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(NASA-TM-X-73912) NASA DIAGONAL-BRAKED TEST VEHICLE EVALUATION OF TRACTION CHARACTERISTICS OF GROOVED AND UNGROOVED RUNWAY SURFACES AT MIAMI INTERNATIONAL AIRPORT, MIAMI, FLORIDA, 8-9 MAY 1973 (NASA) G3/09

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MAY 8-9, 1973

By

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NASA DIAGONAL-BRAKED TEST VEHICLE EVALUATION
OF TRACTION CHARACTERISTICS OF GROOVED
AND UNGROOVED RUNWAY SURFACES AT
MIAMI INTERNATIONAL AIRPORT,
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1.0 INTRODUCTION

The National Transportation Safety Board, in a letter to the Federal Aviation Administration (FAA) dated February 9, 1973, requested FAA Flight Standards Service and the National Aeronautics and Space Administration (NASA) to "evaluate the wet runway stopping characteristics of Runways 27L and 27R at Miami International Airport." This request was initiated in connection with an accident investigation involving a Northwest Airlines B-747 which went off the end of the wet Runway 27L after an engine-out landing on December 15, 1972.

1.1 A FAA/NASA team conducted the requested evaluation on March 14-15, 1973. The preliminary results of this evaluation were reported in Langley Working Paper-1107, April 26, 1973. The Dade County Port Authority decided to groove Runways 27L and 27R after the March 14-15 traction evaluation. A 1 1/2 x 1/4 x 1/4-inch groove pattern was selected. Grooving of Runway 27L commenced on April 9 and was completed on May 2, 1973. Grooving of Runway 27R was started on May 7 and completed on May 23, 1973. A rubber removal program for Runways 27L and 27R was initiated by the Dade County Port Authority and timed to take place along with grooving operations such that the grooving machine always operated on freshly cleaned asphalt. The rubber removal program employed equipment using high pressure (6000 psi) water jets.

1.2 The Dade County Port Authority, in a letter dated May 3, 1973, requested NASA to re-evaluate Runways 27L and 27R at Miami International Airport so that the improvement in traction characteristics of the runway surfaces after grooving could be established. A NASA/FAA team conducted the requested evaluation on May 8-9, 1973.

2.0 TEST EQUIPMENT

The equipment used to evaluate the Miami runways consisted of the NASA Diagonal-Braked Vehicle (DBV), ASTM smooth tread test tires, portable wind and temperature measuring instruments, three portable transceivers for communications, a NASA grease kit to obtain a measure of runway surface texture depth, two NASA water depth gages, water tank trucks furnished by the Dade County Port Authority, and a radio equipped operations car.

3.0 RUNWAYS

Tests were conducted in March on Runways 9R/27L, 9L/27R, and 12/30; and in May on Runways 9R/27L and 9L/27R. The two east-west runways had been resurfaced in November 1972 with a 6-inch asphalt overlay using local limestone aggregate. Before the 1972 overlay, some portions of Runway 9R/27L consisted of 30-year-old asphalt as was also the case for the middle portion of Runway 12/30. The oldest portions of Runway 9L/27R before the 1972 overlay consisted of 20-year-old asphalt. The aggregate for the old asphalt surfaces was also local limestone.

3.1 The 1972 asphalt overlays at Miami International Airport were constructed according to the latest FAA standard specification which incorporated Corps of Engineers requirements, including a field asphalt density of no less than 98 percent or more than 100 percent of a laboratory density. In order to meet this density requirement, heavy vibratory rollers had to be used at Miami. The previous FAA asphalt density requirement (used up to 1968) was 92 percent of a theoretical density (equivalent to 95-97 percent of a laboratory density). For this older requirement, satisfactory compaction (asphalt density) was obtained by use of conventional non-vibratory rollers.

3.2 The use of heavy vibratory rollers during compaction of the asphalt overlays on Runways 9R/27L and 9L/27R tended to depress the limestone aggregate in the pavement surface leaving these runways with a smooth surface finish. These surfaces tended to be planar with random shallow holes rather than planar with asperities projecting above the surface (aggregate partially exposed). This type of surface finish for the new asphalt overlays was in sharp contrast to the 30-year-old asphalt surface in the middle of Runway 12/30. Here, the combination of a lower asphalt density requirement (conventional non-vibratory rollers used) and the effects of 30 years of weathering and aircraft traffic left this asphalt surface with a substantial macrotexture and partial exposure of the limerock aggregate. The aircraft touchdown areas on the runways at Miami International Airport were heavily coated with rubber deposits resulting from aircraft tire spin-up at touchdown during landings under dry pavement conditions.

3.3 The new asphalt overlays at Miami were constructed with a substantial crown to improve water drainage during times of precipitation. On either side of the runway centerline, the transverse gradient of the pavement was 1 percent for the first 25 feet of run. From this point to the runway edge (75 feet), the transverse gradient varied between 1 1/2 - 2 percent.

3.4 Grooving of Runways 9R/27L and 9L/27R at Miami was started on April 9 and completed on May 23, 1973. The runways were transversely grooved from end to end and to within 10 feet of the edges of the 200 feet wide runways using a 1 1/2 x 1/4 x 1/4-inch groove pattern. Two diamond-saw type grooving machines (≈ six foot arbor) were used to groove the runways. Grooving operations were conducted at night during low traffic periods with the runway closed. The runway being grooved was re-opened to airport traffic after the newly grooved runway section was water flushed of the slurry created by grooving at approximately 11:00 a.m. each day. High pressure water jet equipment was used to remove rubber deposits from the runway surface before each night's grooving operation took place.

4.0 TEST PROCEDURE

The evaluation consisted of surveying the runway for rubber deposits, determining the pavement surface texture, and conducting DBV braking stops from 60 m.p.h. under wet and dry conditions to establish the traction characteristics of the runway surfaces.

4.1 Runways 9R/27L and 9L/27R were traversed end to end, and the areas which were contaminated with rubber deposits were established. This survey was conducted during the March DBV tests and represents the rubber accumulation on the runways since November 1972. Figures 1 and 2 show the results of this survey and the layout of the DBV test zones for Runways 9R/27L and 9L/27R, respectively. The runways were not re-surveyed for rubber deposits during the May DBV tests because the runways had just been subjected to a rubber removal program, and the rubber-coated areas on the runway had not stabilized in length. Typical photographs of the pavement surface in each test zone (before grooving) are shown in figure 3. Typical photographs of the pavement surface after grooving (May tests) are shown in figure 4.

4.2 A measurement of the surface texture depth was made for each of the runway test zones evaluated during the March DBV tests. This was accomplished by means of the NASA grease test which entailed spreading a known volume of grease between parallel tapes spaced 4 inches apart on the test zone surface. The length of the surface between the tapes required for the grease to fill all the asperities, divided into the known volume of grease used, yielded the average texture depth of the pavement surface. The results of these measurements are shown in table I.

4.3 During the March DBV tests, a single 2000 gallon water truck equipped with a gravity feed spreader bar (see figure 5) wetted a path approximately 10-feet wide and 1000-1500 feet long, depending upon the rubber contamination, by making two and sometimes three passes over the test zone. More than one pass with this water truck was necessary since the gravity water flow system employed could not put out sufficient water in one pass to adequately wet the test surface. Average water depths on the pavement surface at time of DBV run resulting from this wetting technique ranged between 0.006 inches and 0.045 inches for the March DBV tests as shown in tables II and III. In the May DBV tests, the same water truck and wetting technique used in the March tests was employed to wet ungrooved test zone D of Runway 9L/27R. This resulted in average water depths at the time of DBV runs of between 0.035 and 0.045 as shown in table IV. All other DBV wet runs conducted during the May tests employed multiple water truck wetting (see figure 6) where additional water trucks (up to three) obtained from the grooving contractor were used in trail to increase the water coverage in the runway test zones. The increased water volume was required to provide sufficient wetness on the surfaces of the grooved runway test zones. As shown in tables V and VI, this technique resulted in a damp to puddled wetness condition on the grooved runway test sections. The increased water volume from this wetting technique substantially increased the water depths present at time of DBV test in the ungrooved test areas of zone B, Runway 9L/27R to 0.05-0.06 inches (see table VI). The single water truck wetting performed in this test zone during the March 15 tests yielded water depths of 0.006-0.019 inches. It should be noted that the wetted strip in a test zone was always placed on the "up-wind" side of the runway center line during both the March and May DBV tests to insure maximum runway wetness at time of test run.

4.4 As soon as the water truck(s) made the final wetting pass and cleared the test area, the DBV was accelerated to a speed slightly above or near 60 m.p.h. Just before entering the test zone, the transmission was placed in neutral gear. The DBV then coasted into the wetted test zone where upon the driver sharply applied brakes, locking the diagonal pair of wheels equipped with smooth tread ASTM test tires. At approximately 50 lb/inch pressure in the wheel brakes, circuits to the digital speed meter and the digital stopping distance counter were energized. These circuits held the DBV speed at brake application constant in the speedmeter and started the stopping distance counter to measure stopping distance from the brake application point. The speed at brake application and the stopping distance from this brake application speed were visually read from these instruments by the driver/observer when the DBV came to a complete stop in the test section. Other instrumentation on board the DBV measured the angular velocity of each DBV main wheel, the angular velocity of the trailing test (fifth) wheel, and the longitudinal acceleration of the DBV. These parameters were recorded on a direct writing recorder equipped with an accurate timer in the DBV so that a permanent record and time history of the variation of these parameters during a test run could be obtained. Other parameters manually recorded during a test run included time of day, wind speed and direction, pavement water depth, DBV test heading, and ambient air temperature (see tables II-VI).

5.0 DATA ANALYSIS AND RESULTS.

The data obtained from the DBV tests conducted in March (before grooving) and May 1973 (after grooving), at Miami International Airport were analyzed from pavement drainage, ASTM smooth tread tire braking friction μ_{skid}, and DBV stopping distance ratio points of view. Details of these analyses and the results obtained are presented in this section of the paper.

5.1 Ungrooved Pavement Drainage.- A very comprehensive study on the effects of rainfall intensity, pavement cross-slope, surface texture, and drainage length was recently performed at the Texas Transportation Institute of the Texas A&M University under laboratory conditions (still air) using simulated rain making equipment (reference 1). In this research, the following equation was developed to predict water depths on ungrooved highway pavements.

$$d = \left[3.38 \times 10^{-3} \left(\frac{1}{T}\right)^{-.11} (L)^{.43} (I)^{.59} \left(\frac{1}{S}\right)^{.42}\right] - T \qquad \text{(equation 1)}$$

where d - water depth standing above top of texture, in.
T = average texture depth, in.
L = drainage path length, ft.
I = rainfall intensity, in./hour
S = cross-slope, ft./ft.

Equation 1 was based on water depth measurements obtained on the nine different pavement surfaces described in table VII.

5.1.1 The British Road Research Laboratory conducted a similar study (reference 2) on two extremely course textured pavement surfaces: a brushed concrete surface (texture depth = 0.072) and a rolled asphalt with chippings surface (texture depth = 0.095). The British found no effect of texture depth for these surfaces and developed the following equation for predicting water depths on pavements in still air:

$$d = \frac{0.005\ (LI)^{0.47}}{S^{0.20}} \qquad \text{(equation 2)}$$

where d = water depth (in.)
I = rainfall intensity (in./hour)
L = drainage path length (ft.)
S = slope (ft./ft.)

5.1.2 Figure 7 shows the comparison between the water depths predicted from equations 1 and 2 and the actual water depths obtained during natural rain on two concrete runways having a cross-slope of $\frac{1}{100} \frac{(ft)}{(ft)}$ and an average texture depth (NASA grease test) = 0.004 for rainfall intensities ranging from 0.005 to 1.5 inches/hour. It should be noted that the natural rain on the runways was accompanied by surface winds while the predictions of equations 1 and 2 are for laboratory (still air) conditions. Figure 7 compares the experimental water depth data with predicted water depths for a drainage path length of 10 feet which was the approximate distance from the runway centerline to the water depth measuring points. This distance (10 feet) also corresponds to the approximate main landing gear wheel position for several jet transports (see table VIII) if the aircraft are rolling alined with the runway centerline. It will be noticed that the predicted water depths tend to be considerably less than the actual water depths measured for this drainage path length condition which ignores the effect of winds. Using a drainage path length of 200 feet (figure 7) gives much better correspondence between predicted and experimental water depth values. The actual drainage path directions occurring during natural rainfalls are determined by the vector sum of the wind and gravitational forces acting on the water-covered surface, and a 200 feet drainage path length may not be unreasonable for certain cross slope, longitudinal slope, and wind direction/speed conditions.

5.1.3 A large effect of surface winds on ungrooved pavement drainage was also noted in the May 9 tests on Runway 9L/27R, zone B. In these tests, multiple water trucks were used to wet the upwind side of the runway in the presence of a quartering wind (10 knots/165 degrees). This cross wind was strong enough to prevent water drainage against the wind down the cross slope of the runway, and the water depths in the wetted ungrooved test zone remained constant from approximately 0.05 to 0.06 inches during the DBV test period (4 to 5 minutes) after wetting.

5.1.4 It is concluded from these observations (5.1 to 5.1.3) that wind effects can strongly affect the drainage of water from ungrooved pavements, and that the Texas Transportation Institute and British Road Research Laboratory equations for predicting water depths on ungrooved pavements are valid only for still air conditions.

5.2 Grooved Pavement Drainage.- Grooving pavements increases the average texture depth of the surface as shown in figure 8(b). If the ungrooved texture depth of the pavement is known, then the grooved texture depth of the pavement may be estimated from the equation (derived in figure 8(b)).

$$T_G = \frac{T\ (P-2\ W)\ +\ WD}{P} \qquad \text{(equation 3)}$$

where T_G = grooved pavement texture depth, in.
T = ungrooved pavement texture depth, in.
P = groove pitch, in.
W = groove width, in.
D = groove depth, in.

Using the TTI water depth equation (equation 1), still air water depths were calculated for a cross slope 1/100 (Miami runway design), drainage path length = 10 feet, pavement texture depths ranging from .005 to .100 inches, and for rainfall intensities ranging from 0-6 inches/hour. These results are plotted in figure 8(a). Figure 8(a) may be used with figure 8(b) to demonstrate the improved water drainage resulting from pavement grooving. For example, these plots indicate that standing water will develop on a ungrooved pavement having a average texture depth = 0.02 in. when the rainfall intensity reaches 0.32 inches/hour. Grooving this pavement to a 1 1/2 x 1/4 x 1/4-inch groove configuration increases this pavement's average texture depth to 0.0545 inches, and standing water develops at a rainfall intensity of approximately 1 inch/hour, thus showing a considerable improvement in pavement drainage from grooving.

5.2.1 Actually, the TTI equation considerably underestimates the improved pavement drainage from grooving as the following arguments illustrate. Grooving the pavement with machines using diamond equipped cutting blades produces polished groove channels which considerably decreases fluid flow resistance in the grooves as compared with the flow resistance through the pavement texture. In addition, as soon as water depths develop in the groove channels, a small pressure head from the water depth present tends to accelerate water escape through the channel increasing pavement drainage. Finally, water flow in the pavement grooves is not disturbed by surface wind effects as is water draining through or on top of the ungrooved pavement texture. The total result of these grooving effects on water drainage is to dramatically improve the drainage characteristics of the pavement as shown in figure 6. This figure shows that the grooved wetted test section was completely drained of standing water 25 seconds after wetting, whereas the same pavement ungrooved still retained 0.05 - 0.06 inches of standing water 4-5 minutes after wetting (see paragraph 5.1.3). This is an improvement in drainage time of at least 12 fold.

5.2.2 It is concluded that grooving the Miami runways to a 1 1/2 x 1/4 x 1/4 inch pattern has greatly improved runway pavement drainage, especially under rainfall conditions accompanied with wind. Chiefly responsible for this improvement is the fact that as long as the grooves are not flowing full, the grooves force the draining water to take a minimum drainage path length (the groove channels). Water drainage in the groove channels is shielded from the surface winds, and water flow is accelerated (over water flow through or on top of the pavement surface texture) by increased flow depths and decreased flow resistance. It is estimated that the groove channels will not choke (develop standing water on the pavement surface) until natural rainfall intensities of at least 2-3 inches/hour are reached. Thus, aircraft operating problems resulting from spray ingestion and dynamic hydroplaning on flooded runways at Miami will be greatly reduced because such high rainfall intensities required to flood the grooved pavement are infrequently encountered during most rainstorms.

5.3 ASTM smooth tread tire braking friction coefficient, μ_{skid}.- As mentioned in paragraph 4.4, permanent record time histories were obtained for the DBV ground speed (from the trailing bicycle wheel instrumentation) from the point of brake application to the vehicle stopping point for each DBV run. Typical velocity time histories obtained from the test records are presented in figures 9-11 for wet runway tests and figure 12 for dry runway tests. The time history data presented in these figures has been normalized to a velocity zero/time zero base for each test run by subtracting the record time at each velocity reading from the total time required to bring the DBV from brake application speed (immediately after diagonal-wheel lockup) to a complete stop (velocity zero).

5.3.1 The deceleration encountered by the DBV during a diagonal-braking stop is obtained by measuring the slope $(\frac{dv}{dt})_{vehicle}$ of the velocity-time curves shown in figures 9-12 between adjacent velocity readings. The ASTM smooth tread tire braking friction coefficient μ_{skid} may be obtained from these slope measurements by means of the equation

$$\mu_{skid} = 2\left[(\frac{dv}{dt})_{vehicle} - (\frac{dv}{dt})_{tare} - \chi\right] \qquad \text{(equation 4)}$$

where $(\frac{dv}{dt})_{vehicle}$ DBV braking deceleration, g

$(\frac{dv}{dt})_{tare}$ DBV unbraked deceleration, g

χ incremental DBV deceleration due to longitudinal runway gradient, g

μ_{skid} locked-wheel braking friction coefficient

The DBV unbraked deceleration, $(\frac{dv}{dt})_{tare}$, variation with speed is shown in figure 13(a) and is attributed to air resistance, unbraked tire rolling resistance, and transmission drag effects. Figure 13(b) shows the calculated effect of head or tail winds on the DBV unbraked deceleration with speed. At 60 m.p.h. the curves indicate that a 10 knot head/tail wind increases/decreases the DBV unbraked deceleration by approximately 0.007g. The incremental DBV deceleration due to longitudinal uphill runway gradients increases approximately 0.01g for each 1 percent increase in longitudinal gradient. For longitudinal downhill gradients, the sign of χ must be reversed because the gravitational component now imposes an acceleration to the DBV. For the purposes of this analysis (Miami longitudinal gradient ≈ 0), wind and runway longitudinal gradient effects can be ignored with little loss in accuracy, thus simplifying the calculation of μ_{skid}.

5.3.2 Using the procedure described in paragraph 5.3.1, values of ASTM smooth tread tire braking friction coefficient μ_{skid} were calculated from the DBV normalized time histories given in figures 9-12 and are plotted against speed in figures 14-16.

5.4 Pavement skid resistance.- Research performed at NASA and elsewhere concur in that pavement wet skid resistance is highly dependent upon the macrotexture and microtexture of a pavement surface. Tire/ground friction losses that occur on wet pavements result from the development of viscous and dynamic water pressures under the rolling or sliding tire footprint as vehicle or aircraft speeds increase. Only very thin unbroken water films need to be present on a smooth pavement surface for viscous hydroplaning to occur at the higher speeds. A good sharp pavement surface microtexture (like gritty sand paper) can puncture and displace the thin water film trapped in the tire footprint and thus prevent or greatly alleviate the buildup of viscous water pressures with speed that create this type of friction loss. Standing water on the pavement must be present for dynamic water pressures to be developed under the tire footprint. This type water pressure develops with the square of the vehicle speed and creates the well known phenomenon called tire dynamic hydroplaning unless alleviated by the pavement macrotexture. A good pavement macrotexture has hills and valleys produced by the protruding aggregate exposed in the pavement surface over which the tire drapes during the rolling or sliding process. Drainage channels are thus formed in the valleys of the pavement macrotexture which allows bulk water trapped in the tire footprint to escape and thus alleviate the development of dynamic water pressures with increasing vehicle speed and reduce this type of friction loss.

5.5 Skid resistance-Runway 9L/27R.- The clean ungrooved asphalt surface of Runway 9L/27R (zone B) had an average texture depth of 0.017 inches (see table I) from the NASA grease test. This surface is comparable in texture depth to surface four of the TTI drainage study (reference 1) described in table VII. This relatively low value of average texture depth indicates that the zone B pavement surface has a small macrotexture and possible poor tire/pavement drainage under standing water conditions. This point of view is supported by the μ_{skid} data obtained on this surface shown in figure 16. These data indicate that the ungrooved pavement skid resistance decreases with increasing water depth and speed. Aircraft and ground vehicles operating on this surface at high speeds will therefore encounter dynamic hydroplaning when standing water develops on this surface during rainstorms. Grooving this pavement to an 1 1/2 x 1/4 x 1/4-inch pattern considerably reduces the μ_{skid} speed gradient as shown in figure 16, indicating that the pavement grooves have greatly alleviated the susceptability of this surface to dynamic hydroplaning effects.

5.5.1 Rubber deposits on Runway 9L/27R tend to reduce both the ungrooved pavement macrotexture and microtexture. The macrotexture loss is shown clearly in table I where the average texture depth decreases from 0.017 inch (clean asphalt) to 0.006 inch in the heavy-rubber-coated touchdown area. This reduction in macrotexture makes the rubber-coated ungrooved surface more susceptible to dynamic hydroplaning effects as reflected by the lower high speed friction coefficients (figure 14) developed on this surface compared to the high speed friction coefficients of the ungrooved clean surface (figure 16). The loss in pavement microtexture from rubber deposits cannot be ascertained from the NASA grease test, but (according to the discussion of paragraph 5.4) may be inferred from pavement skid resistance losses that occur at low vehicle speeds where dynamic hydroplaning (V^2 law) effects are small or negligible. Comparison of the μ_{skid} values at low speeds for the clean ungrooved surface (figure 16) with the low speed μ_{skid} values for the ungrooved rubber coated surface (figure 14) clearly shows a large drop in skid resistance for the rubber-coated surface. This loss is increased with increased amounts of rubber deposits as shown in figure 14. It is evident from these data that rubber contamination of the pavement tends to reduce the surface microtexture and makes the pavement more susceptible to viscous hydroplaning effects.

5.6 Skid resistance-Runway 9R/27L.- Figure 15 shows the variation of μ_{skid} with speed for the four clean and rubber contaminated areas of Runway 9R/27L tested by the DBV before and after grooving under wet and dry conditions. These data for the ungrooved surfaces show the same trends with regard to macrotexture and microtexture effects as just described (paragraph 5.5) for Runway 9L/27R. The increase in skid resistance for the grooved clean asphalt surface as compared with ungrooved surface (figure 15c) also shows the same trends as found for the clean asphalt grooved and ungrooved surfaces of Runway 9L/27R (figure 16). The main point to be discussed with figure 15 is the effect of rubber contamination on the wet id resistance of the grooved pavement. Figure 4 shows that the lands between the grooves of the grooved pavement in zone D are heavily-coated with rubber and the microtexture of the lands is very smooth. The grooved pavement μ_{skid} curve on heavy rubber (figure 15A) shows considerably less skid resistance with speed than that found for the clean grooved surface (figure 15(c)), although a substantial improvement is indicated over the ungrooved rubber-coated surface. This result suggests that the 1 1/2 x 1/4 x 1/4-inch groove pattern cannot completely restore or take the place of pavement microtexture. As a result, friction losses due to viscous hydroplaning effects must be expected on grooved pavements having no appreciable microtexture on the lands between the grooves. It is not expected that the wet skid resistance of the grooved surface of zone D of Runway 9R/27L will decrease much more than that shown in figure 15(A). However, it is expected that the other rubber-contaminated areas of Runway 9R/27L (zones B & D) will decrease to the skid resistance level of zone D upon further rubber deposit accumulation. This observation suggests that periodic rubber removal programs may be required on the touchdown areas of the grooved runways at Miami to restore the pavement microtexture when the rubber-coated areas become extensive in length.

5.7 The comparison of the skid resistance of clean grooved and porous pavement surface treatments obtained under wet and dry conditions by the DBV is shown in figure 17. This comparison indicates that 1 1/2 x 1/4 x 1/4-inch groove pattern used at Miami International Airport compares favorably with both the 1 x 1/4 x 1/4-inch groove pattern used at Beale AFB, and the porous asphalt surface used at Marham RAFB, England. On these latter two surfaces, a C-141 jet transport developed near dry stopping performance when tested under the same wet runway braking conditions of the DBV test.

5.8 DBV stopping distance ratio (SDR).- The NASA developed DBV SDR method for estimating the slipperiness of airport runways is extremely simple in concept and easily obtainable from DBV wet and dry pavement stopping distance measurements. Correlation tests performed with several jet transport type aircraft indicate that the DBV SDR reasonably predicts the aircraft SDR up to DBV SDR's of approximately 2.0 for many wet runway surfaces. The NASA method is based on a DBV brake application speed of 60 m.p.h. Usually, the DBV will not be at exactly 60 m.p.h. when brakes are applied, and the test stopping distance obtained is corrected to the 60 m.p.h. base by means of the equation

$$S_B = \frac{3600}{V^2_{B\ (test)}} S_{B\ (raw)} \qquad \text{(equation 5)}$$

where

S_B - DBV stopping distance (V_B = 60 m.p.h), ft

$S_{B\ (raw)}$ - DBV stopping distance at $V_{B\ (test)}$, ft

$V_{B\ (test)}$ DBV test brake application speed, m.p.h.

The DBV SDR is obtained from the equation

$$SDR = \frac{S_{B\ (wet)}}{S_{B\ (dry)}} \qquad \text{(equation 6)}$$

where

$S_{B\ (wet)}$ - DBV wet pavement stopping distance corrected to 60 m.p.h. base (equation 5), ft

$S_{B\ (dry)}$ - DBV dry pavement stopping distance corrected to 60 m.p.h. base (equation 5), ft

Tables II-VI list the raw stopping distances and brake application speeds obtained for the DBV runs made during the March (before grooving) and May (after grooving) tests at Miami International Airport. Also shown in tables II-VI are the corrected DBV stopping distances (equation 5) and the SDR values obtained from equation 6.

5.8.1 Reference 3 developed a method for estimating the average DBV SDR for a given aircraft landing condition on a wet runway. This method is illustrated in figure 18 (obtained from reference 3). At the present time no federal standards for acceptable or unacceptable levels of runway slipperiness exist for civil airports in this country. However, the present Federal Aviation Regulations for aircraft landing certification (FAR-25.125), and aircraft landing operation (FAR-121.195) may be used to obtain a reference runway slipperiness level.

5.8.1.1 Using the aircraft landing terminology shown in figure 18, the aircraft dry landing distance, S_L, is determined from dry landing certification tests (without use of reverse thrust) in accordance with Federal Aviation Regulation (FAR-25.195). The Federal Aviation Regulation landing operational rule (FAR-121.195) increases this dry landing distance, S_L, by the factor 1.667 to arrive at the aircraft dry landing field length, S_{FAR}. For jet transport operation on wet runways, FAR-121.195 arbitrarily increases S_{FAR} by an additional 15 percent or by a factor of 1.15. Thus, the aircraft certification dry landing distance S_L is increased by the factors 1.667 x 1.15 = 1.92 to obtain the jet transport wet runway field length, $S_{FAR\ (wet)}$. Using the terminology of figure 18, each segment comprising the certification dry landing distance S_L may be individually increased by the factor 1.92 to obtain the wet landing field length $S_{FAR\ (wet)}$

$$S_{FAR\ (wet)} = 1.92\ S_A + 1.92\ S_T + 1.92\ S_B \qquad \text{(equation 7)}$$

Since S_B in equation 7 is the aircraft certification dry runway braking distance, 1.92 S_B is the equivalent of an aircraft SDR = 1.92. Thus, the present Federal Aviation Regulation (FAR-121.195) governing jet transport landings on wet runways makes allowance for a runway slipperiness level equivalent to SDR = 1.92.

5.8.1.2 The DBV on a level runway under zero wind conditions requires approximately 3900 feet to coast to a stop from 60 m.p.h. in an unbraked condition due to the relatively small decelerations acting on the DBV resulting from air resistance, unbraked tire rolling resistance, and transmission drag (see figure 12). This test condition is equivalent to a pavement skid resistance of zero (μ_{skid} = 0) and results in a DBV SDR ≈ 12.7. Pavements with high skid resistance under wet conditions develop DBV SDR values near 1.0 while pavements with low skid resistance in the wet tend to produce higher SDR values that approach the zero friction boundary SDR ≈ 12.7. The highest DBV SDR values encountered in runway evaluations up to the time of the present tests were obtained on a wet asphalt surface and a hard packed snow-covered surface. The wet asphalt surface studied was a heavily rubber-coated tar seal coat with granite chips (3/16 in-minus) rolled into hot tar and heavily broomed. The average texture depth for this surface (NASA grease test) was 0.0039 in.

When artifically wetted (water depth ≈ 0.02 in.) and tested with the DBV, an SDR = 4.05 was obtained. The dry compacted snow-covered concrete ramp studied was tested by the DBV and a C-141 jet transport (reference 3). On this surface, the DBV obtained an SDR = 4.16 and the C-141 aircraft an SDR = 3.71. It thus can be seen that smooth runway surfaces when covered with small amounts of water can be as slippery to aircraft and ground vehicles as runways covered with compacted snow or ice.

5.8.2 DBV SDR evaluation of Miami International Airport runways before and after 1972 asphalt overlay.- Table IX shows the comparison of DBV SDR measurements obtained on Runways 9R/27L and 9L/27R before and after the 1972 asphalt overlays. These data indicate that the new asphalt overlay surfaces tended to be more slippery when wet than the old surfaces they replaced. Also shown in table IX are Mu-Meter friction reading values obtained before and after the 1972 asphalt overlays. The Mu-Meter friction readings, especially on Runway 9L/27R, does not show this trend and indicate a directly opposite trend--that the new asphalt overlay surface on Runway 9L/27R was a superior wet friction surface to the old asphalt surface it replaced.

5.8.3 DBV SDR evaluation of Miami International Airport runways before and after grooving.- Table X shows the DBV SDR comparison for Runways 9L/27R and 9R/27L before and after grooving. These data are in good agreement with the trends shown from the ASTM braking friction coefficient, μ_{skid}, analysis of these surfaces performed in paragraphs 5.3-5.7. The DBV SDR tends to increase with decreasing values of μ_{skid}. The improved skid resistance of the grooved wet pavements noted in the μ_{skid} analysis over the ungrooved pavement μ_{skid} values is reflected in table X by correspondingly lower DBV SDR values.

5.8.4 Average DBV SDR for Runway 9R/27L before and after grooving.- The runway survey, described in paragraph 4.1, indicated the following lengths for the DBV test zones on Runway 9R/27L for March 14, 1973:

Zone	Length, ft
A	3000
B	3200
C	1150
D	2000

Using the highest DBV SDR values found for these test zones in table II (before grooving) and table V (after grooving), the average DBV SDR for Runway 9R/27L was computed according to the method described in figure 18. The results obtained are shown in table XI. The data shown in this table indicate that Runway 9R/27L before grooving was more slippery than the reference wet runway developed in paragraph 5.8.1.1., while the runway after grooving was less slippery than the reference wet runway. It should be noted that by using the zone lengths measured in March 1973, a very conservative average DBV SDR is obtained in table XI for the grooved runway. This results from the fact that the rubber deposits on Runway 9R/27L were removed at the time of grooving. The length of the rubber deposits observed but not measured during the May DBV tests (after grooving) were much shorter than those found during the March survey, which represented an approximately 4-month rubber accumulation period (since the November 1972 overlay). Research at the NASA landing loads track indicates a trend for aircraft tire spin-up at touchdown to occur in a shorter time period for a grooved runway than for an ungrooved runway. Thus rubber deposits from an aircraft touchdown on a grooved runway should be at least shorter in length than those found on an ungrooved runway for similar landing conditions. It is anticipated, therefore, that the average SDR of 1.71 found for Runway 9L/27R in table XI will not be reached until September-October 1973 when the rubber deposits on the runway should then approximate the March 14, 1973, survey condition.

5.8.5 Average DBV SDR for Runway 9L/27R before grooving.- The runway survey, described in paragraph 4.1, indicated the following lengths for the DBV test zones on Runway 9L/27R for March 14, 1973.

Zone	Length, ft
A	1700
B	4800
C	1000
D	3000

Using the highest DBV SDR values found for these test zones in table III (before grooving), the average DBV SDR for Runway 9L/27R was computed according to the method described in figure 18. The results obtained are shown in table XI. The data shown in this table indicate that Runway 9L/27R before grooving was more slippery than the reference wet runway developed in paragraph 5.8.1.1 when tested in an artifically wetted condition. An average DBV SDR for Runway 9L/27R (after grooving) could not be computed because grooving of the runway had not been completed at the time of the May 8-9 DBV tests.

6.0 CONCLUDING REMARKS

Runways 9R/27L and 9L/27R were evaluated under artifically wetted conditions with the NASA DBV before and after grooving the runway surfaces to a 1 1/2 x 1/4 x 1/4-inch groove pattern. Results of the evaluation which included a pavement drainage analysis, a pavement skid resistance analysis, and a DBV wet/dry stopping distance ratio (SDR) analysis yield the following general observations:

1. The construction techniques employed in laying the November 1972 asphalt overlays on runways 9R/27L and 9L/27R resulted in obtaining a smooth surface finish on these runways with adequate microtexture, but rather small macrotexture.

2. The drainage analysis indicated that the ungrooved runway surfaces were slow draining under wet conditions, specially in the presence of surface winds. In contrast, the grooved pavements drained rapidly under wet conditions even in the presence of surface winds.

3. The pavement skid resistance analysis indicated the following:

(a) The high speed skid resistance of the wet ungrooved runway surfaces was low under wet conditions indicating poor internal water drainage at the tire/pavement-surface-macrotexture.

(b) The low speed skid resistance of the wet ungrooved runway surfaces was high in areas of the runway uncontaminated with rubber deposits, and low in the touchdown areas that were heavily contaminated with rubber deposits.

(c) Grooving the runways decreased the μ_{skid} speed gradient at high speeds, and substantially raised the high speed skid resistance of the runway surfaces under wet conditions.

(d) Grooving the runways improved the low speed skid resistance of the wet pavements in the heavy rubber contaminated areas.

(e) Grooving the pavements did not change the skid resistance of the surfaces under dry conditions.

4. The DBV SDR analysis indicated the following:

(a) Vehicle stopping performance was poor on wet ungrooved runway surfaces that were heavily contaminated with rubber. The SDR values measured on such surfaces were of the same order of magnitude as SDR values measured on snow- and ice-covered runways.

(b) Vehicle stopping performance was greatly improved on wet grooved clean asphalt runway surfaces and approached the vehicle stopping performance obtained under dry pavement conditions.

(c) Vehicle wet stopping performance was considerably improved when the heavy rubber coated touchdown areas of the runway were grooved (SDR = 2.5 grooved compared with SDR = 4.62 ungrooved), but the reduced slipperiness level from grooving still exceeded the slipperiness level of the reference wet runway (SDR = 1.92). This result indicates periodic rubber removal programs may be required to restore the pavement microtexture when the rubber deposits on the runways become extensive in area.

7.0 REFERENCES

7.1 Galloway, R.M., Schiller, R.E., Jr., and Rose, Jerry G.: The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths. Research Report No. 138-5. Vehicle-Pavement Interaction Research Study No. 2-8-69-138, May 1971. Texas Transportation Institute, Texas A&M University, College Station, Texas.

7.2 Ross, N.F. and Russam, K.: The Depth of Rain Water on Road Surfaces. Ministry of Transport, Road Research Laboratory, Report LR 236, Great Britain, 1968.

7.3 Yager, T.J., Phillips, W.P., and Horne, W.B., Langley Research Center, and Sparks, H.C., Aeronautical Systems Division, Wright-Patterson AFB: A Comparison of Aircraft and Ground Vehicle Stopping Performance on Dry Wet, Flooded, Slush-, Snow-, and Ice-Covered Runways. Final Report on Project Combat Traction, A Joint USAF-NASA Program. NASA TN D-6098. November 1970.

TABLE I.- Ungrooved pavement average texture depths at Miami International Airport March 14-15, 1973 (obtained from NASA grease test).

RUNWAY	ZONE	GREASE AREA	AVERAGE TEXTURE DEPTH, INCHES
9R/27L	A	$9.25 \times 4 = 37$ IN^2	.013
	B	$6.75 \times 4 = 27$ IN^2	.018
	C	$7.5 \times 4 = 30$ IN^2	.016
	D	$16.75 \times 4 = 67$ IN^2	.007
9L/27R	A	$11 \times 4 = 44$ IN^2	.011
	B	$7 \times 4 = 28$ IN^2	.017
	C	$6.25 \times 4 = 25$ IN^2	.019
	D	$20.375 \times 4 = 81.5$ IN^2	.006
12/30	MIDDLE	$2.75 \times 4 = 11$ IN^2	.044

VOLUME OF GREASE USED = 0.486 IN^3

$$\text{TEXTURE DEPTH} = \frac{\text{VOLUME}}{\text{AREA}}$$

TABLE II.- DBV stopping distance data obtained on Runway 9R/27L (before grooving) March 14, 1973, asphalt surface, Miami International Airport (single water truck wetting).

TEST ZONE	HEADING	SURFACE CONDITION	RUN NO.	VBg MPH	RAW SB FT.	CORRECTED SB FT.	INTEGRATED SB FT.	SDR	AVG WATER DEPTH AT DBV STOP	TIME OF DAY	WIND VELOCITY KTS	WIND DIRECTION DEG.	OAT °F
A	27	WET	1A	59.9	1086	1089	1102	3.51	.026	0844	6-8	120/140	75
	9		2	58.9	946	981	-	3.16	.020	0845			
	27		3	59.2	1007	1034	-	3.33	.010	0848			
	9		4	59.9	1015	1018	-	3.28	.010	0849			
B	27		5	58.1	669	713	-	2.34	.034	0909	10-12	140	83
	9		6	59.2	753	773	-	2.53	.020	0910			
	27		7	60.7	639	624	-	2.04	.010	0913			
	9		8	60.4	707	697	-	2.28	.010	0914			
C	27		9	59.4	754	769	-	2.52	.045	0932	12-15	140	85
	9		10	59.7	727	734	-	2.40	.025	0934			
	27		11	59.6	667	675	-	2.21	.014	0936			
	9		12	58.6	664	695	-	2.28	.010	0938			
D	27		13A	61.1	1475	1422	1525	4.62	.027	1006	12-15	140	86
	9		14	59.9	1013	1016	963	3.10	.012	1009			
	27		15	58.9	1349	1399	1449	4.46	.015	1011			
	9		16A	58.9	939	973	1019	3.12	.006	1016			
E	27		17	39.2	147	344	-	1.13	-	1030			
A	27	DRY	18	60.5	315	310	-	-	-	1035	12-15	140	86
B/C	27	DRY	19	60.6	311	305	-	-	-	1038			
D	27	DRY	20	60.1	320	319	-	-	-	1040			

TABLE III.- DBV stopping distance data obtained on Runways 9L/27R and 12/30 (before grooving) March 15, 1973, asphalt surfaces, Miami International Airport (single water truck wetting).

TEST ZONE	HEADING	SURFACE CONDITION	RUN NO.	VBg MPH	RAW SB FT.	CORRECTED SB FT	INTEGRATED SB FT.	SDR	AVG WATER DEPTH AT DBV STOP	TIME OF DAY	WIND VELOCITY KTS	WIND DIRECTION DEG.	OAT °F
A	27	WET	1	60.1	633	631	-	2.15	.022	0731	9-10	130/140	78
	9		2	60.8	697	679	-	2.32	.015	0732			
	27		3	58.7	668	698	-	2.38	.016	0738			
	9		4	60.7	735	718	-	2.45	.010	0740			
B	27		5	59.5	519	528	-	1.78	.019	0755	8-10	120/130	78
	9		6	59.9	540	542	-	1.83	.010	0757			
	27		7	60.0	519	519	-	1.75	.008	0759			
	9		8	60.1	512	510	-	1.72	.006	0801			
C	27		9	59.9	678	680	-	2.29	.035	0829	7	160	80
	9		10	58.4	605	637	-	2.15	.023	0830			
	27		11	58.8	568	591	-	1.99	.010	0832			
	9		12	60.1	586	584	-	1.97	.010	0834			
D	27		13	58.2	1064	1131	-	3.59	.042	0851	10	130	81
	9		14	59.7	979	989	-	3.14	.020	0854			
	27		15	59.1	967	997	-	3.16	.025	0857			
	9		16	60.0	1005	1005	-	3.19	.018	0859			
A	27	DRY	17	60.1	294	293	-	-	-	0911	10	130	81
B&C	27		18	60.6	302	296	-	-	-	0914			
D	27		19	60.8	324	315	-	-	-	0918			
RUNWAY	12/30	15 MARCH 1973											
	12	WET	1	58.3	471	499	-	1.67	.030	1006	10-12	150	83
	30		2	59.2	531	545	-	1.83	.020	1007			
	12		3	58.3	518	548	-	1.84	.015	1013			
	30		4	60.1	566	564	-	1.89	.010	1014			
	12	DRY	5	59.4	291	297	-	-	-				
	30		6	60.9	308	299	-	-	-				

TABLE IV.- DBV stopping distance data obtained in zone D, Runway 9L/27R (before grooving) May 8, 1973, Miami International Airport (single water truck wetting).

ZONE	HEADING	SURFACE	SURFACE CONDITION	RUN NO.	V_{BRAKE} MPH	RAW SB FT	CORRECTED SB FT	SDR	WATER DEPTH, IN.
D	09	RUBBER/COATED ASPHALT	WET	1	60.8	999	972.9	3.09	.05-.03
D	27			2	58.9	808	338.5	2.66	.03-DAMP
D	27			3	61.2/37.4	997	ABORT	-	.05-.03
D	09			4	60.2	1017	1010.3	3.21	.05-.04
D	27			5	59.5	1128	1147.0	3.64	.05-.04
D	09			6	59.6	941	953.7	3.03	.05-.03
D	27			7	60.3	1075	1064.3	3.41	.05-.02

TABLE V.- DBV stopping distance data obtained on Runway 9R/27L (after grooving) May 8, 1973, Miami International Airport (multiple water truck wetting).

ZONE	HEADING	SURFACE	SURFACE CONDITION	RUN NO.	V_{BRAKE} MPH	RAW SB FT	CORRECTED SB FT	SDR	WATER DEPTH, IN.
D	27	RUBBER/COATED ASPHALT	DAMP	8	59.5	754	766.7	2.40	< 0.01
D	09			9	58.0	745	797.3	2.50	
D	27			10	59.3	710	726.9	2.28	
C	27			11	64.1	554	484.5	1.59	
C	09			12	61.2	557	535.4	1.76	
B	27	CLEAN ASPHALT		13	61.6	448	425.0	1.39	
B	09			14	60.0	420	420.0	1.38	
B	27			15	60.2	428	425.0	1.39	
A	27	RUBBER/COATED ASPHALT		16	61.9	544	511.1	1.65	
A	09			17	59.1	401	413.3	1.33	
A	27			18	62.2	506	470.9	1.52	
A	09			19	61.1	486	468.7	1.51	

TABLE VI.- DBV stopping distance data obtained on Runway 9L/27R (before and after grooving) clean asphalt, Miami International Airport (multiple water truck wetting).

ZONE	HEADING	SURFACE	SURFACE CONDITION	RUN NO.	V_{BRAKE} MPH	RAW SB FT	CORRECTED SB FT	SDR	WATER DEPTH, IN.
B	27	GROOVED	DAMP	20	60.9	359	348	1.18	-
↓	27	UNGROOVED	WET	21	61.0	776	751	2.50	0.05
	09	UNGROOVED	WET	22	60.3	746	739	2.46	0.05
	09	GROOVED	DAMP	23	60.4	354	349	1.18	-
	27	GROOVED	DAMP/PUDDLED	24	59.2	361	371	1.25	-
	27	UNGROOVED	WET	25	60.6	779	764	2.55	0.06
	09	GROOVED	DAMP/PUDDLED	26	61.5	440	419	1.42*	-
	09	UNGROOVED		27	59.7	812	820	2.73	0.06
	09	GROOVED	DAMP/PUDDLED	28	60.8	375	365	1.23	-
	09	GROOVED	DRY	29	59.9	295	296	-	-
	09	UNGROOVED	DRY	30	59.2	292	300	-	-

* DBV RIGHT WHEELS RUNNING ON ℄ PAINT

TABLE VII.- Description of pavement surfaces used in Texas Transportation Institute study on pavement drainage (reference 1).

Surface Number	Surface Type	Aggregate Maximum Size, in.	Texas Highway Department Specifications	Average Texture Depth, ** in.
1	Rounded Siliceous Gravel Portland Cement Concrete (Transverse drag)*	3/4	Class A Item 364	0.035
1A	Rounded Siliceous Gravel Portland Cement Concrete (Longitudinal drag)*	3/4	Class A Item 364	0.036
2	Clay Filled Tar Emulsion (Jennite) Seal	No Aggregate	———	0.009
3	Crushed Limestone Aggregate Hot Mix Asphalt Concrete (Terrazzo Finish)	1/2	Type D Item 340	0.003
4	Crushed Siliceous Gravel Hot Mix Asphalt Concrete	1/4	Type F Item 340	0.019
5	Rounded Siliceous Gravel Hot Mix Asphalt Concrete	5/8	Type C Item 340	0.039
6	Rounded Siliceous Gravel Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.141
7	Synthetic Lightweight Aggregate Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.164
8	Synthetic Lightweight Aggregate Hot Mix Asphalt Concrete	1/2	Type L Sp. Item 2103	0.020

*With respect to direction of vehicular travel

**Obtained by Putty Impression Method (31)

TABLE VIII.- DISTANCE BETWEEN MAIN LANDING GEARS FOR SOME JET TRANSPORT TYPE AIRCRAFT.

AIRCRAFT TYPE	DISTANCE BETWEEN MAIN LANDING GEARS, FEET
BAC 1-11	14.25
DC-9	16.42
CARAVELLE SE-210	17.08
B-737	17.17
B-727	18.75
CV-880	18.83
CV-990	19.92
DC-8	20.83
B-707	22.08
B-747	36.08

TABLE IX.- Comparison of traction measurements on Miami International Airport Runways 9R/27L and 9L/27R obtained before and after 1972 asphalt overlays.

RUNWAY	ZONE	DBV SDR		MU-METER FRICTION READING	
		*DEC 1971	MARCH 1973	*DEC 1971	**JAN 1973
9R/27L	A	2.87	3.51	.52	.455
	B	1.59	2.34	.63	.55
	C	--	2.52	--	--
	D	4.64	4.62	.30	.435
9L/27R	A	2.18	2.38	.58	.70
	B	1.68	1.78	.58	.665
	C	--	2.29	--	--
	D	2.73	3.16	.50	.58

* FROM TABLE II REPORT NO. FAA-RD-72-61

** FROM MEASUREMENTS MADE BY PAVEMENT SAFETY CORP. FOR DADE COUNTY PORT AUTHORITY. (SOURCE NTSB)

TABLE X.- DBV SDR evaluation of grooved and ungrooved pavements at Miami International Airport.

RUNWAY	DBV HEADING, DEG.	TEST ZONE	DBV WET/DRY STOPPING DISTANCE RATIO,SDR		COMMENTS
			MARCH 14/15,1973	MAY 8/9, 1973	
9L/27R	90	D	3.17	3.12	Before rubber removal and grooving of test zone. Single water truck wetting.
	270		3.38	3.53	
9R/27L	90	D	3.11	2.50*	Single water truck wetting used in March tests. Multiple water truck wetting used in May tests.
	270		4.54	2.34*	
	90	C	2.34	1.76*	
	270		2.37	1.59*	
	90	B	2.41	1.38*	
	270		2.19	1.39*	
	90	A	3.22	1.42*	
	270		3.42	1.59*	
9L/27R	90	B	1.77**	(Grooved)1.18*-1.43*	Single water truck wetting used in March tests
				(Ungrooved)2.46-2.73	
	270		1.77**	(Grooved)1.18*-1.25*	Multiple water truck wetting used in May tests.
				(Ungrooved)2.50-2.55	

* Tests made on grooved pavement

** Differences in SDR values between March and May tests on ungrooved surfaces attributed to water depth (dynamic hydroplaning) effects.

TABLE XI.- Average DBV SDR for Miami International Airport Runways 9R/27L and 9L/27R before and after grooving.

RUNWAY	DBV HEADING, DEG.	WET/DRY STOPPING DISTANCE RATIO, SDR_{AVG}		REFERENCE WET RUNWAY, SDR (BASED ON FAR 25.125 & FAR 121.195)
		BEFORE GROOVING	AFTER GROOVING	
9R/27L	270	3.22	1.71	1.92
	90	2.88	1.71	
9L/27R	270	2.32	N.A.*	
	90	2.35	N.A.*	

*Grooving of Runway 9L/27R was not completed at time of May 9 DBV tests.

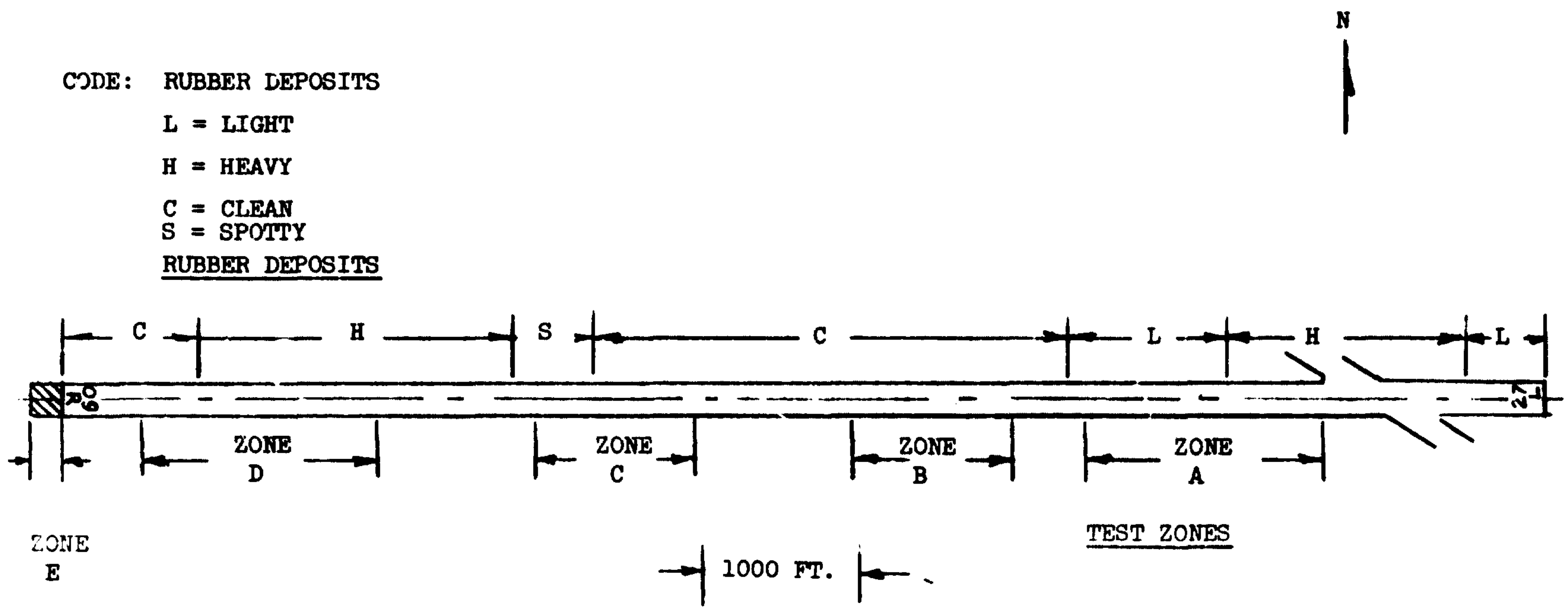


FIGURE 1.- MIAMI INTERNATIONAL AIRPORT RUNWAY 9R/27L 14 MARCH 1973

CODE: RUBBER DEPOSITS

L = LIGHT

H = HEAVY

C = CLEAN

S = SPOTTY

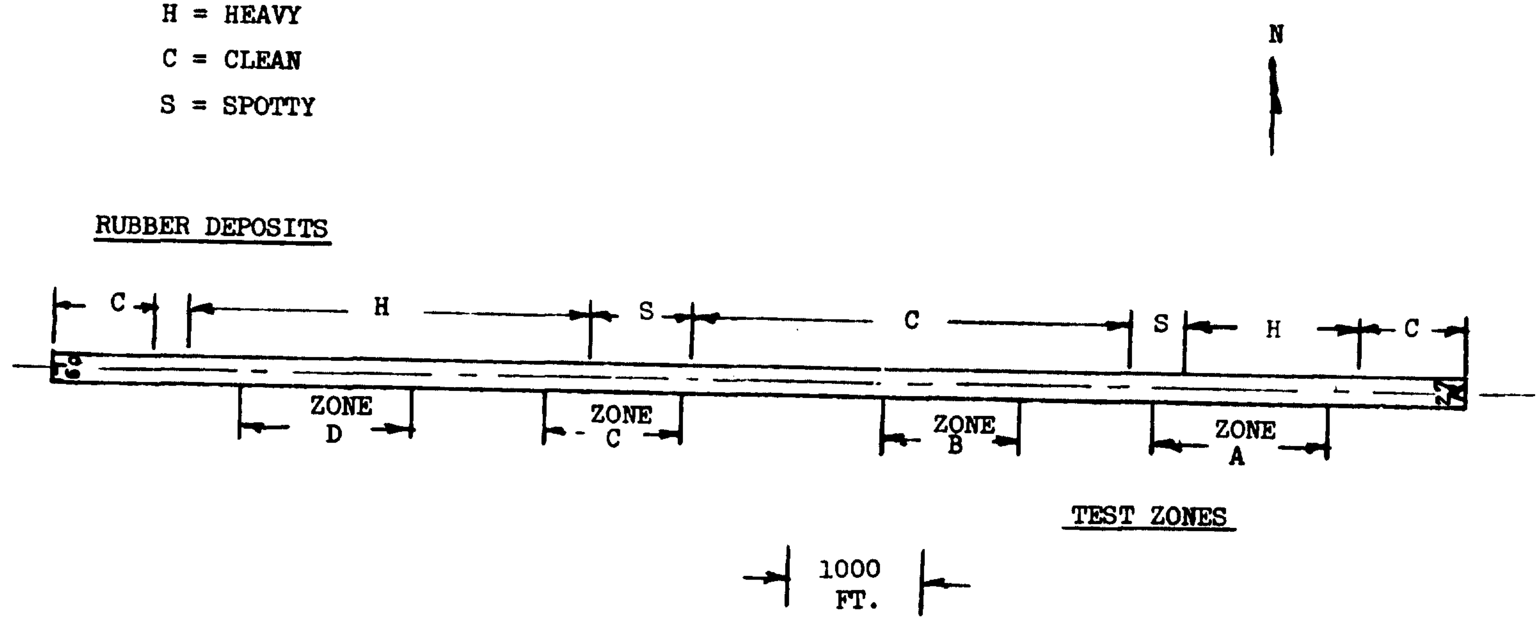
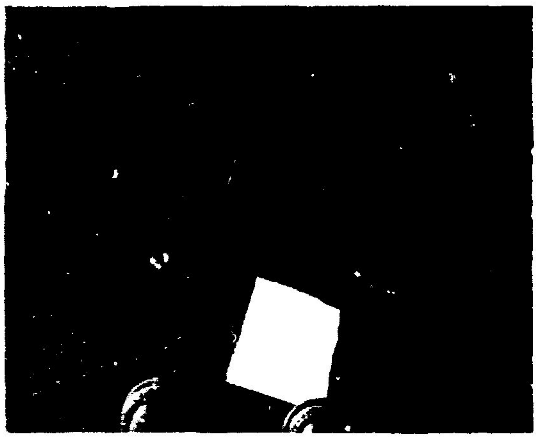
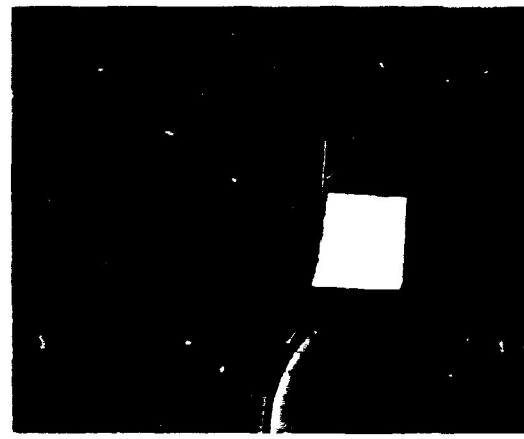


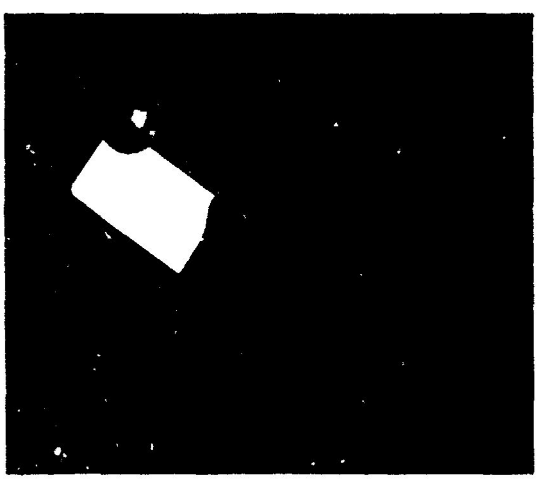
FIGURE 2.- MIAMI INTERNATIONAL AIRPORT RUNWAY 9L/27R 15 MARCH 1973



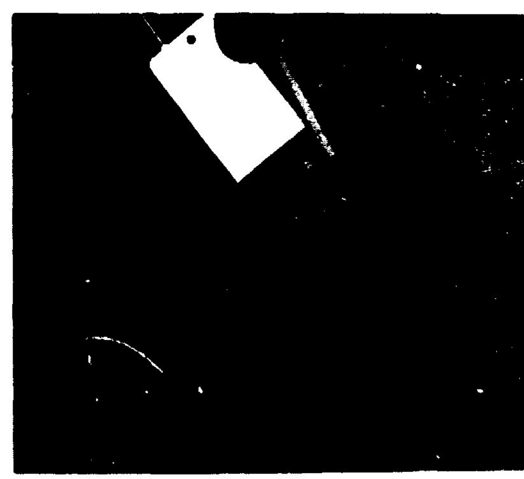
A) RUNWAY 9R/27L ZONE A.



B) RUNWAY 9R/27L ZONE B.



C) RUNWAY 9R/27L ZONE C.

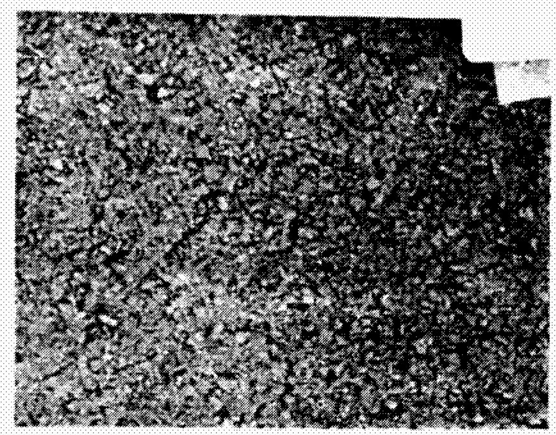


D) RUNWAY 9R/27L ZONE D.

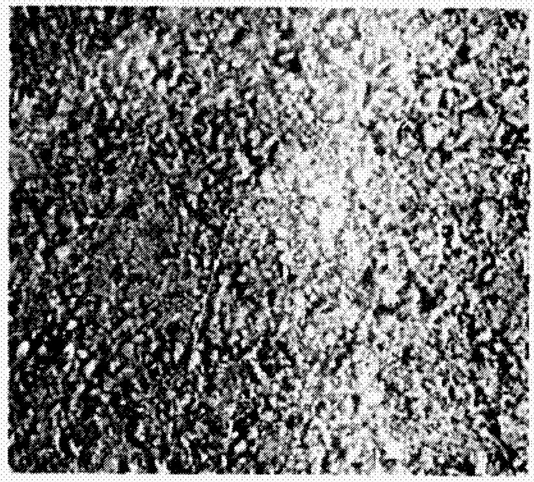
E) RUNWAY 9R/27L ZONE E (OVERRUN).

FIGURE 3.- PHOTOGRAPH OF PAVEMENT SURFACE IN RUNWAY TEST ZONE. (MARCH 14-15 TESTS)

F) RUNWAY 9L/27R ZONE A.

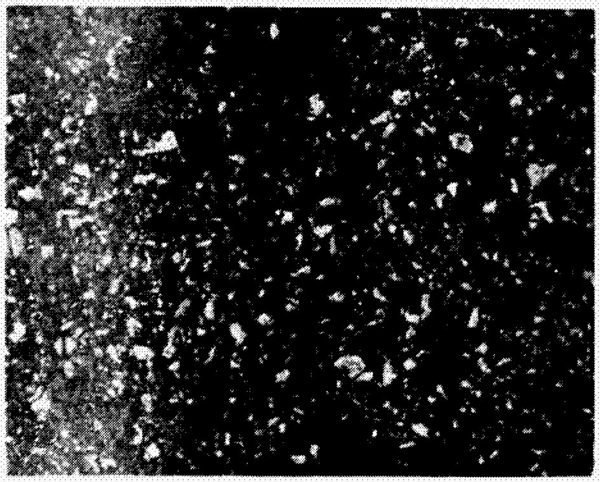


G) RUNWAY 9L/27R ZONE B.



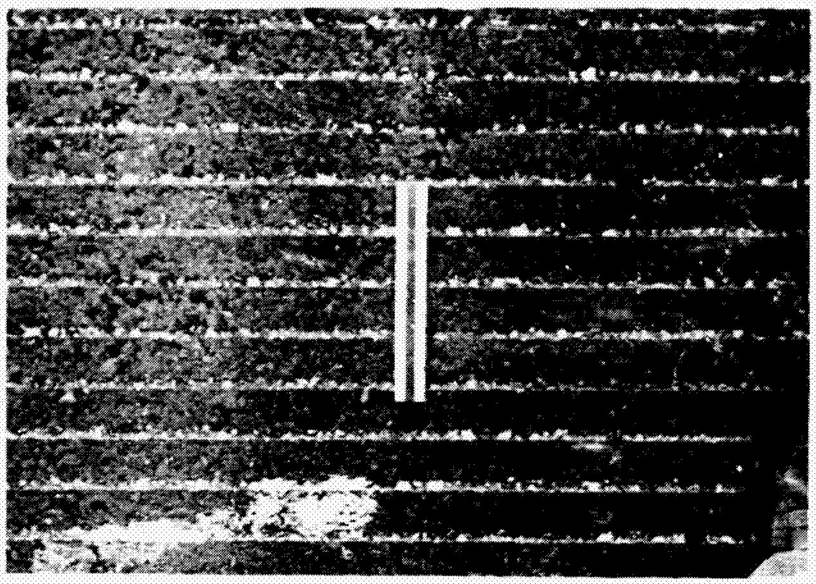
H) RUNWAY 9L/27R ZONE C.

I) RUNWAY 9L/27R ZONE D.

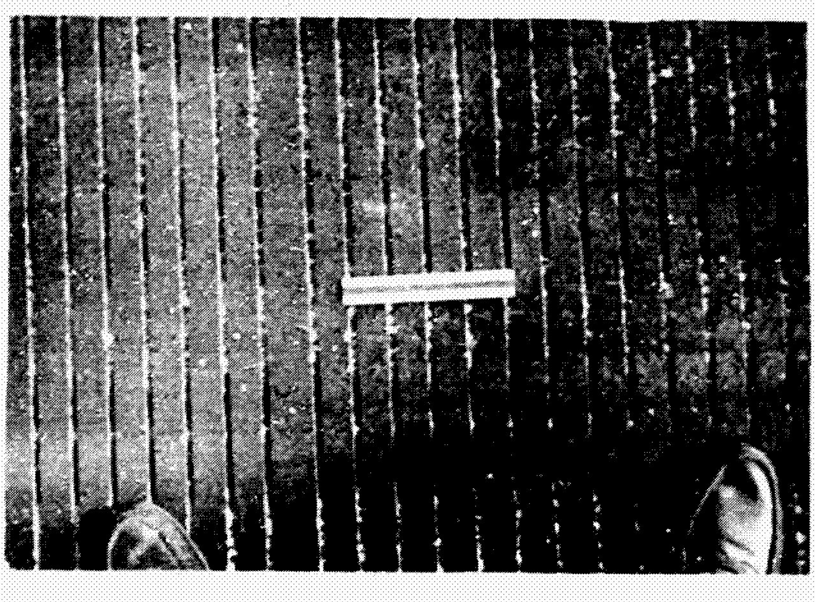


J) RUNWAY 12/30 MIDDLE.

FIGURE 3.- CONCLUDED.



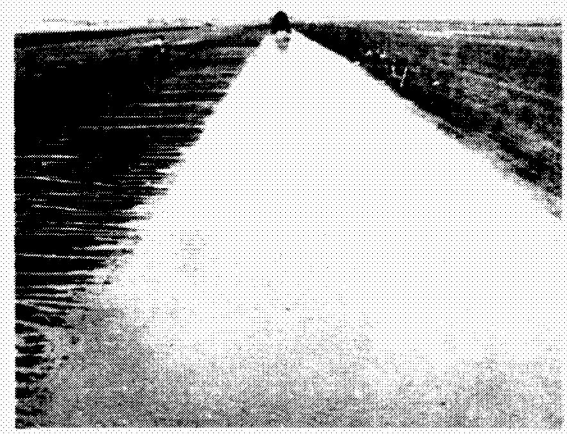
A) CLEAN GROOVED SURFACE (ZONE B).



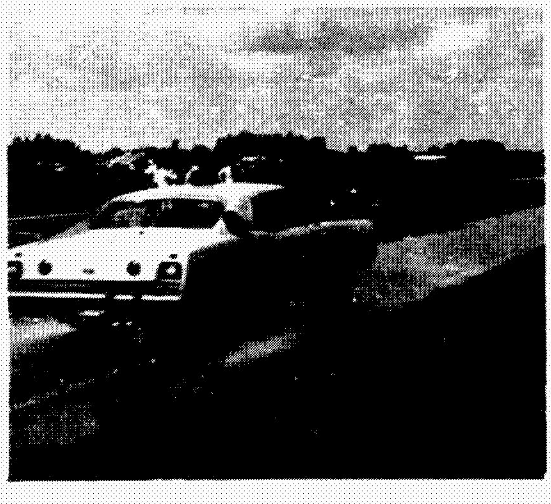
B) RUBBER-COATED GROOVED SURFACE (ZONE D).

FIGURE 4.- SURFACE PHOTOGRAPHS AFTER GROOVING OF RUNWAY 9R/27L, MAY 8, 1973.
GROOVE PATTERN 1 INCH x 1/4 INCH x 1/4 INCH. MIAMI INTERNATIONAL AIRPORT

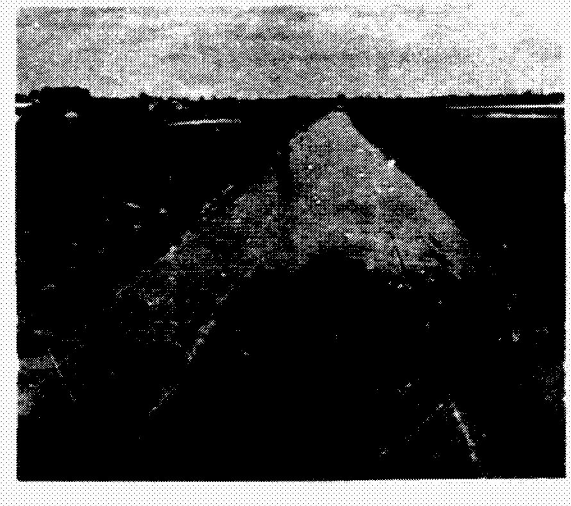
A) WATER TRUCK WETTING RUNWAY.



B) WET RUNWAY PRIOR TO DBV TEST RUN.

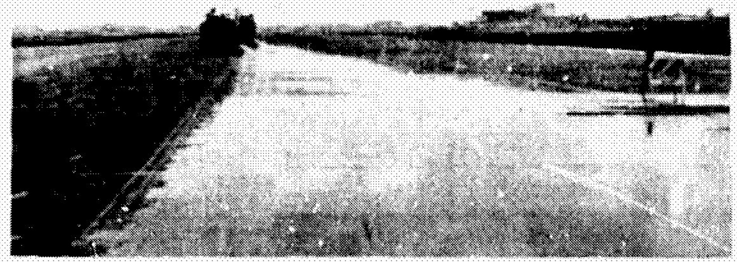


C) DBV TEST RUN.



D) WET RUNWAY AFTER DBV TEST RUN.

FIGURE 5.- TYPICAL RUNWAY WETTING SEQUENCES (MARCH 14-15 TESTS).



TIME ZERO

TIMF ZERO + 25 SECONDS

A) WATER TRUCKS WETTING RUNWAY BEFORE DBV RUN. PHOTOGRAPH TAKEN PARALLEL TO RUNWAY CENTER-LINE.

B) AFTER DBV RUN. PHOTOGRAPH TAKEN NORMAL TO RUNWAY CENTER-LINE.

FIGURE 6 .- COMPARISON OF WATER DRAINAGE FROM GROOVED AND UNGROOVED SURFACES OF RUNWAY 9L-27R, ZONE B. MIAMI INTERNATIONAL AIRPORT, MAY 9, 1973.

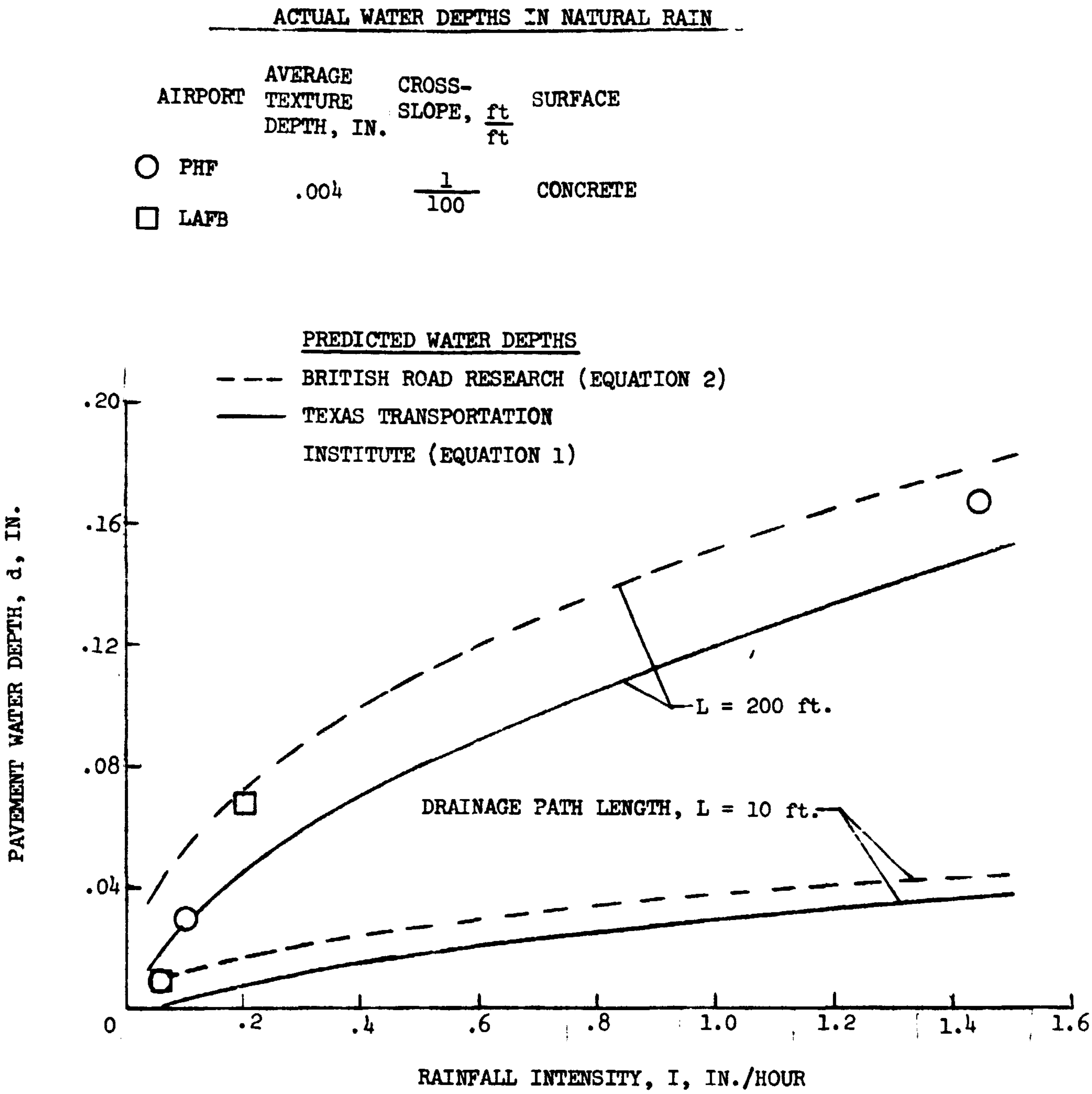
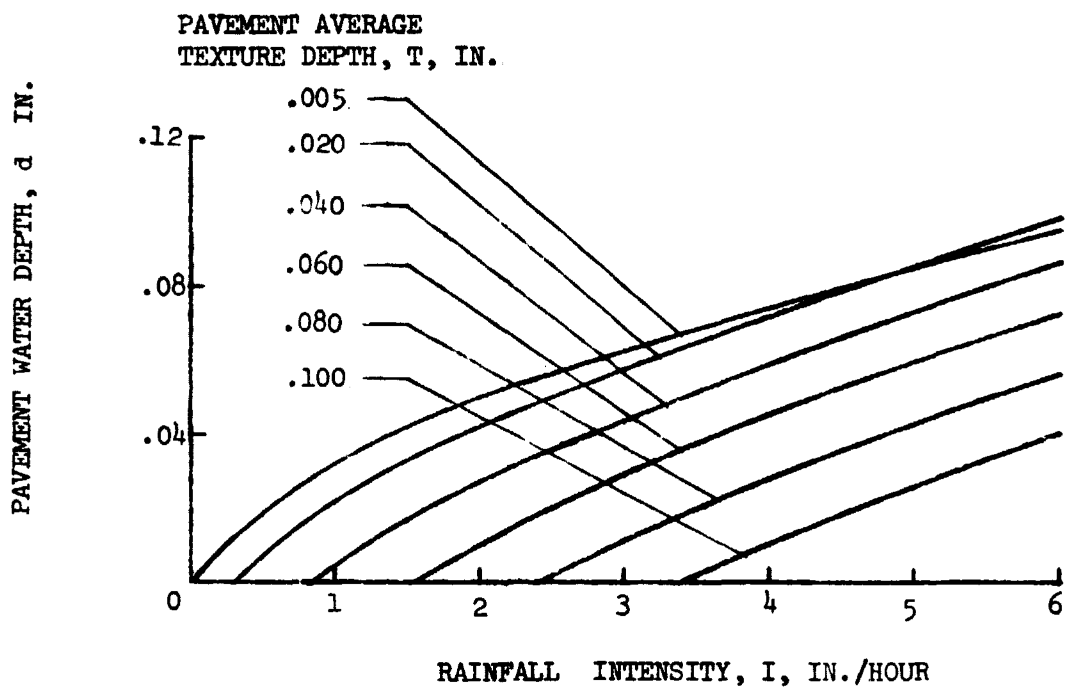
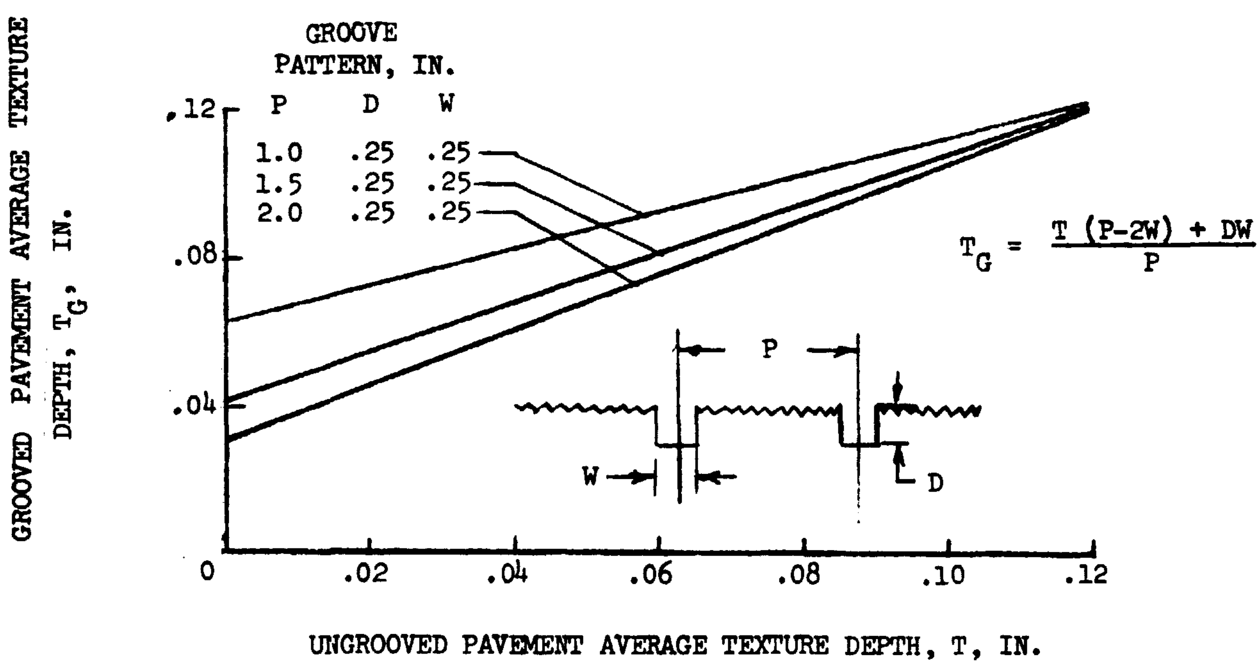


FIGURE 7.- EFFECTS OF RAINFALL INTENSITY AND DRAINAGE PATH LENGTH ON UNGROOVED PAVEMENT WATER DEPTH.

$$d = \left[3.38 \times 10^{-8} \left(\frac{1}{T}\right)^{-.11} (L)^{.43} (I)^{.59} \left(\frac{1}{S}\right)^{.42} \right] - T \quad \text{(equation 1)}$$

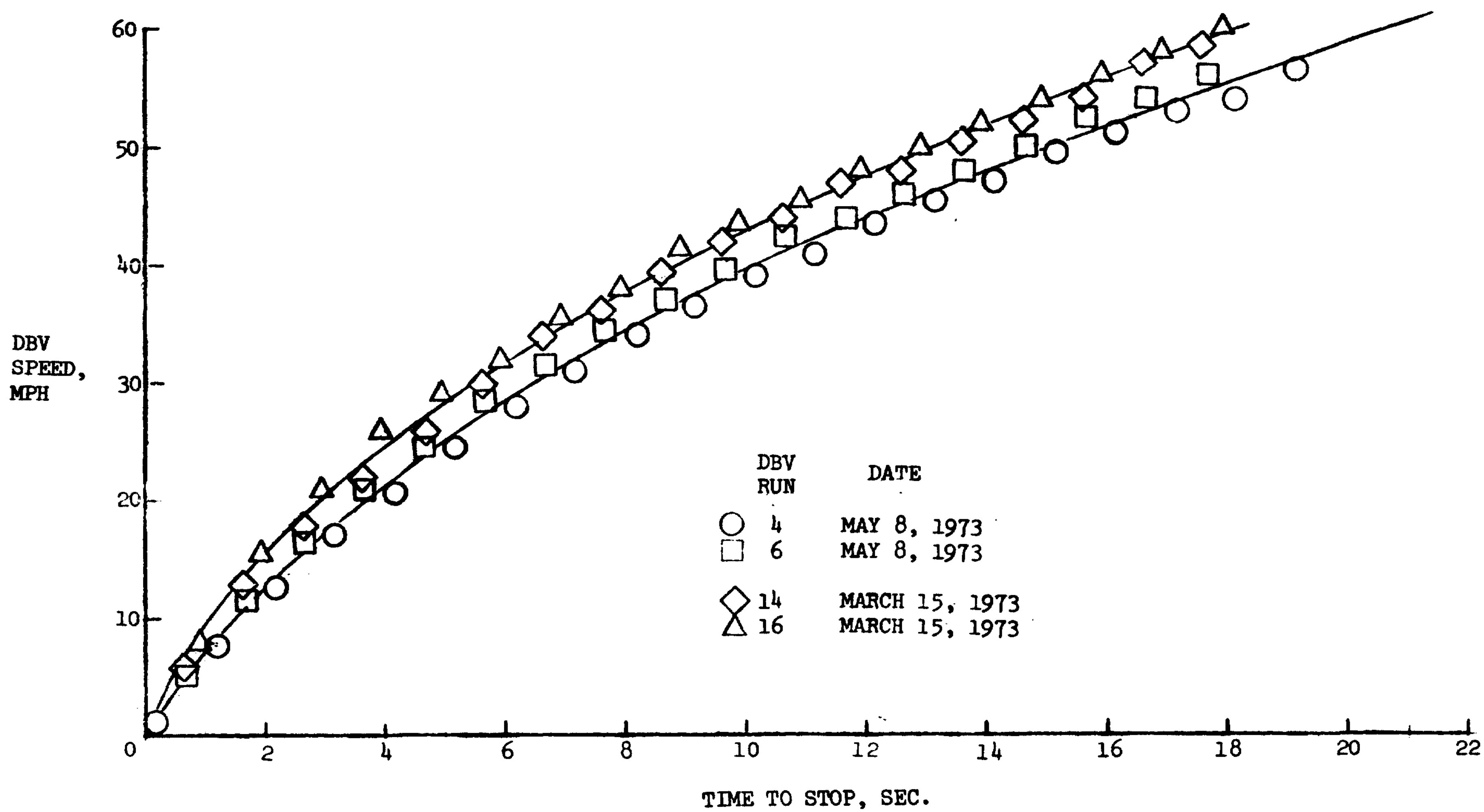


A) CALCULATED EFFECTS OF RAINFALL INTENSITY AND PAVEMENT AVERAGE TEXTURE DEPTH ON PAVEMANT WATER DEPTH IN STILL AIR.



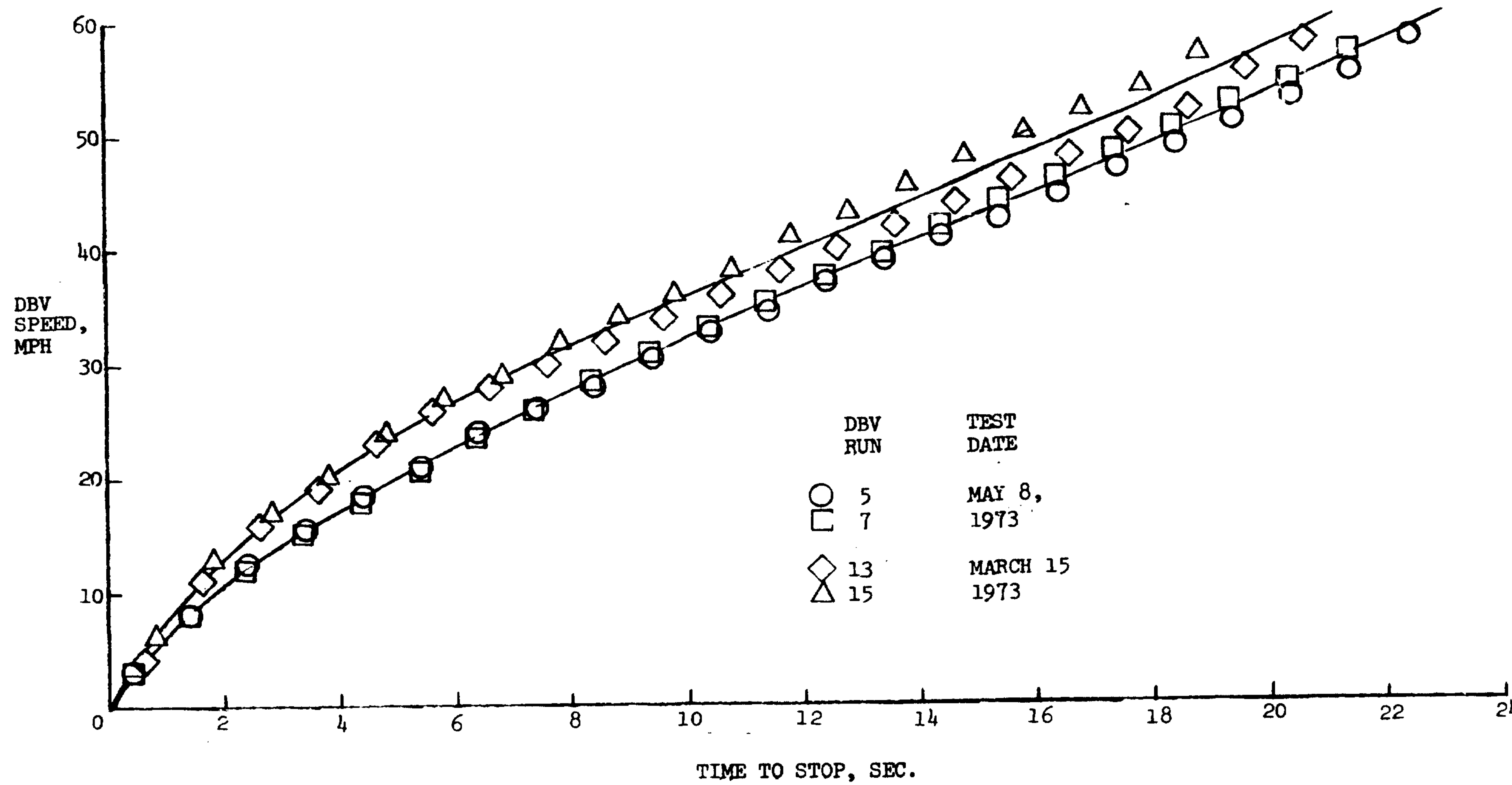
B) CALCULATED INCREASE IN PAVEMENT AVERAGE TEXTURE DEPTH FROM RUNWAY GROOVES.

FIGURE 8.- CALCULATED EFFECTS OF PAVEMENT AVERAGE TEXTURE DEPTH AND RAINFALL INTENSITY ON WATER DEPTHS DEVELOPED ON PAVEMENTS DURING RAINSTORMS IN STILL AIR. PAVEMENT CROSS SLOPE, (S), $\frac{1}{100}$. DRAINAGE PATH LENGTH, (L), 10 feet.



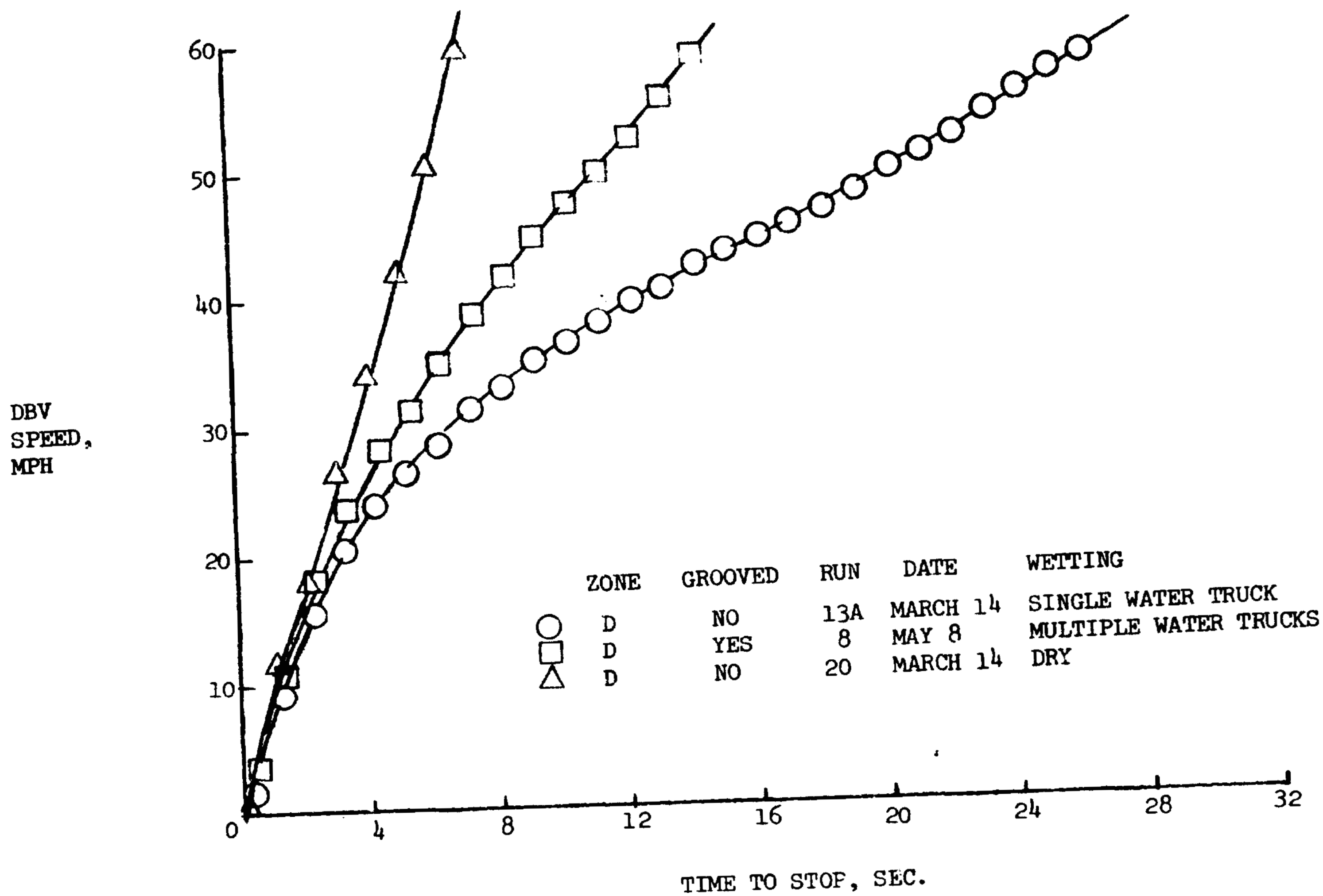
A) DBV HEADING 90 DEGREES (RUNWAY 9L).

FIGURE 9.- NORMALIZED DBV VELOCITY TIME HISTORIES OBTAINED ON MIAMI INTERNATIONAL AIRPORT RUNWAY 9L-27R, ZONE D (HEAVY RUBBER DEPOSITS), BEFORE GROOVING.



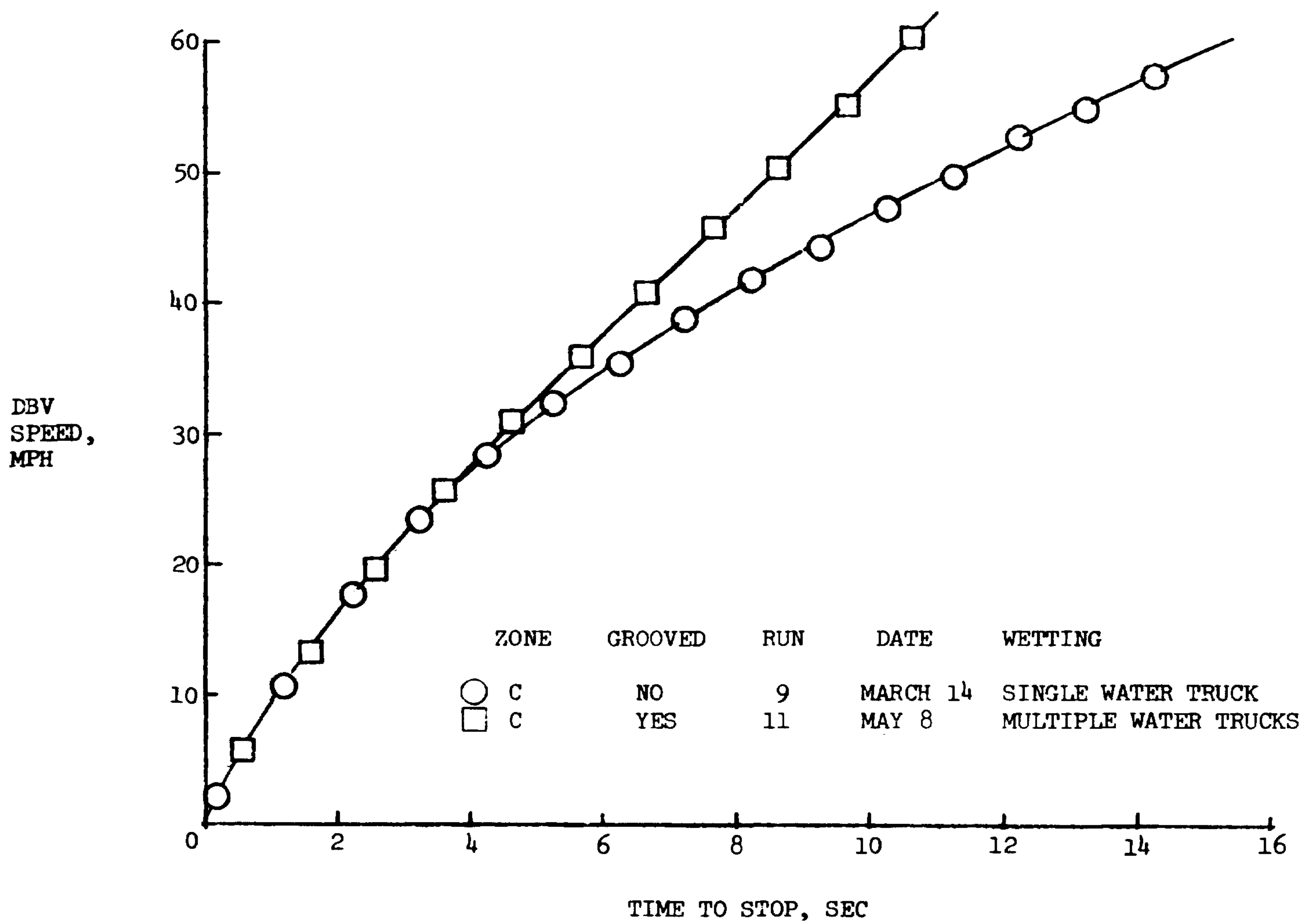
B) DBV HEADING 270 DEGREES (RUNWAY 27R).

FIGURE 9.- CONCLUDED.



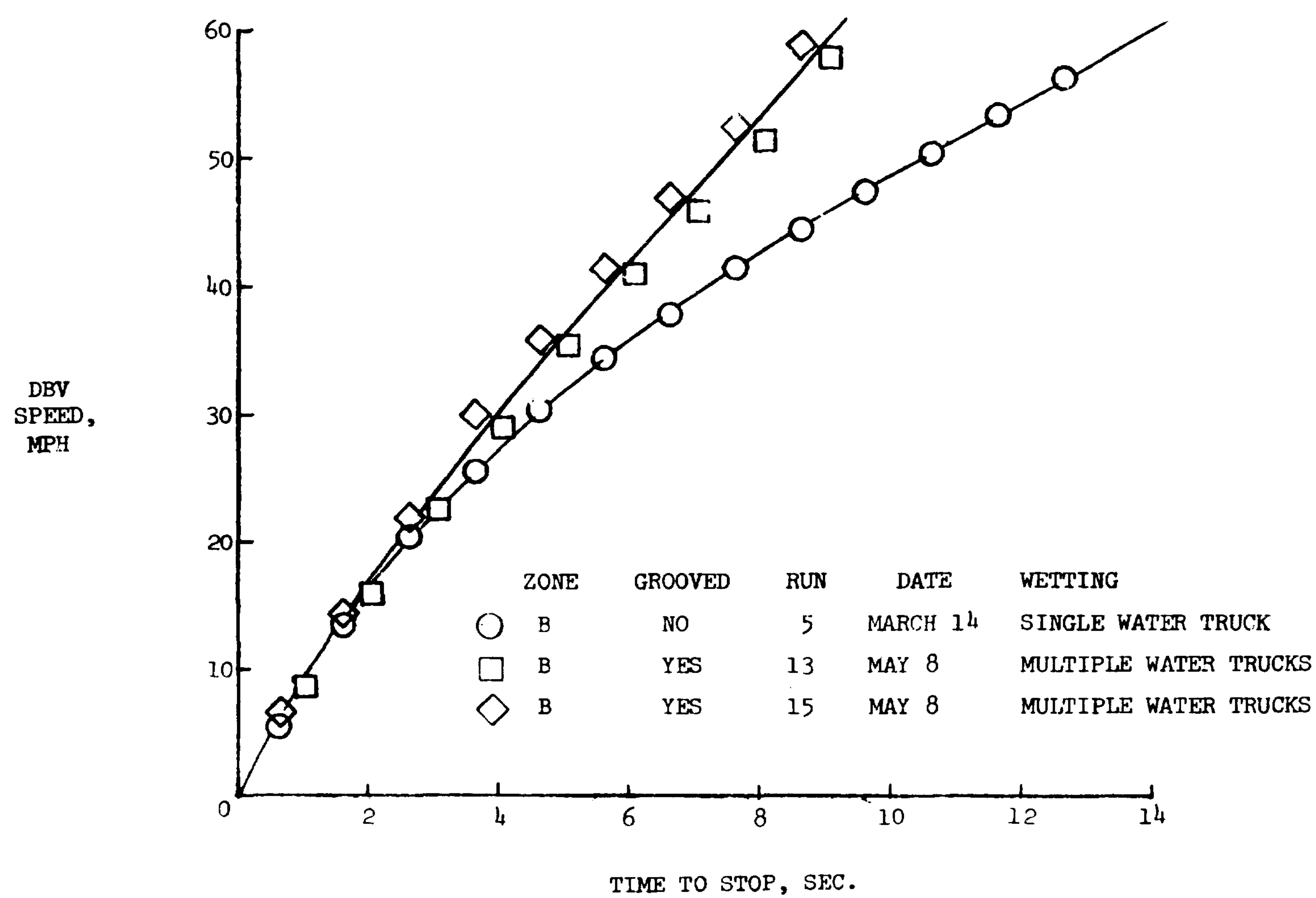
A) HEAVY RUBBER DEPOSITS, ZONE D.

FIGURE 10.- NORMALIZED DBV VELOCITY TIME HISTORIES OBTAINED ON MIAMI INTERNATIONAL AIRPORT RUNWAY 9R-27L BEFORE AND AFTER GROOVING. DBV HEADING 270DEGREES (RUNWAY 27L).



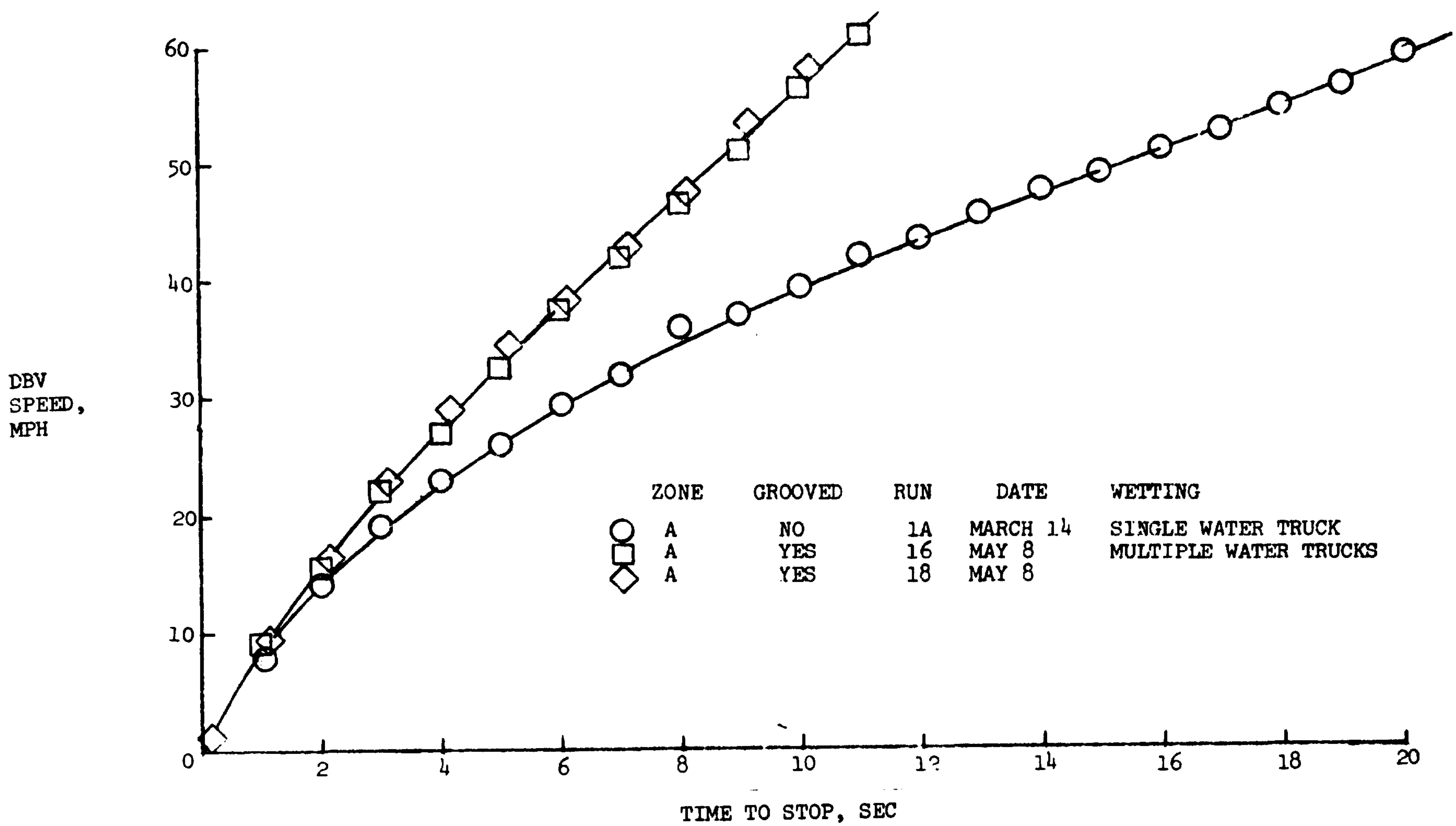
B) CLEAN/SPOTTY RUBBER DEPOSITS, ZONE C.

FIGURE 10.- CONTINUED.



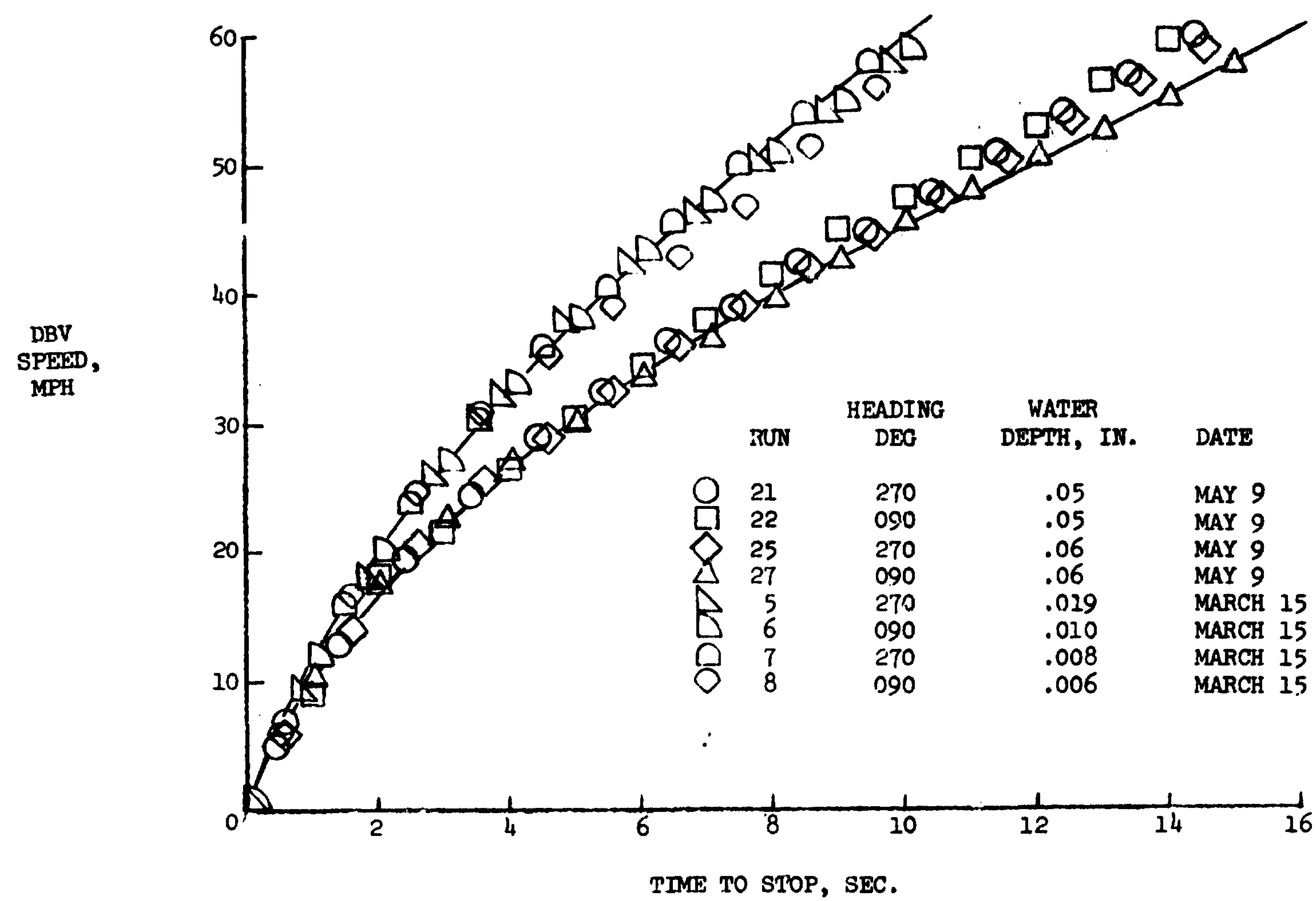
c) CLEAN SURFACE, ZONE B.

FIGURE 10.- CONTINUED.



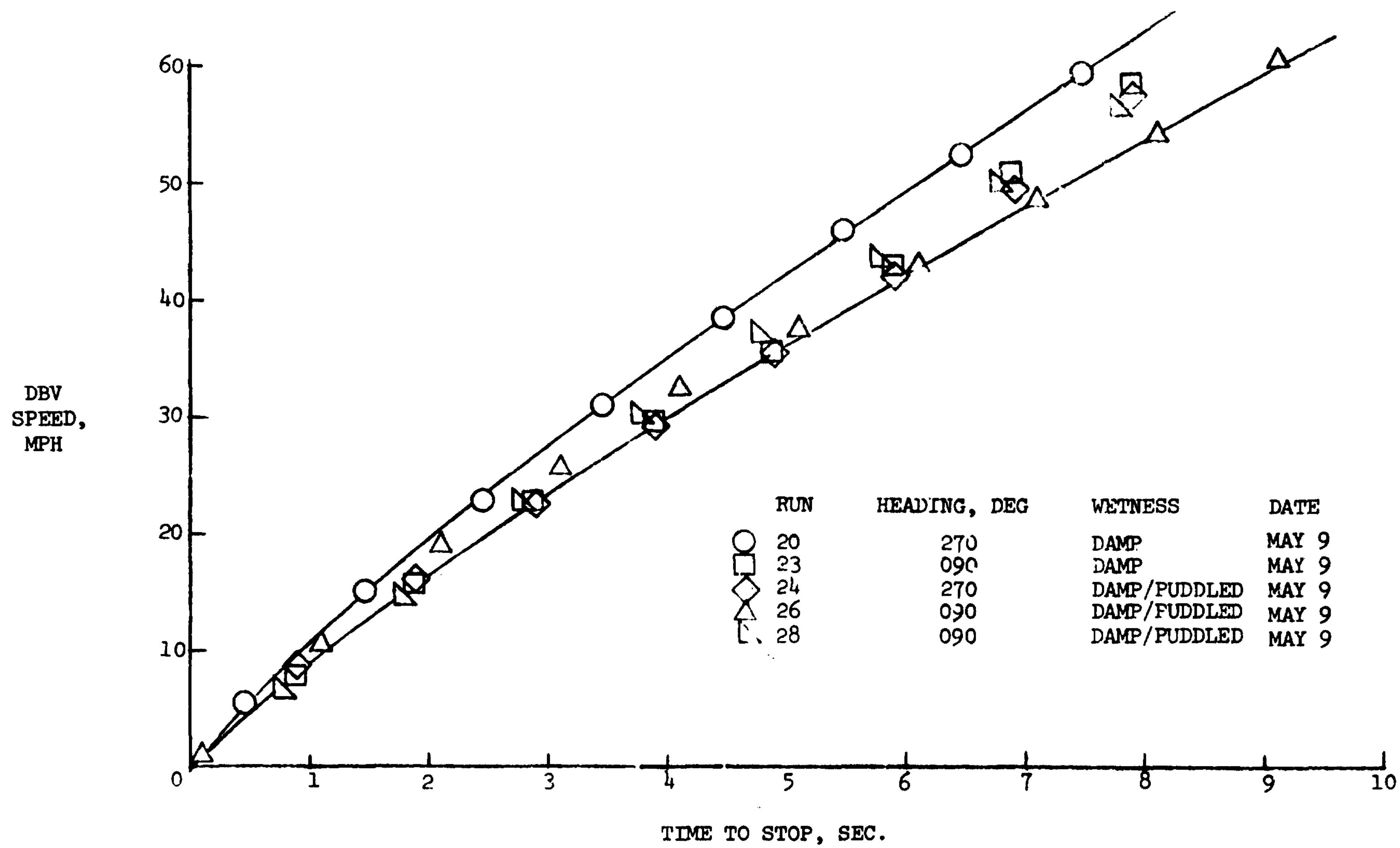
D) LIGHT/HEAVY RUBBER DEPOSITS, ZONE A.

FIGURE 10.- CONCLUDED.



A) BEFORE GROOVING

FIGURE 11.- NORMALIZED DBV VELOCITY TIME HISTORIES OBTAINED ON MIAMI INTERNATIONAL AIRPORT RUNWAY 9L-27R, ZONE B (NO RUBBER DEPOSITS), BEFORE AND AFTER GROOVING.



B) AFTER GROOVING.

FIGURE 11.- CONCLUDED.

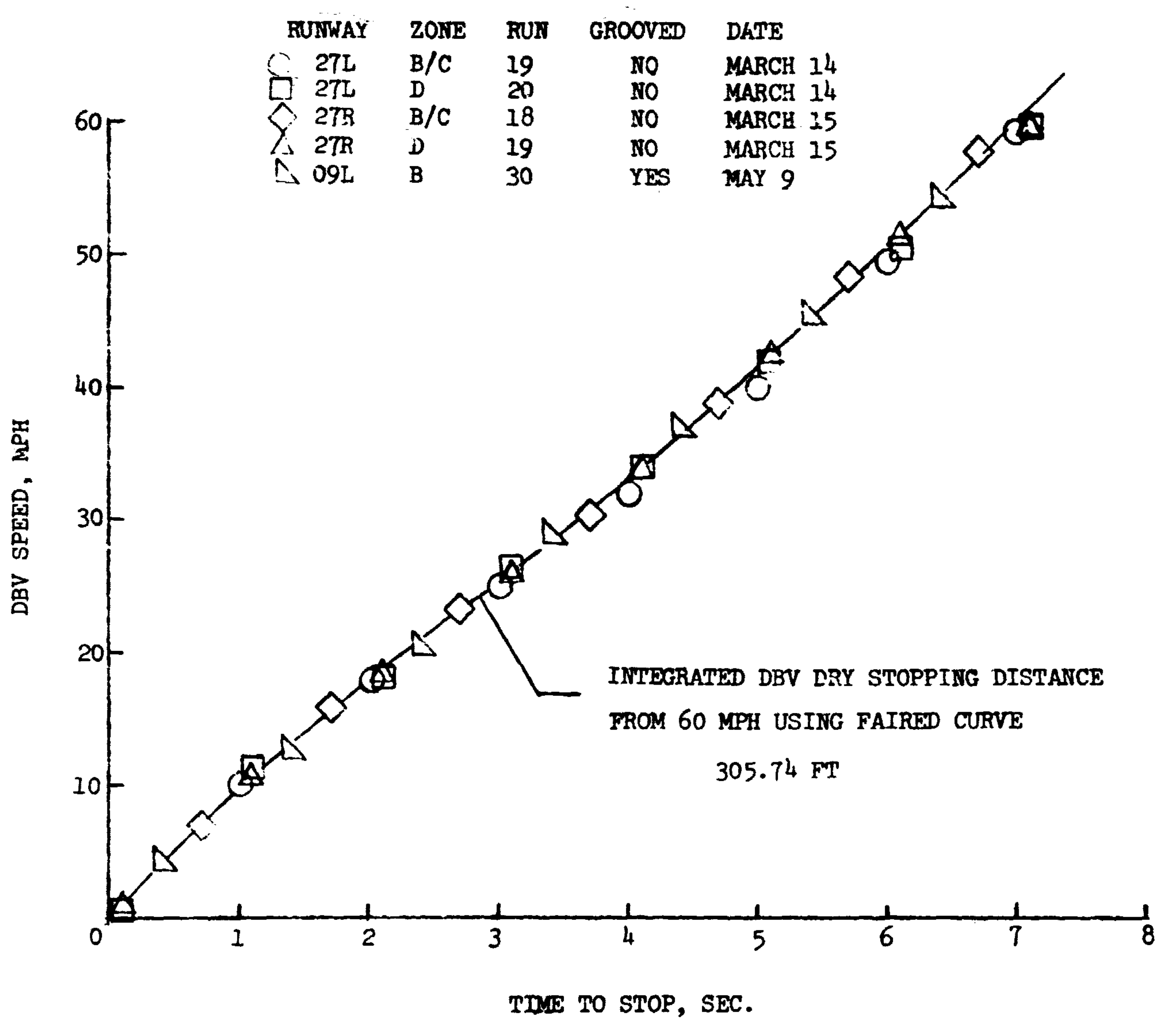


FIGURE 12.- COMPARISON OF DBV NORMALIZED VELOCITY TIME HISTORIES OBTAINED DURING TESTS ON DRY RUNWAYS AT MIAMI INTERNATIONAL AIRPORT.

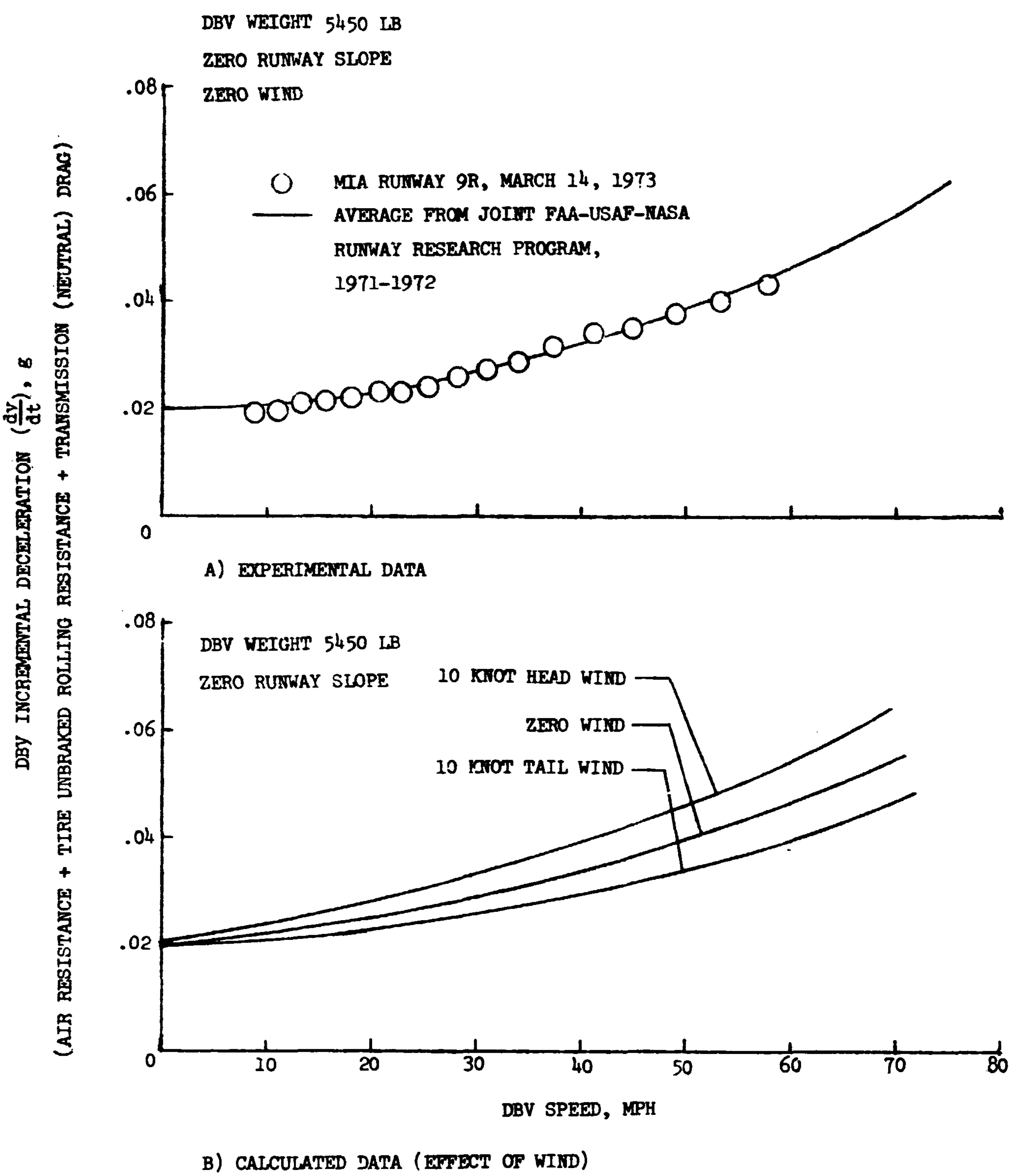


FIGURE 13.- UNBRAKED DECELERATION CHARACTERISTICS OF NASA DBV (TRANSMISSION IN NEUTRAL).

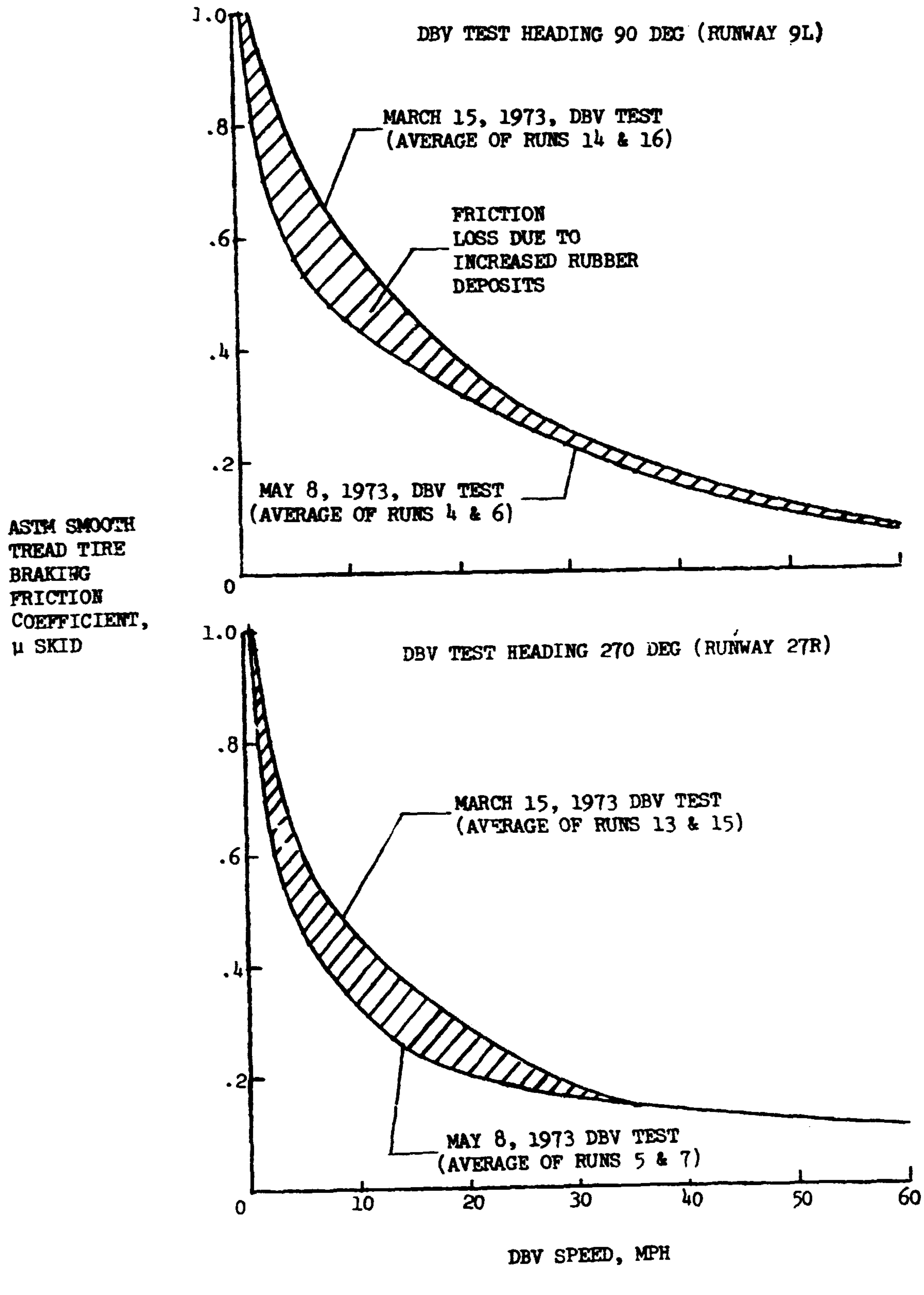


FIGURE 14.- EFFECT OF INCREASED RUBBER DEPOSITS (ACCRUED BETWEEN MARCH 15 AND MAY 8, 1973) IN ZONE D OF RUNWAY 9L/27R ON ASTM TIRE BRAKING FRICTION COEFFICIENT, μ SKID. TESTS MADE WITH SINGLE WATER TRUCK WETTING.

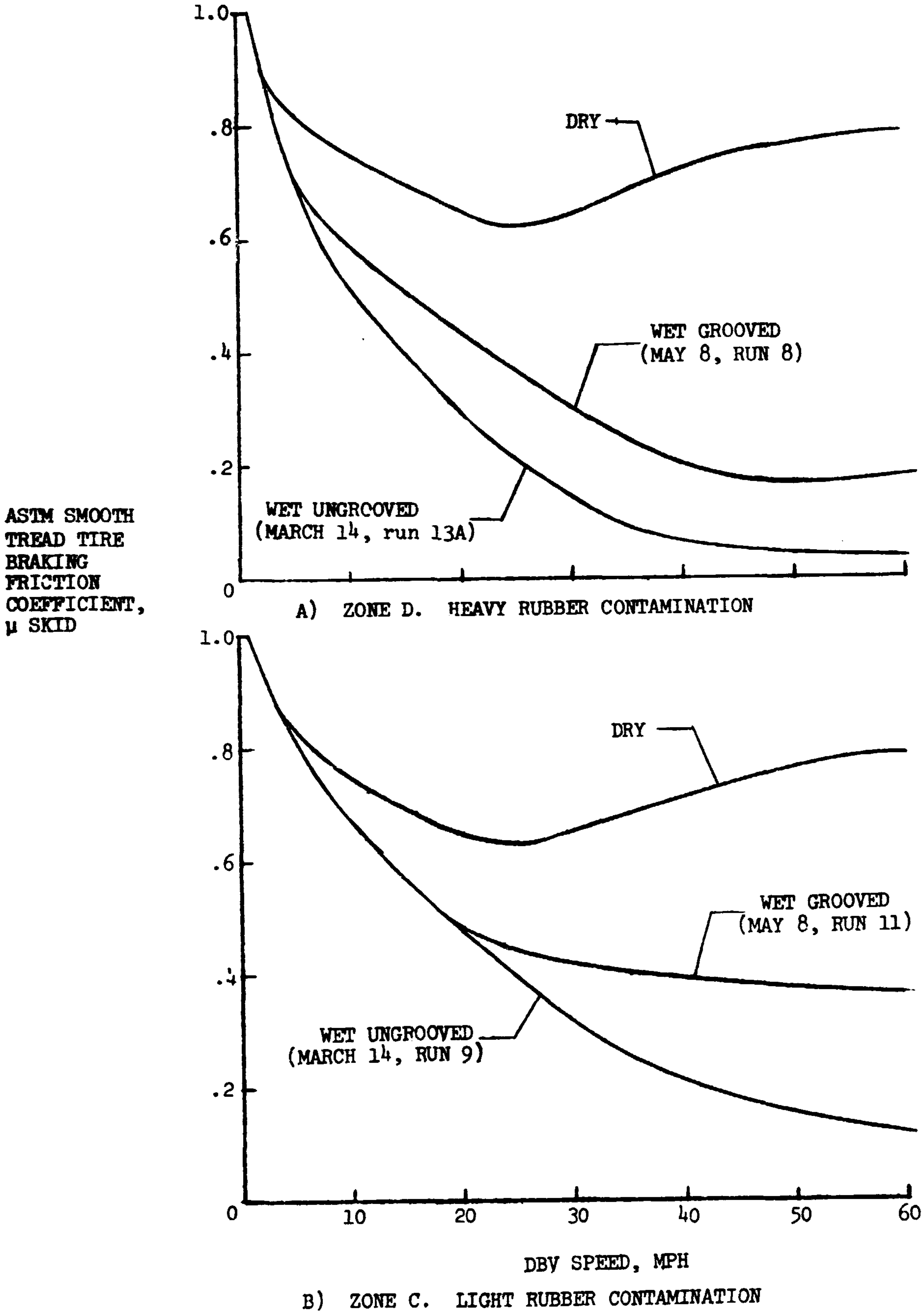


FIGURE 15.- EFFECT OF RUBBER CONTAMINATION ON FRICTION CHARACTERISTICS OF RUNWAY 27L BEFORE AND AFTER GROOVING THE RUNWAY. DBV HEADING 270 DEGREES.

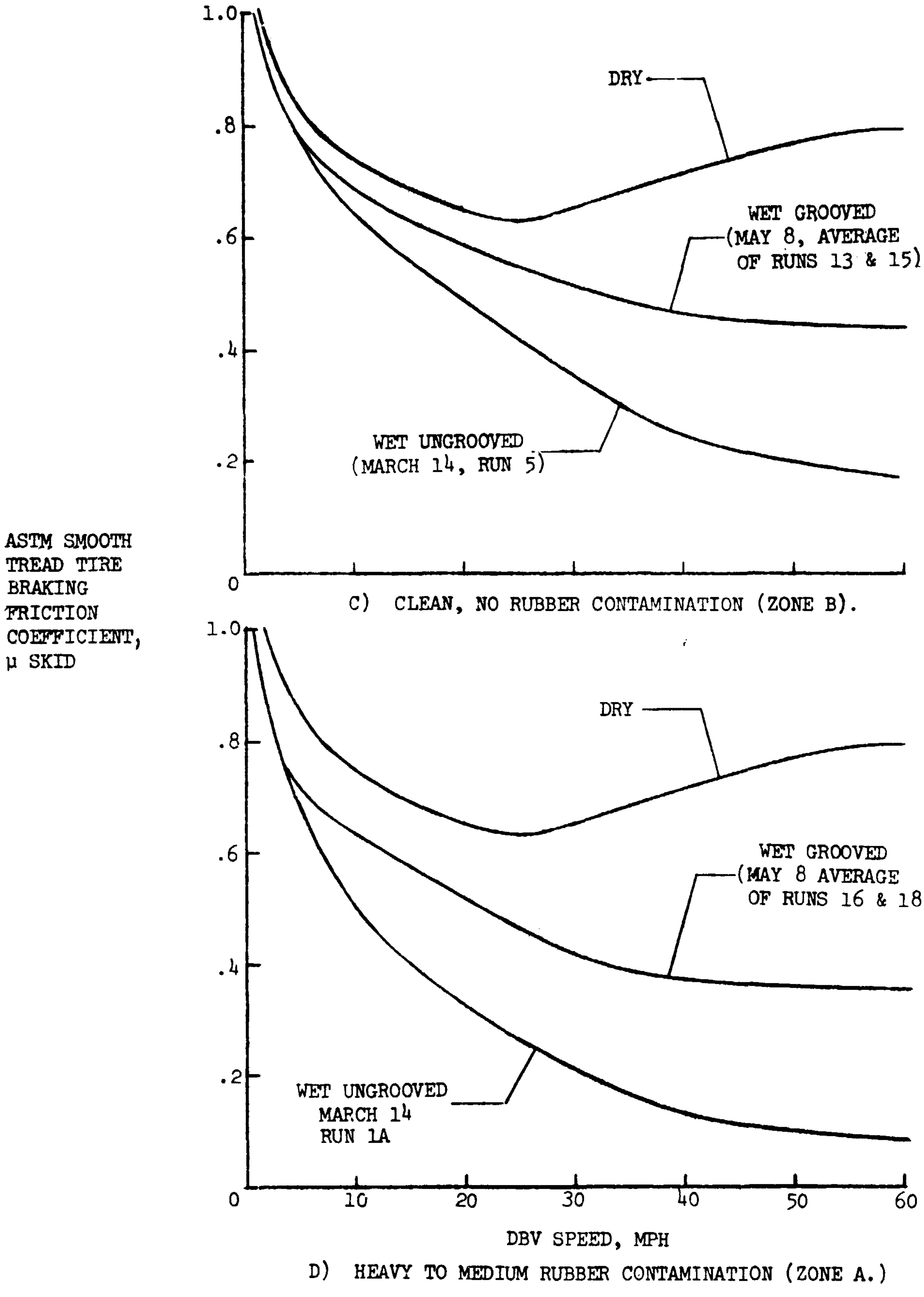


FIGURE 15.- CONCLUDED.

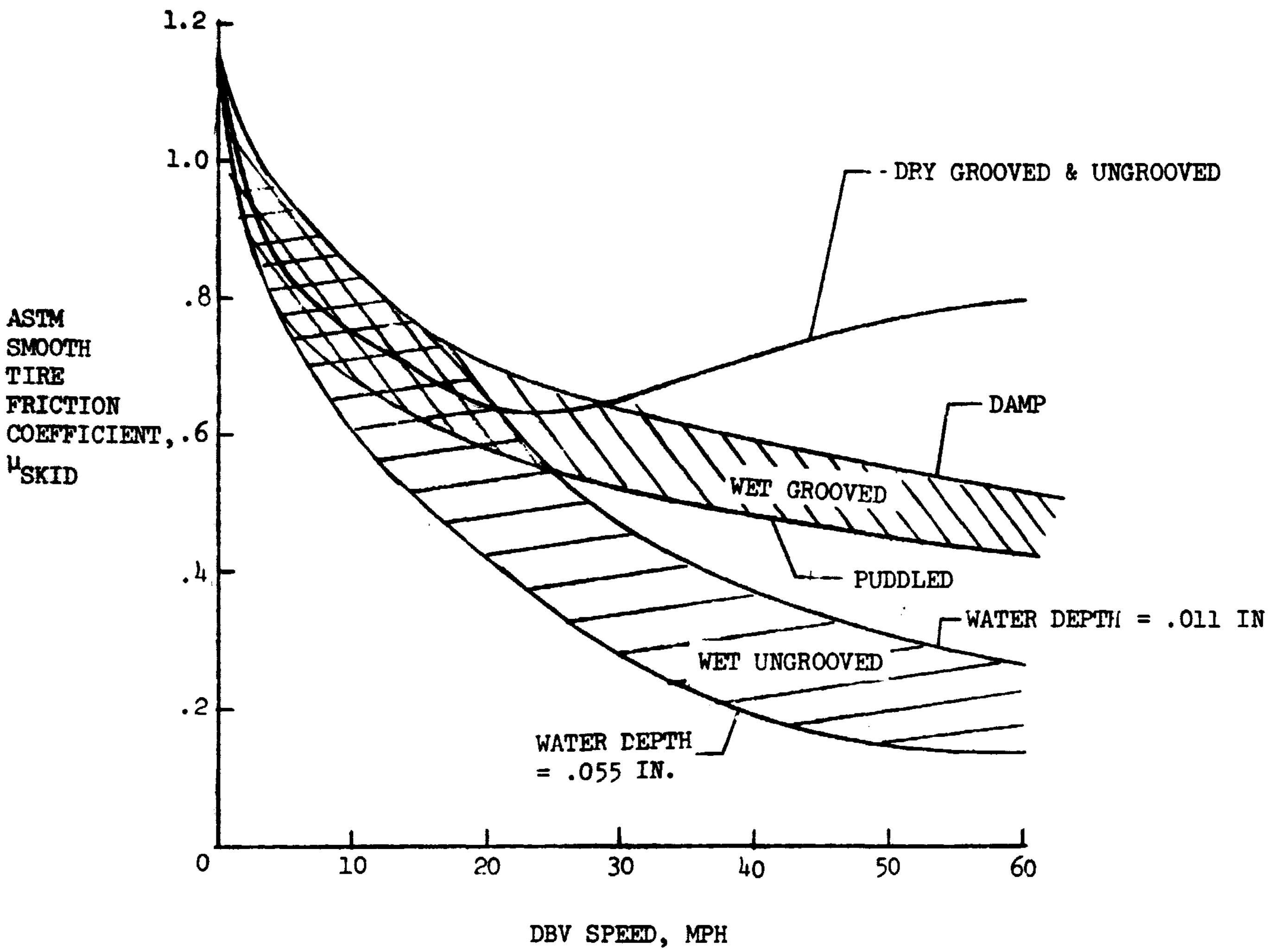


FIGURE 16.- SKID RESISTANCE OF MIA RUNWAY 9L/27R ZONE B (CLEAN ASPHALT) BEFORE AND AFTER GROOVING UNDER DRY AND WET CONDITIONS.

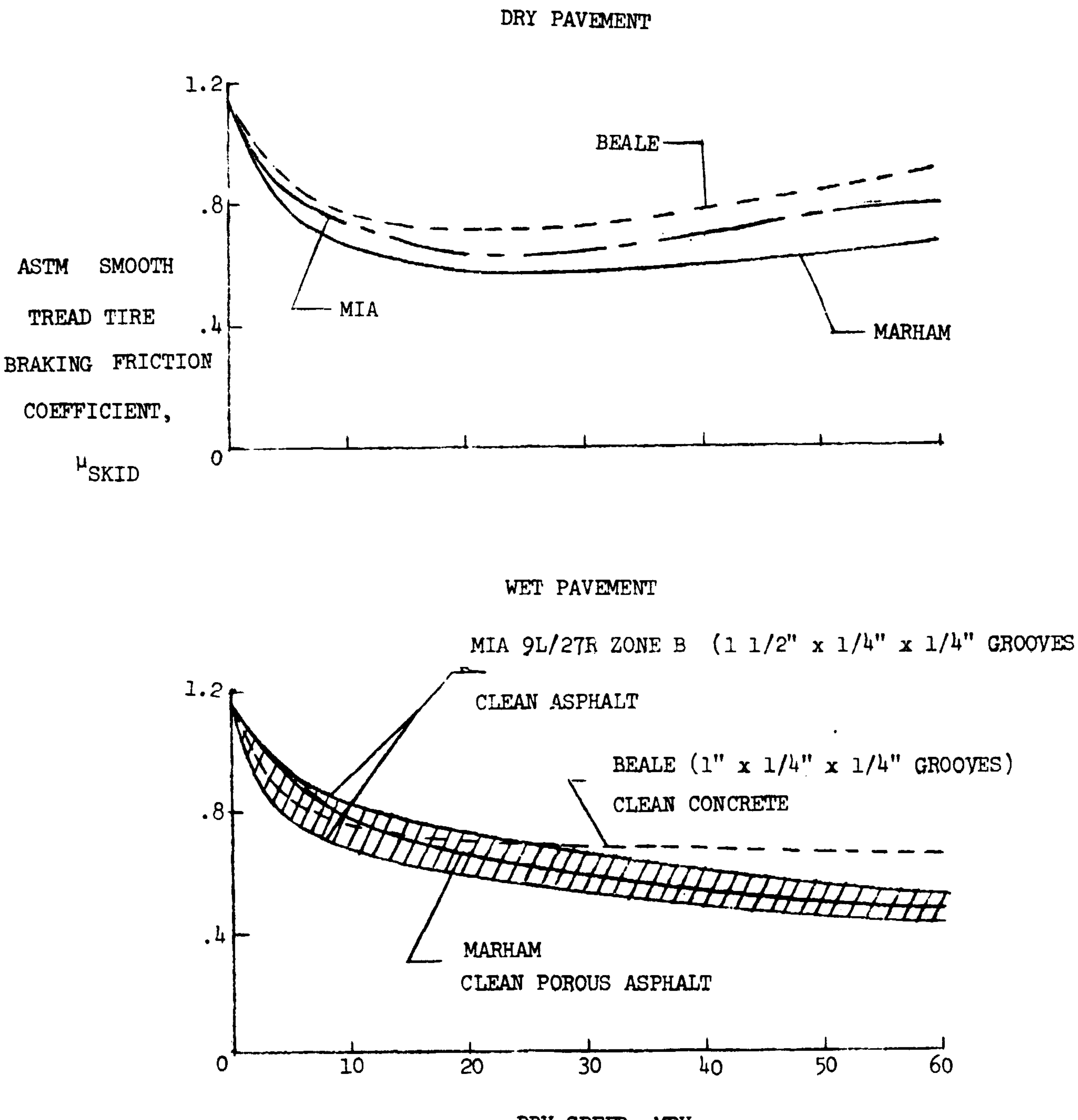
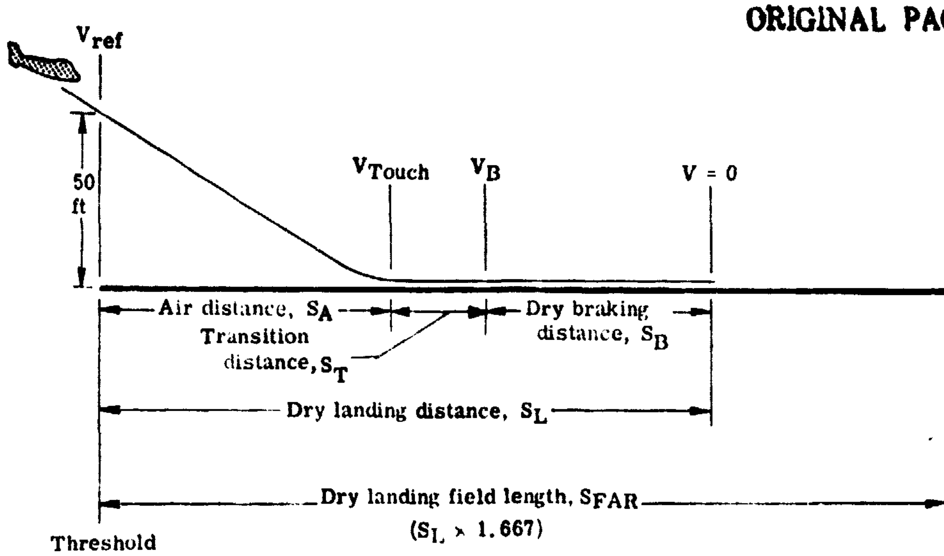
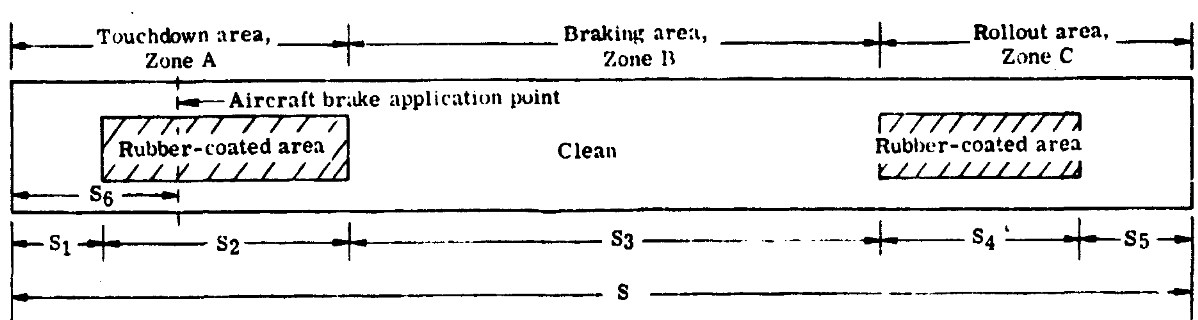


FIGURE 17.- COMPARISON OF SKID RESISTANCE OF GROOVED AND POROUS PAVEMENT SURFACE TREATMENTS UNDER DRY AND WET CONDITIONS.



Aircraft landing terminology.

NASA diagonal-braked test vehicle runway slipperiness measurements	
Runway location	Stopping distance ratio, wet/dry
Touchdown area: zone A, rubber coated	X_A
Braking area: zone B, clean	X_B
Rollout area: zone C, rubber coated	X_C



$$\bar{X} = \frac{(S_1 + S_2 - S_6)\,X_A + (S_3 + S_5)\,X_B + S_4 X_C}{S - S_6}$$

FIGURE 18.- METHOD FOR CALCULATING THE AVERAGE DIAGONAL-BRAKED TEST VEHICLE WET-DRY STOPPING DISTANCE RATIO $\bar{X}$ FOR A GIVEN AIRCRAFT LANDING CONDITION.

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15. Supplementary Notes

16. Abstract

Runways 9R/27L and 9L/27R at Miami International Airport were evaluated under artificially wetted conditions with the NASA diagonal-braked vehicle (DBV). Results of the evaluation which included a pavement drainage analysis, a pavement skid resistance analysis, and a DBV wet/dry stopping distance ratio (SDR) analysis indicated that the ungrooved runway surfaces had poor water drainage characteristics and poor skid resistance under wet conditions at high speeds especially in rubber-coated areas of the runways. Grooving runways 9R/27L and 9L/27R to a transverse 1-1/4 x 1/4 x 1/4 inch pattern greatly improved both the water drainage and pavement skid resistance capability of these asphaltic concrete runway surfaces.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Runway slipperiness Runway surface treatments Aircraft-ground vehicle stopping performance Friction coefficient	Unclassified - Unlimited

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