush and a value of C_D between 0.70 and 0.75 for water.

For aircraft having negligible wing lift during the take-off roll up to rotational velocity, vertical tire deflections based on the average vertical load acting on the tires during take-off may be used in equation (3) to compute retardation force. For aircraft having a large reduction in wheel load due to wing lift, it is necessary to compute the vertical tire deflection during take-off roll by the following means.

Test results from the present investigation indicate that negligible differences exist between the static and freely rolling vertical-tire-deflection characteristics of the test specimen up to the maximum test forward speeds (approximately 180 feet per second). It is assumed,

therefore, that the static vertical-tire-deflection characteristics represent the take-off condition (rolling tire) with small loss in accuracy. If static vertical-load-deflection curves for the tires of the airplane under consideration are unavailable, the static vertical deflection for each tire and vertical-load condition may be determined by the following equation obtained from reference 2:

$$\delta = \frac{F_{z,g}}{2.4(p + 0.08p_r) \sqrt{wd}} + wC_z \quad (4)$$

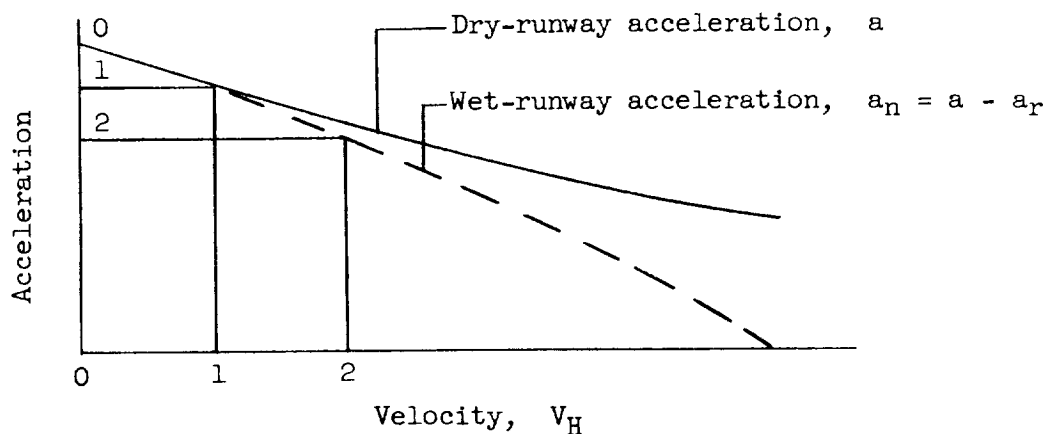
If retardation forces due to spray impingement on other aircraft surfaces are disregarded, the total retardation force acting on an aircraft due to slush or water $F_{x,g,\epsilon}$ is at any instant

$$F_{x,g,\epsilon} = N_n F_{x,g,n} + N_m F_{x,g,m}$$

The aircraft deceleration due to slush or water at any instant is

$$a_r = \frac{F_{x,g,\epsilon}}{W} \quad (5)$$

The slush-take-off calculation procedure requires that the variation of aircraft horizontal acceleration with forward velocity during take-off roll on a dry runway be known. A typical variation is represented in sketch 1.



Sketch 1.

The net airplane acceleration a_n (dashed curve) on a slush- or water-covered runway may be obtained by subtracting a_r (calculated from eq. (5)) from the acceleration on a dry runway at each velocity increment considered.

The incremental distance traversed by the aircraft in going from $V_{H,0}$ to $V_{H,1} = \Delta s_1$;

$$\Delta s_1 = \frac{(V_{H,1})^2 - (V_{H,0})^2}{a_{n,0} + a_{n,1}} \quad (6a)$$

In the same manner, the incremental distance traversed in going from $V_{H,1}$ to $V_{H,2} = \Delta s_2$;

$$\Delta s_2 = \frac{(V_{H,2})^2 - (V_{H,1})^2}{a_{n,1} + a_{n,2}} \quad (6b)$$

The curve of forward velocity plotted against runway distance for the take-off roll may be step integrated from equations (6).

The comparison between an actual take-off in 0.6 inch of slush for a four-engine jet transport (ref. 4) and the predicted take-off distance obtained by use of this method is presented in figure 13. The prediction overestimates the actual take-off distance by 500 feet.

Effect of Slush Depth on Take-Off Distance

The predicted increase in take-off distance required for an airplane taking off on runways covered with slush to depths equal to 0.5, 1.0, 1.5, and 2.0 inches is shown in figures 14 and 15 for two different airplane take-off thrust conditions. Also shown in these figures are the variations of airplane net acceleration and slush retardation force with airplane forward velocity. The data shown indicate that, as the slush depths increase, the aircraft net acceleration is reduced with correspondingly longer take-off distances being required.

Increasing the aircraft take-off thrust, of course, increases an aircraft's performance on slush-covered runways as is shown in figures 14 and 15. If the maximum commercial runway length available is 10,000 feet, the take-off of an airplane having a 13,000-pound-thrust engine configuration is marginal for a slush depth of 1 inch and impossible for slush depths of 1.5 and 2.0 inches. The take-off of an airplane having a 17,000-pound-thrust engine configuration is marginal only for the 2.0-inch

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slush depth. It should be noted that the possibility of severe damage to airplane surfaces under spray impingement might practically limit the slush depth permissible for take-off even if the airplane has the capability for take-off in greater slush depths.

CONCLUSIONS

L Under the test conditions for the experimental data on a 32 x 8.8,
1 type VII, 22-ply-rating rib-tread airplane tire and the assumptions made
2 in the studies described in this report, the following conclusions may
6 be stated with respect to the unbraked rolling of aircraft tires and
0 airplanes on slush- or water-covered runways:

1. The retardation forces measured on a tire rolling in slush and water suggests a parabolic variation with increasing forward velocity.
2. The retardation force acting on a tire on a water-covered runway increases approximately linearly with increasing water depth.
3. Data obtained by use of the retardation-force equation were in reasonable agreement with experimental data when drag coefficients between 0.70 and 0.75 were used.
4. Calculations in which the retardation-force equation was used together with the horizontal acceleration and velocity characteristics of a jet transport operating on a dry runway were in good agreement with results obtained in an actual slush take-off of this airplane.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 15, 1960.

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2. Smiley, Robert F., and Horne, Walter B.: Mechanical Properties of Pneumatic Tires With Special Reference to Modern Aircraft Tires. NASA TR R-64, 1960. (Supersedes NACA TN 4110, 1958.)
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4. Sparks, Allan R.: Report on Effect of Slush on Ground Run Distance to Lift-Off. Doc. No. D6-5198, Boeing Airplane Co., Jan. 1960.

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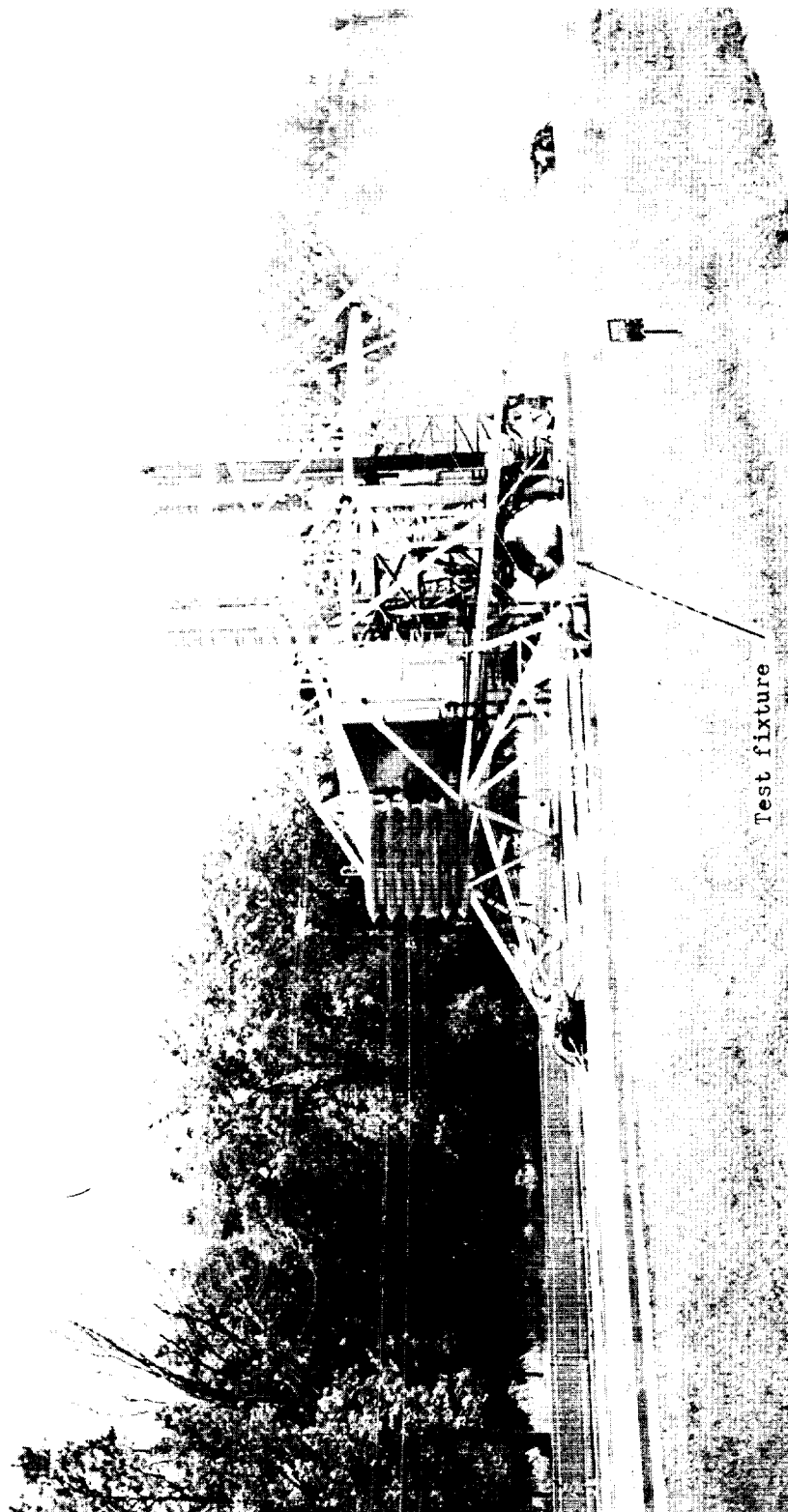
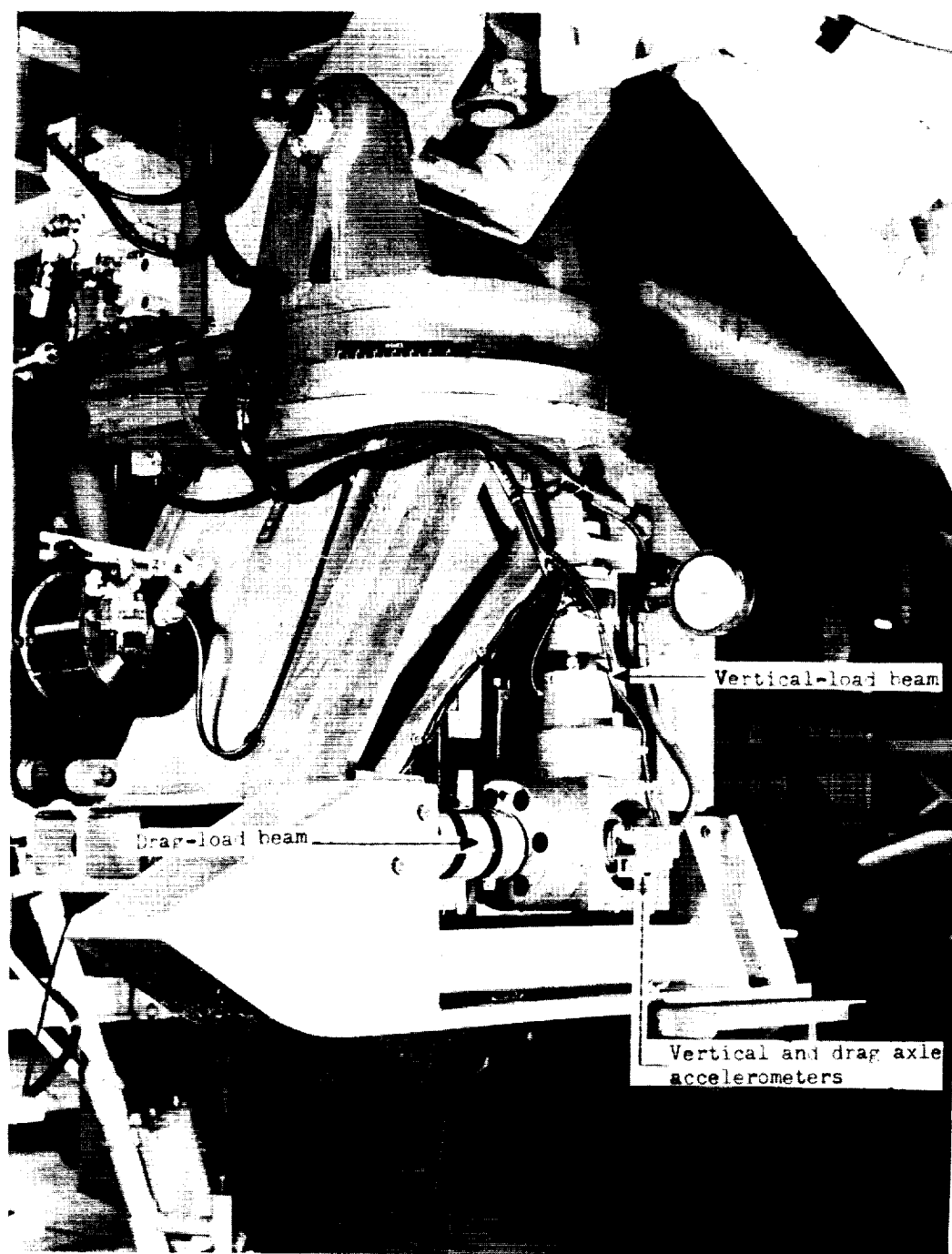


Figure 1.- Main carriage of Langley landing-load track traveling at 80 knots. Test tire running on wet concrete.



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Figure 2.- Test fixture suspended below main carriage shown in figure 1.

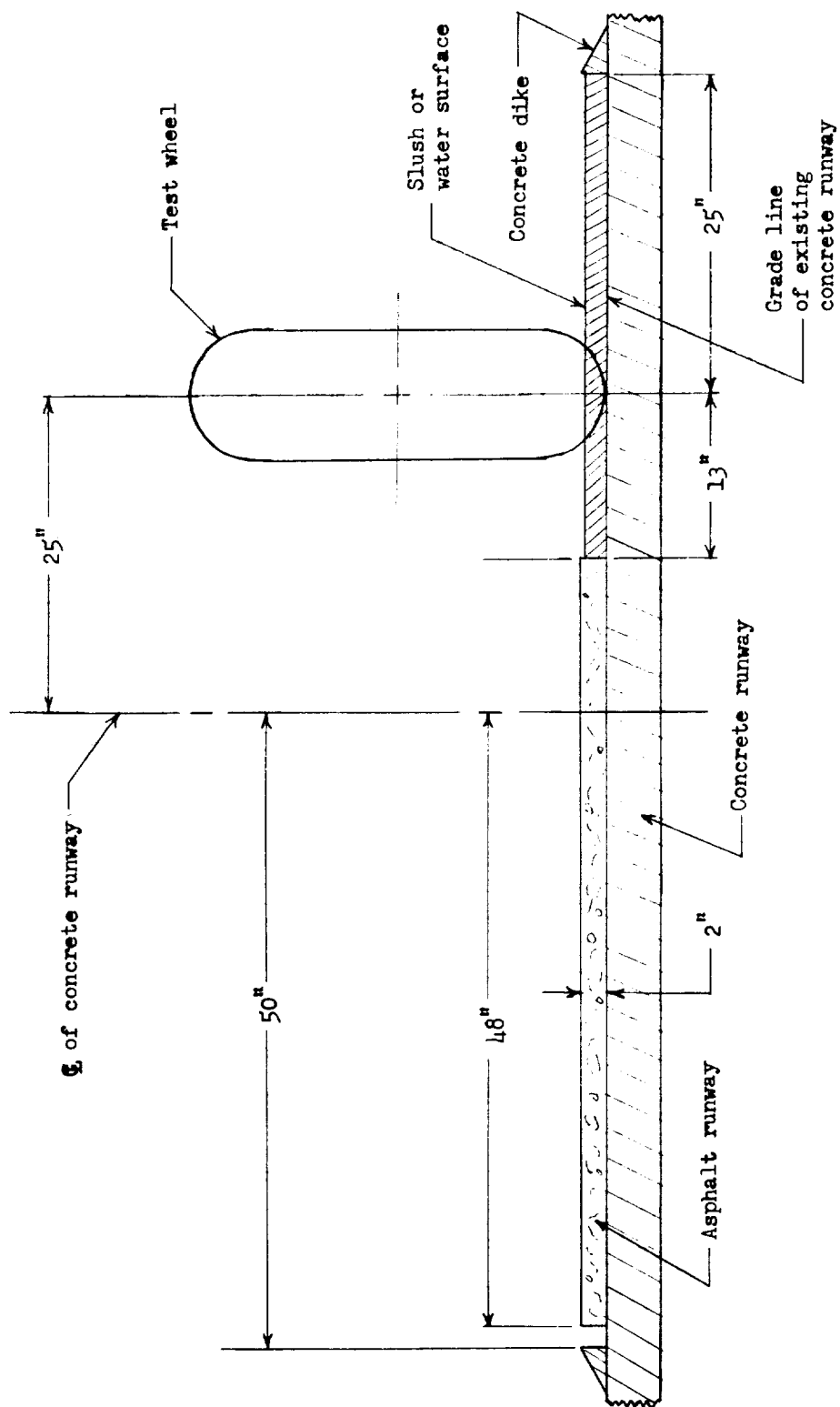


Figure 3.- Cross section of test runway surfaces at Langley landing-loads track.

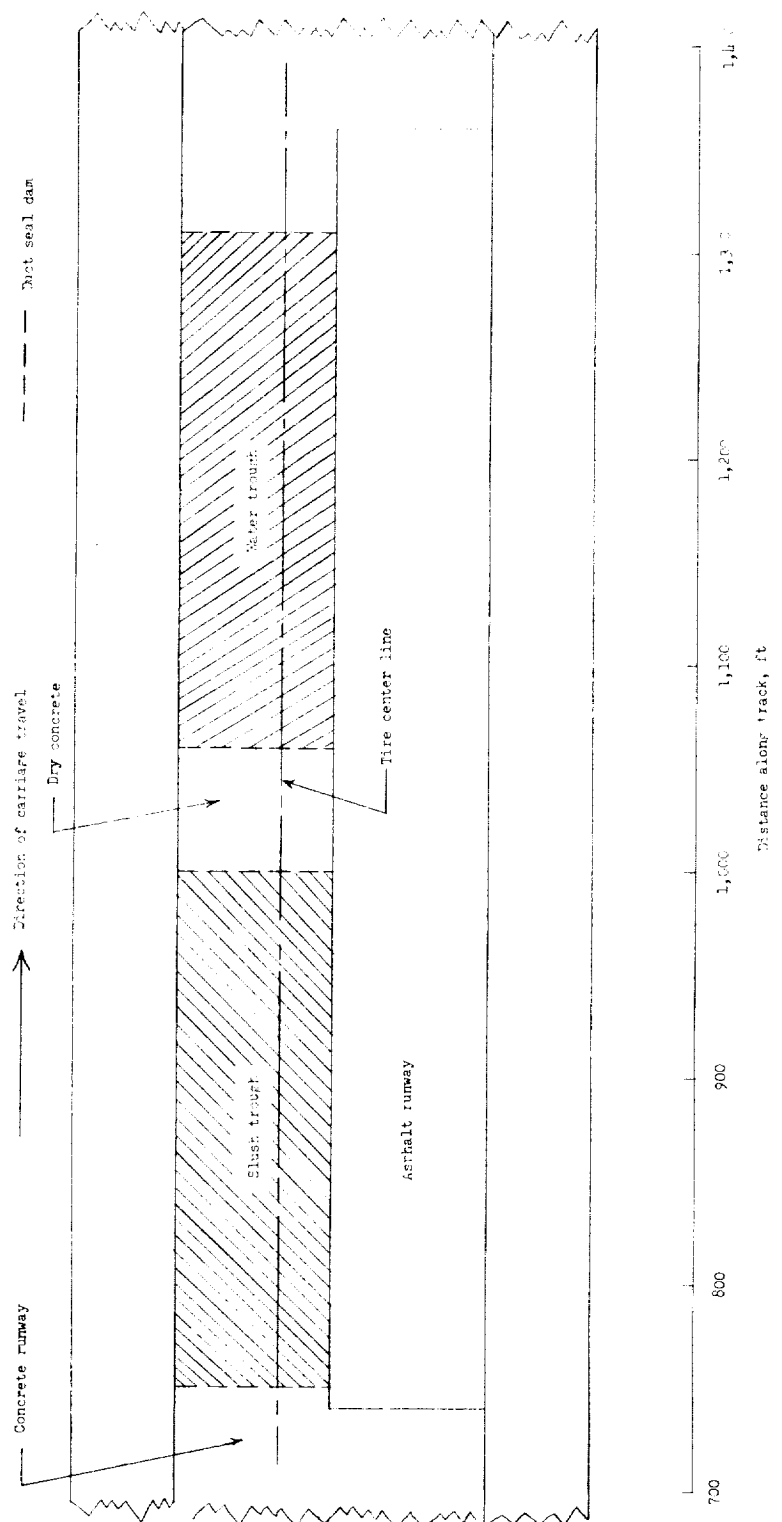


Figure 4.- Schematic diagram of slush and water troughs at the landing-loads track.

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(a) Snow ice being deposited in trough.

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Figure 5.- Slush trough at landing-loads track.



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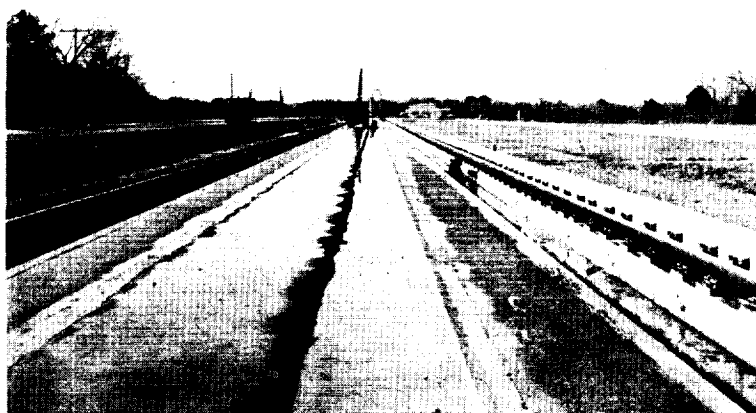


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(b) Slush being trimmed to a 2-inch depth immediately before a test run.

Figure 5.- Continued.

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(c) Appearance of slush trough immediately after a test run.

Figure 5.- Concluded.

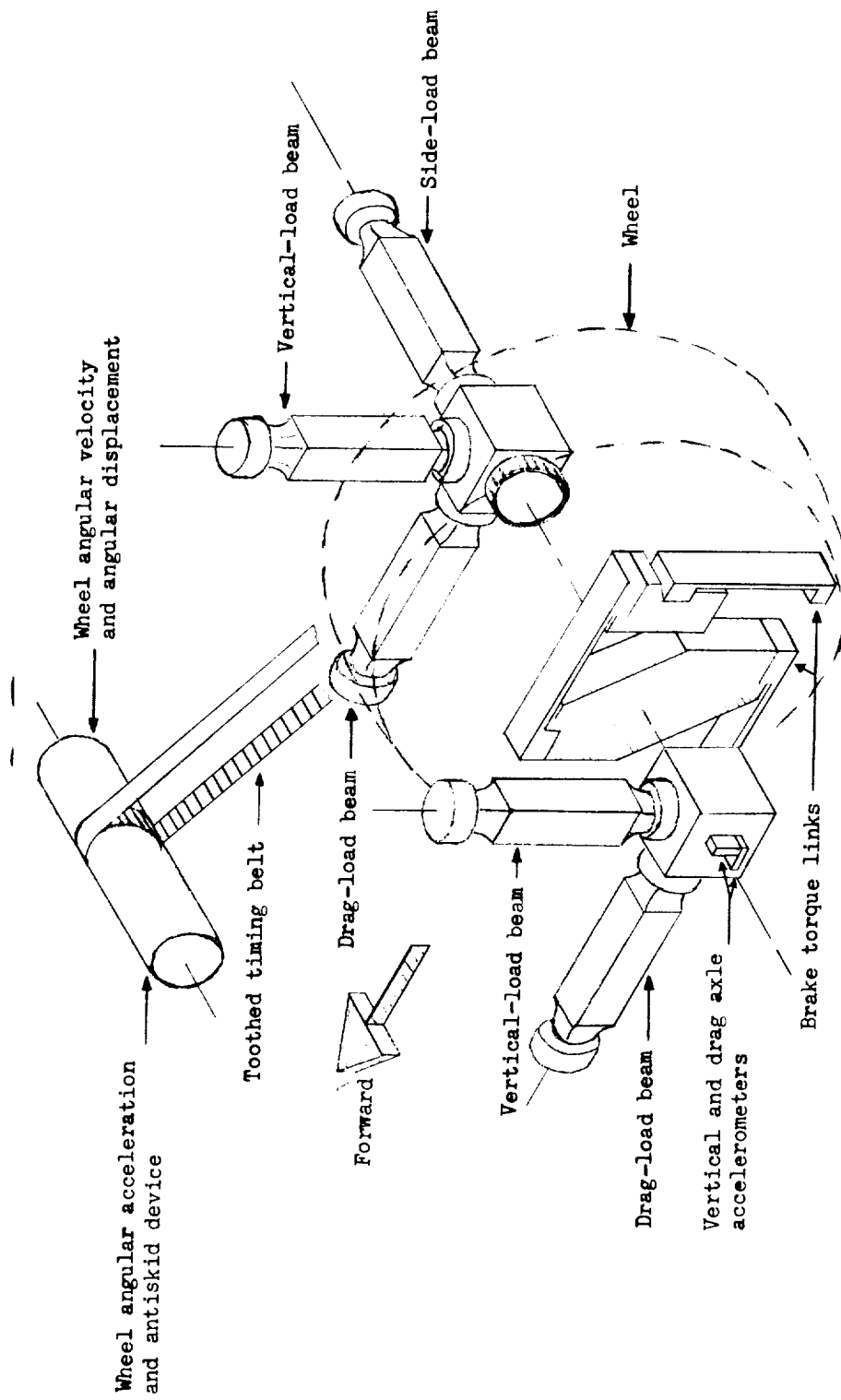


Figure 6.- Schematic diagram of test fixture.

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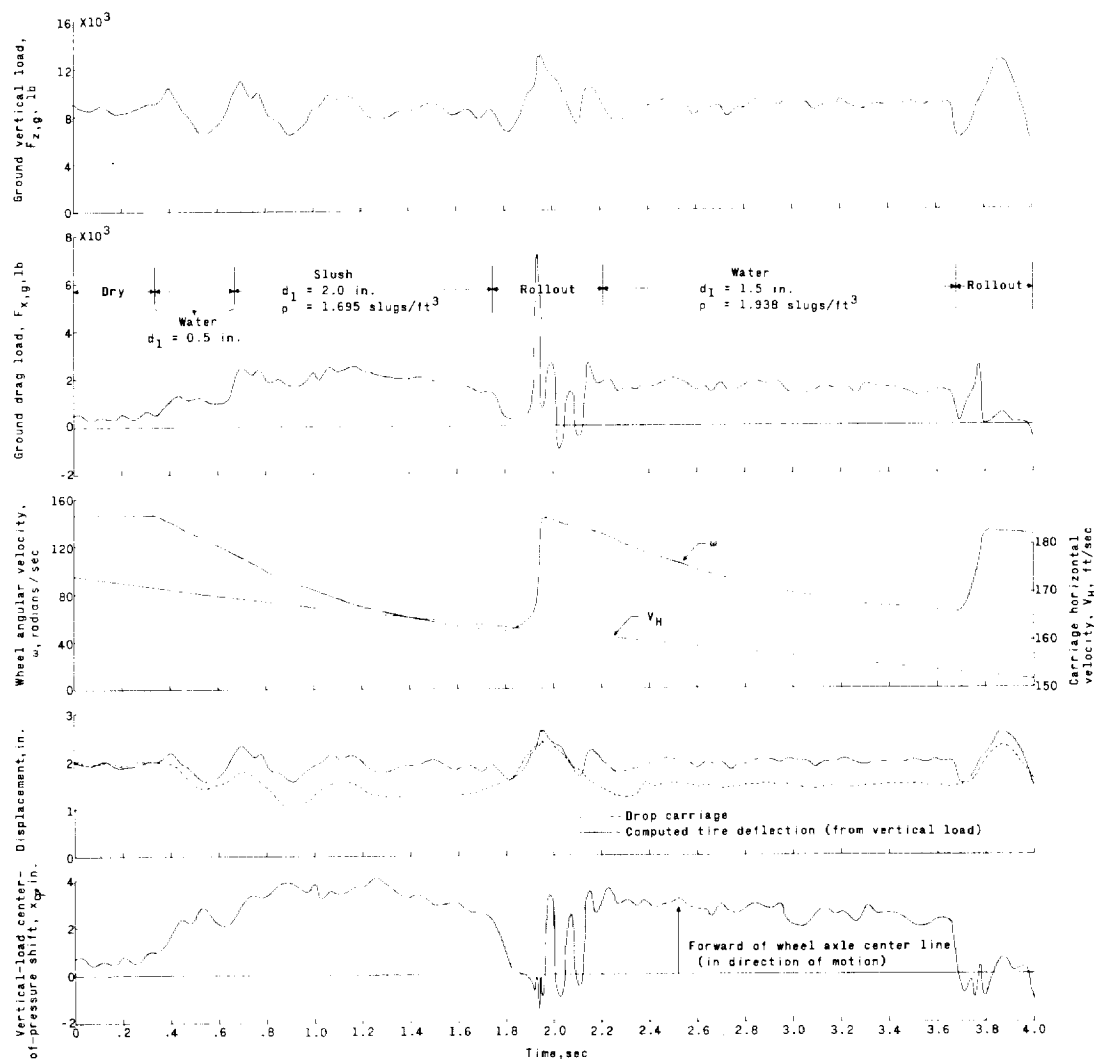


Figure 7.- Time histories of a typical run, showing variation of wheel loads, velocities, and displacement during unbraked rolling through slush and water troughs. $p = 115$ pounds per square inch.

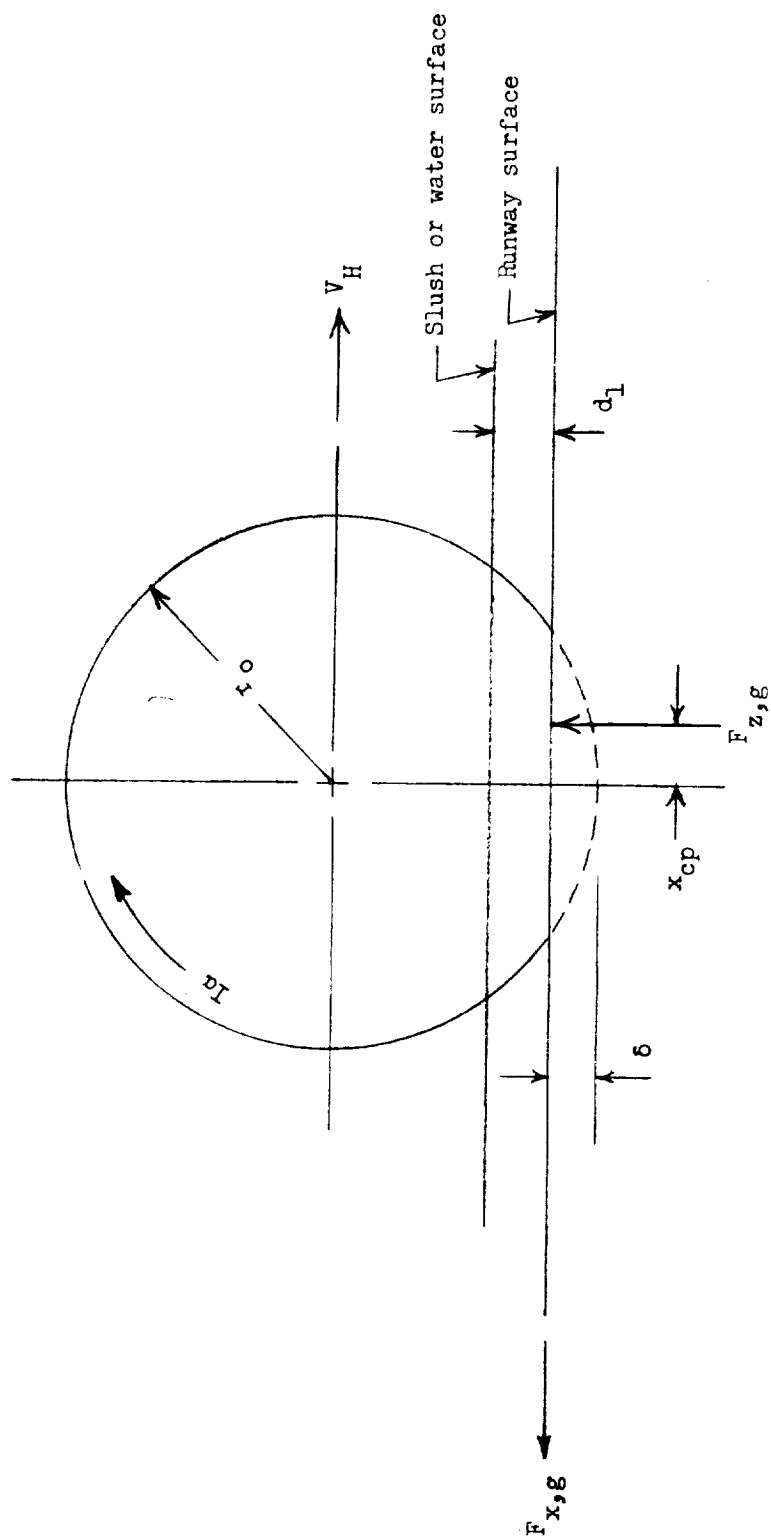


Figure 8.- Torque and moments acting about the wheel axle during wheel spin-down in slush or water when tire is aquaplaning (frictional torque of wheel bearings is disregarded).

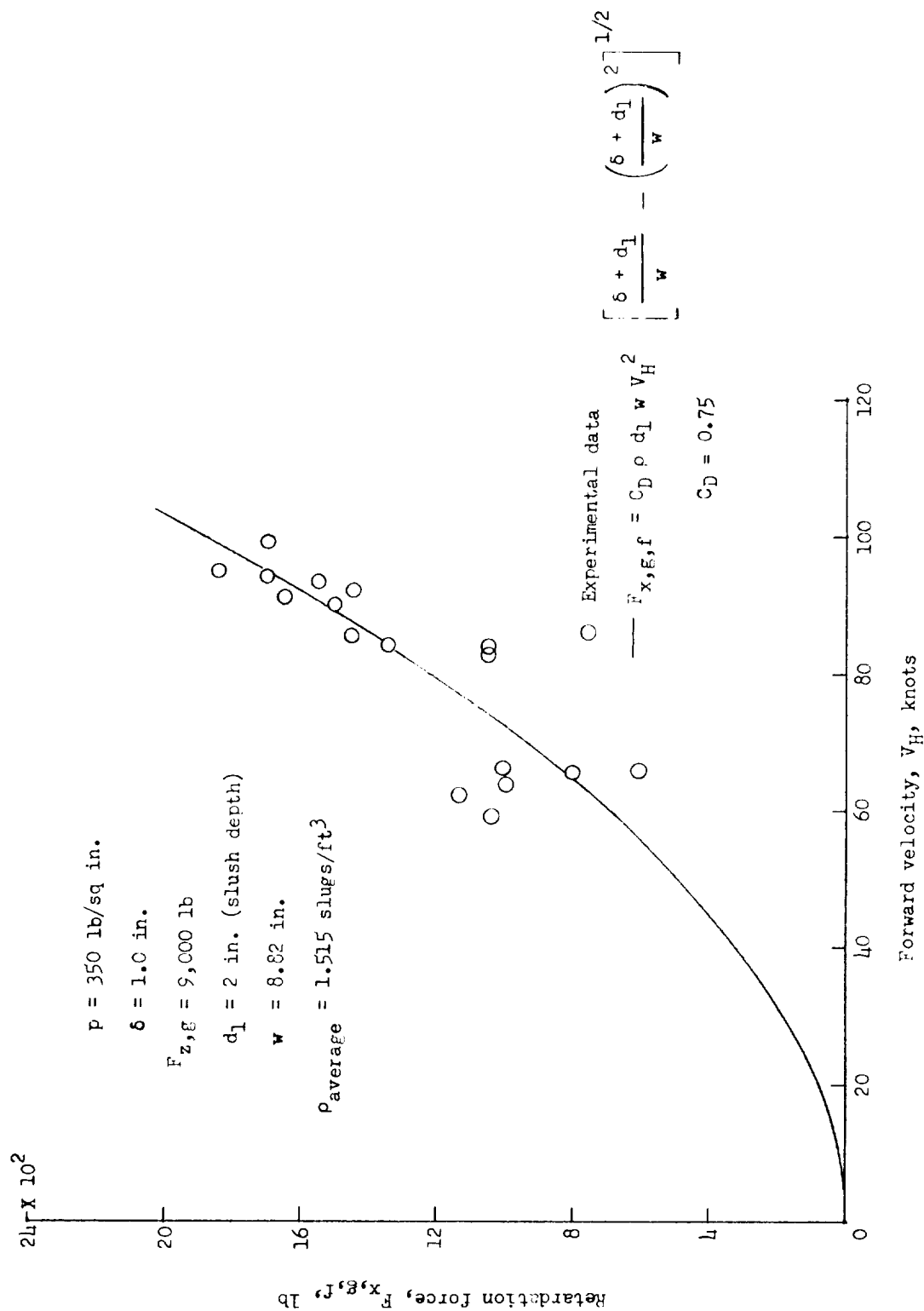


Figure 9.- Variation of retardation force with forward velocity on slush-covered runway.

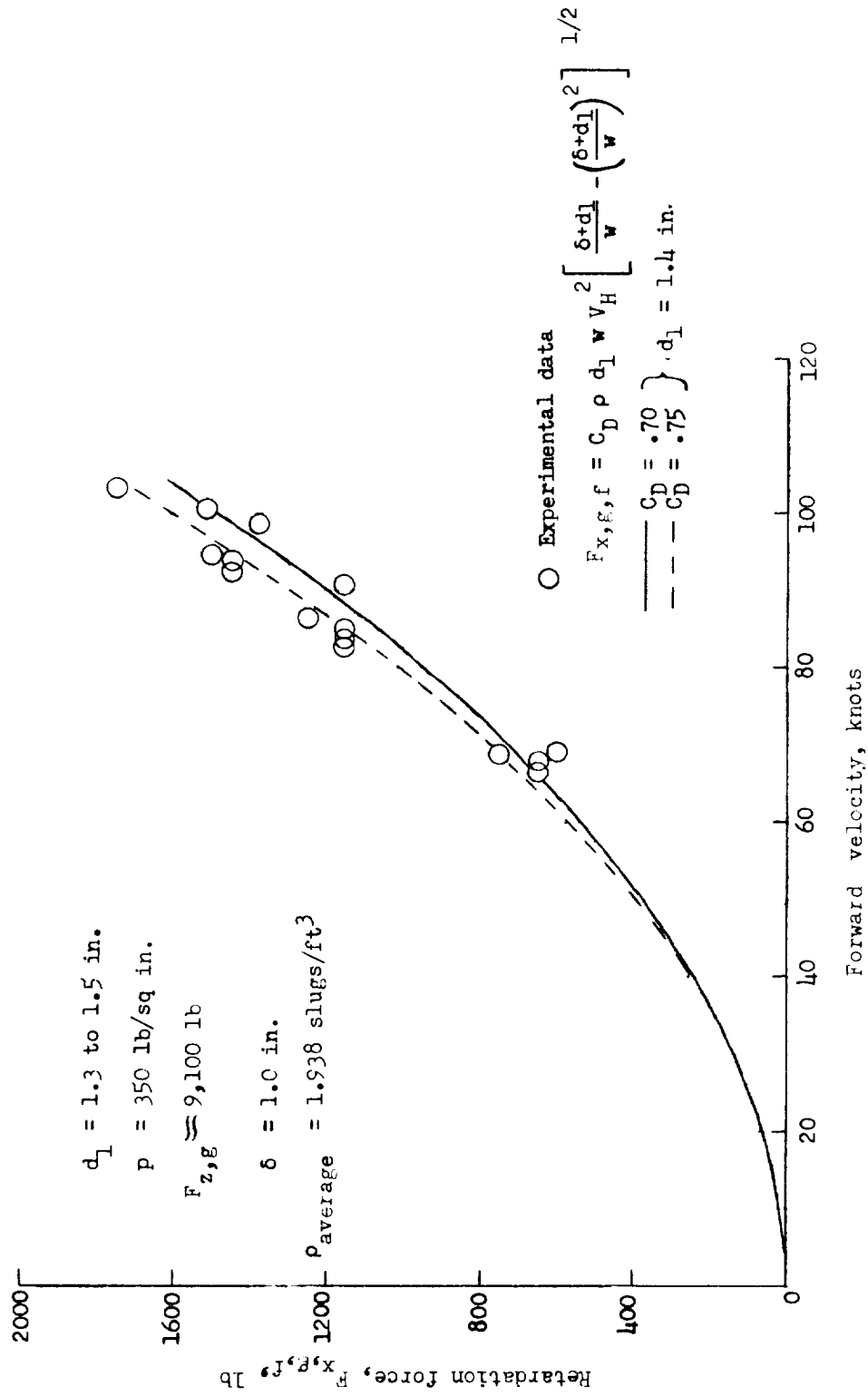


Figure 10.- Variation of retardation force with forward velocity on water-covered runway.

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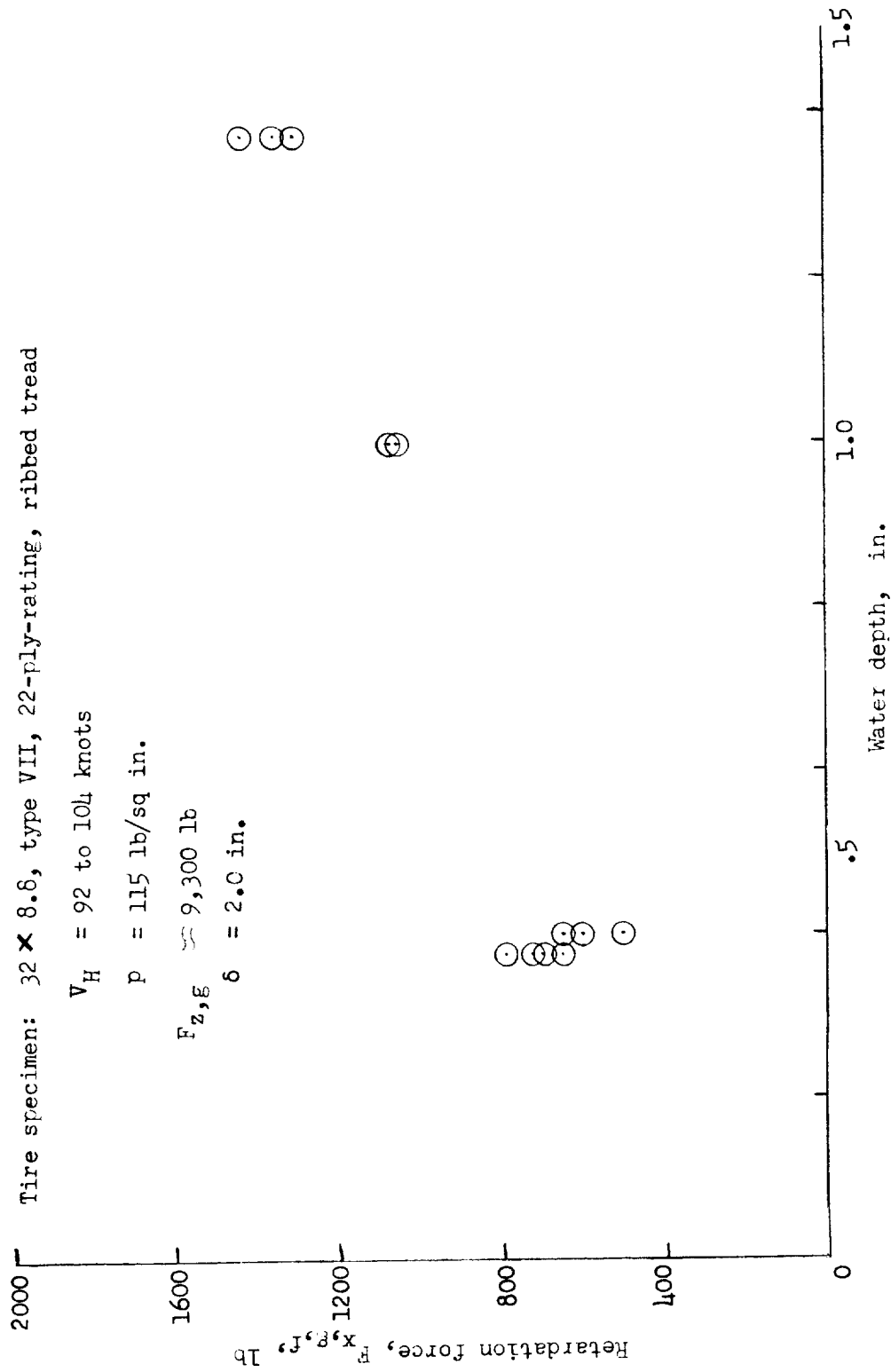


Figure 11.- Variation of retardation force with water depth for forward velocities of 92 to 104 knots.

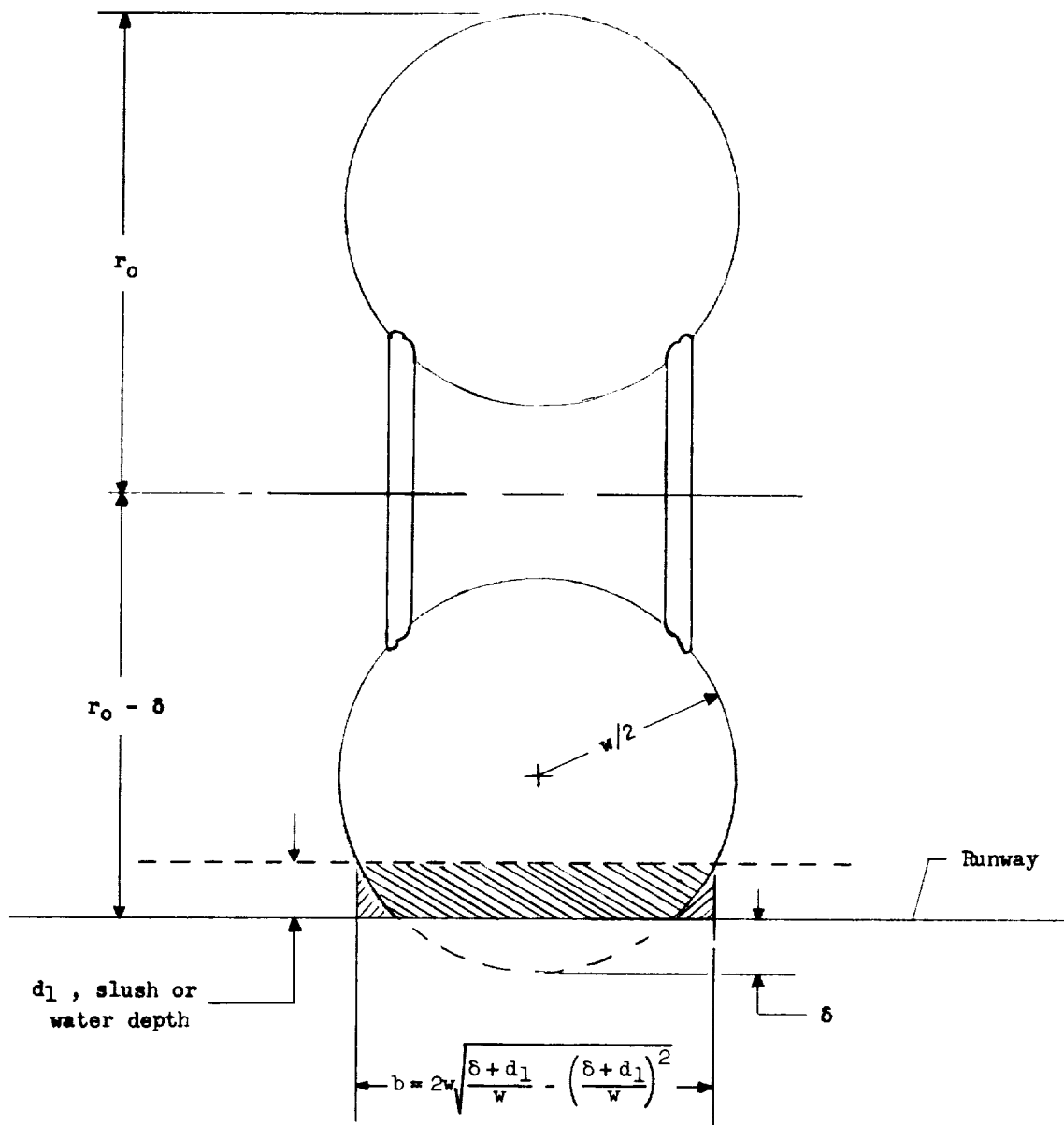


Figure 12.- Tire cross section.

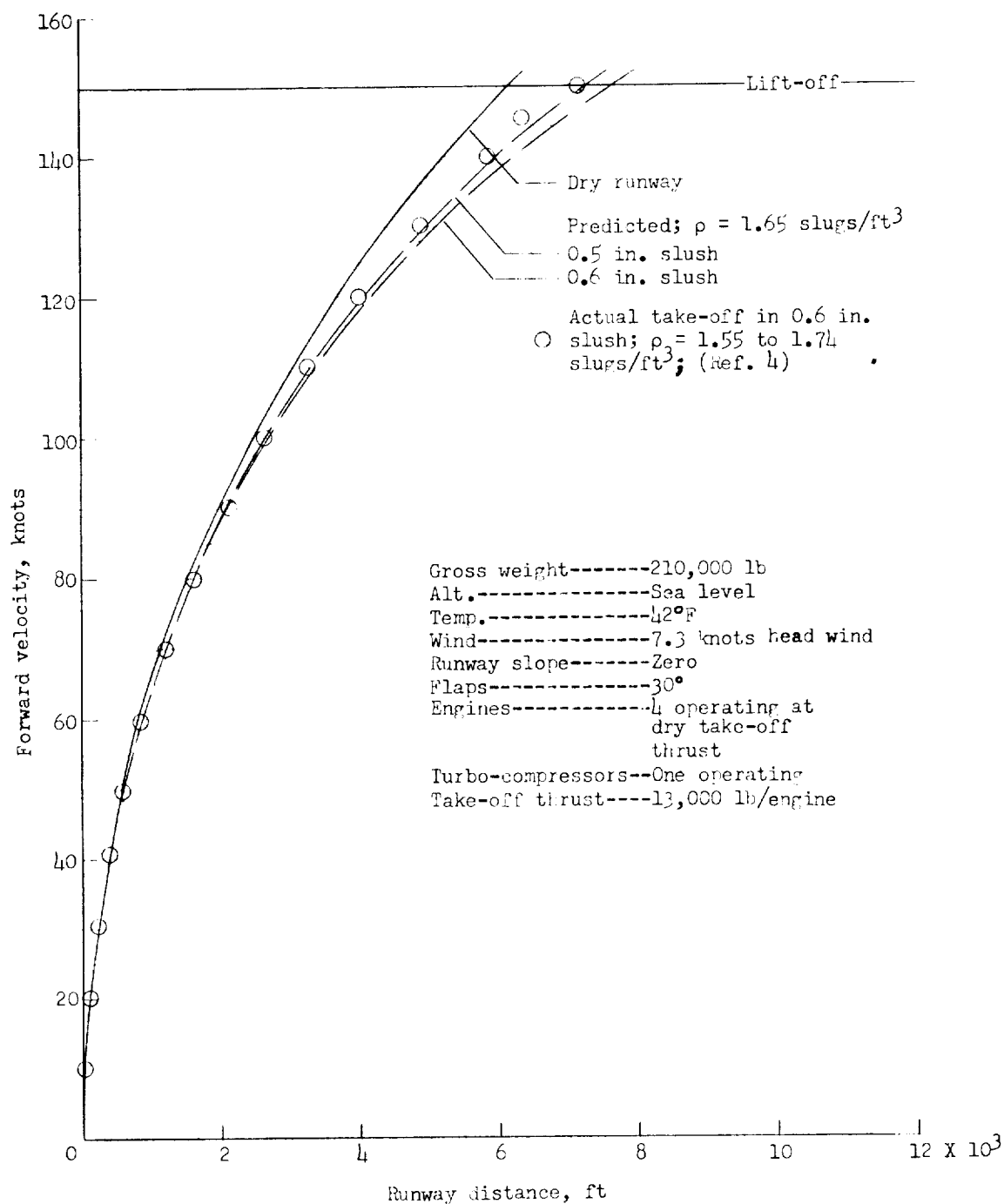


Figure 13.- Comparison of the calculated take-off distance with the actual take-off distance required for a four-engine jet transport on a runway covered with 0.6 inch of slush.

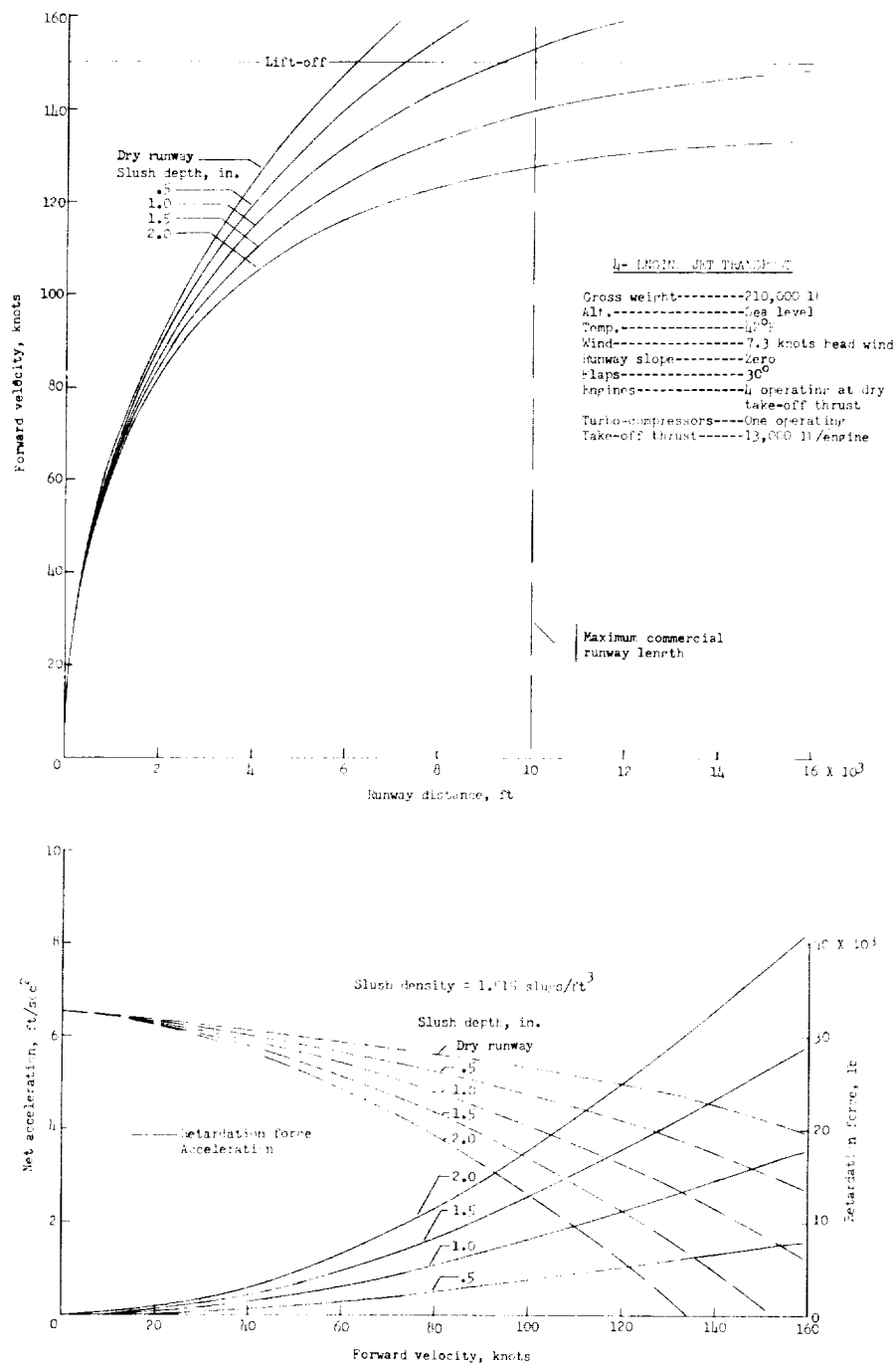


Figure 14.- Effect of slush depth on the take-off distance required for a four-engine jet transport operating at 210,000 pounds gross weight with 13,000-pound-thrust engines.

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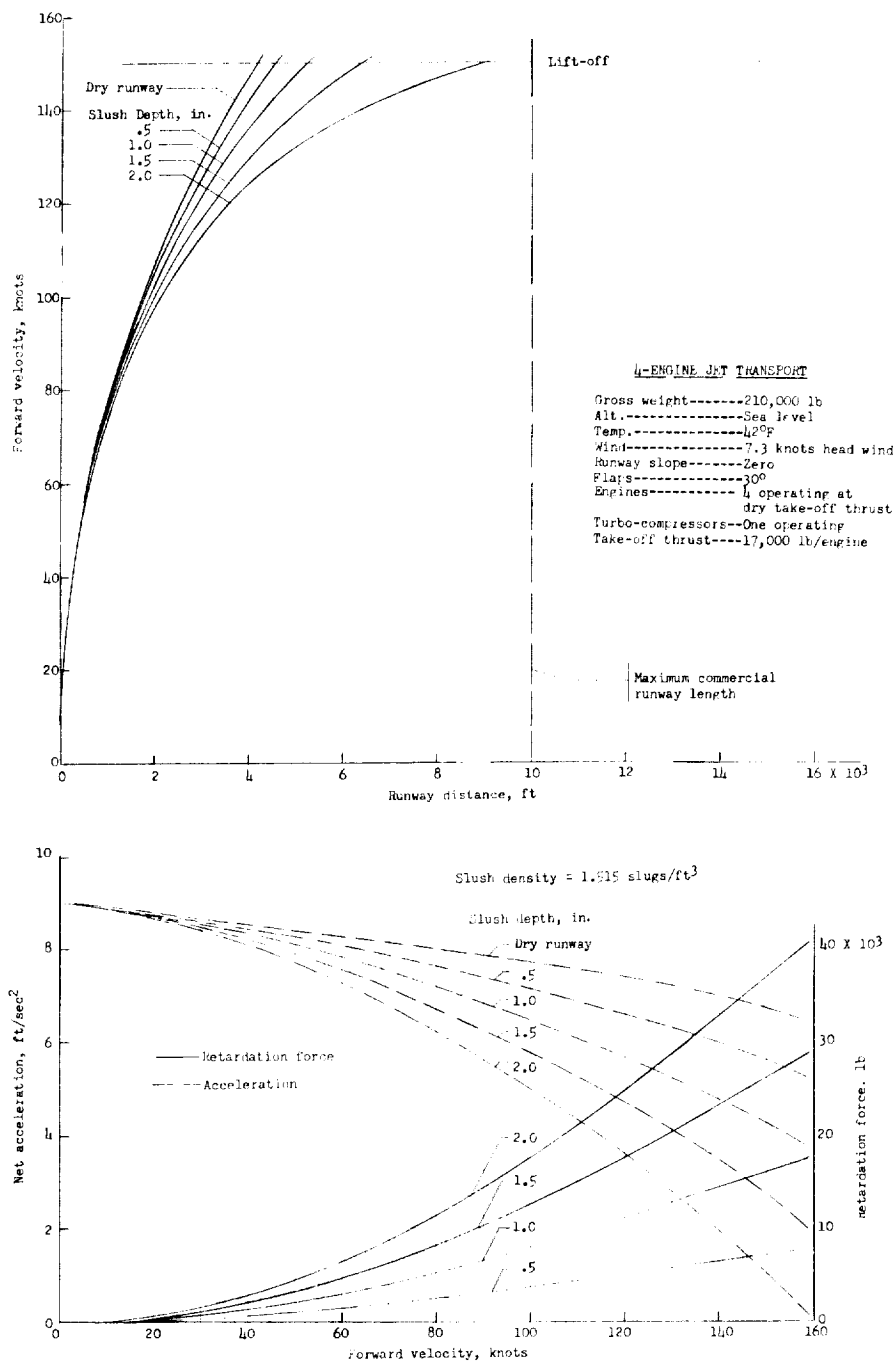


Figure 15.- Effect of slush depth on the take-off distance required for a four-engine jet transport operating at 210,000 pounds gross weight with 17,000-pound-thrust engines.

<p>NASA TN D-552 National Aeronautics and Space Administration. STUDIES OF THE RETARDATION FORCE DEVELOPED ON AN AIRCRAFT TIRE ROLLING IN SLUSH OR WATER. Walter B. Horne, Upshur T. Joyner, and Trafford J. W. Leland. September 1960. 29p. OTS price, \$0.75. (NASA TECHNICAL NOTE D-552)</p> <p>A series of unbraked taxi tests was conducted with a 32×8.8, type VII, 22-ply-rating aircraft tire to obtain data on tire retardation forces developed during rolling on both slush- and water-covered runway surfaces at forward velocities from 59 to 104 knots. Results indicated a parabolic increase of retardation force with increasing forward velocity in both slush and water. The retardation force was found to increase approximately linearly with increasing water depth. Calculations made to determine the effect of slush on the take-off distance of a jet transport are in agreement with the results obtained for an actual take-off in slush.</p> <p>Copies obtainable from NASA, Washington (over)</p>	<p>I. Horne, Walter B. II. Joyner, Upshur Tucker III. Leland, Trafford J. W. IV. NASA TN D-552</p> <p>NASA</p>	<p>I. Horne, Walter B. II. Joyner, Upshur Tucker III. Leland, Trafford J. W. IV. NASA TN D-552</p> <p>NASA</p>
<p>NASA TN D-552 National Aeronautics and Space Administration. STUDIES OF THE RETARDATION FORCE DEVELOPED ON AN AIRCRAFT TIRE ROLLING IN SLUSH OR WATER. Walter B. Horne, Upshur T. Joyner, and Trafford J. W. Leland. September 1960. 29p. OTS price, \$0.75. (NASA TECHNICAL NOTE D-552)</p> <p>A series of unbraked taxi tests was conducted with a 32×8.8, type VII, 22-ply-rating aircraft tire to obtain data on tire retardation forces developed during rolling on both slush- and water-covered runway surfaces at forward velocities from 59 to 104 knots. Results indicated a parabolic increase of retardation force with increasing forward velocity in both slush and water. The retardation force was found to increase approximately linearly with increasing water depth. Calculations made to determine the effect of slush on the take-off distance of a jet transport are in agreement with the results obtained for an actual take-off in slush.</p> <p>Copies obtainable from NASA, Washington (over)</p>	<p>I. Horne, Walter B. II. Joyner, Upshur Tucker III. Leland, Trafford J. W. IV. NASA TN D-552</p> <p>NASA</p>	<p>I. Horne, Walter B. II. Joyner, Upshur Tucker III. Leland, Trafford J. W. IV. NASA TN D-552</p> <p>NASA</p>

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