6. CALCULATED AIRPLANE STOPPING DISTANCES BASED ON TEST RESULTS OBTAINED AT THE LANDING RESEARCH RUNWAY, NASA WALLOPS STATION

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SUMMARY

Data are presented from an analytical study made to predict improvements in adverse-weather landing and balanced take-off field performance levels for transversely grooved runways. The results indicate that the use of the landing-research-runway transverse-groove configuration (1-inch pitch by 1/4-inch width by 1/4-inch depth) effectively reduces landing field lengths for the Convair 990A and McDonnell Douglas F-4D airplanes under adverse weather conditions on a variety of runway surfaces.

In addition, essentially dry balanced field take-off performance is attainable for grooved runway surfaces in a wet and puddled condition, since grooving increases the critical engine-failure speed to practically dry-surface values. Only slight reductions in balanced field lengths are provided by grooving for take-offs from slush-covered runways.

INTRODUCTION

Recent airplane braking research programs conducted by the National Aeronautics and Space Administration have shown that pavement grooving is an effective means of producing higher friction levels for airplanes involved in adverse-weather runway operations (ref. 1). The braking programs were conducted with 990A and F-4D airplanes on the landing research runway at Wallops Station, Virginia.

The purpose of this paper is to indicate the effects of transverse runway grooving on airplane ground operating distances for the 990A and F-4D. The results were obtained from an analytical study made to determine all-weather landing and balanced take-off field lengths for hypothetical operations from ungrooved and grooved concrete and asphalt runways of various surface textures. The pavement groove configuration and surface textures of the runways included in this study were assumed to be identical to those reported in reference 1, since the braking data used herein were obtained from tests on surfaces A to D and F to I of the landing research runway. Also included is a brief assessment of some effects of pavement grooving with regard to cross-wind landings made on flooded runways.

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All comparisons used in the study were selected to place the results applicable to ungrooved and grooved runways on a consistent basis and do not necessarily reflect actual day-to-day runway operations of either commercial or military airplanes.

SYMBOLS

C_m — pitching-moment coefficient

h_2 — obstacle clearance height

$\dot{h}$ — rate of sink

L — lift

n — normal load factor, L/W

T — thrust

Δt — time increment following engine failure

V — velocity

V_1 — critical engine-failure speed

V_2 — velocity at obstacle clearance height

W — weight

γ — flight-path angle

$\ddot{\psi}$ — angular acceleration about vertical axis

Subscripts:

app — approach

BR — conditions at brake engagement

G — grooved

R remaining engine(s) after a single engine failure

r conditions at take-off rotation point

TD conditions at touchdown

T_1 thrust from failed engine

3PT conditions at nose-wheel touchdown in landing

DISCUSSION

Landing Analysis

The conditions considered in the landing analysis are indicated in figure 1. Standard-day sea-level ambient conditions were assumed with no wind and level runway surfaces. The landing field length is defined as the horizontal distance from a height of 50 feet to a full stop. The airplane weights used in the landing analysis were assumed to be constant at 202 000 pounds for the 990A and at 36 000 pounds for the F-4D. Initial conditions included stabilized flight at 50 feet, with approach flight-path angles of 3.0° for the 990A and 2.75° for the F-4D. Corresponding sink rates were 13.33 and 11.60 feet per second, respectively. Constant normal-load-factor flares were executed from the stabilized approach to reduce the sink rates at touchdown (T.D.) to acceptable levels. After attaining a three-point attitude the throttles were retarded to idle, the spoilers were deployed for the 990A, and the F-4D horizontal stabilizers were deflected to produce maximum positive C_m. Then maximum antiskid braking was initiated and maintained to a stop by assuming friction values obtained from new to moderately worn tires. No other braking aids were employed, such as reverse thrust for the 990A or the F-4D parabrake.

The computed comparisons of ungrooved and grooved all-weather landing field lengths (i.e., landing distances) for the 990A are shown in figure 2. Identical approach and landing characteristics up to brake engagement were assumed for each landing represented; therefore, the distance traveled prior to brake engagement (2800 feet) is the same for all the field lengths shown. This distance was held constant to facilitate comparison of all-weather braking distances and does not allow for increased decelerations due to spray and slush drag for the flooded and slush-covered runway surfaces.

For dry runway surfaces similar to the landing-research-runway test surfaces, the landing field length was approximately 4480 feet with or without grooving. The calculated dry-surface stopping distance from 135 knots is approximately 12 percent lower than that given in reference 2 for the same brake-engagement speed. Landing distances for the two wet and puddled ungrooved concrete surfaces A and D (see ref. 1 for descriptions of all lettered surfaces) were increased to approximately 7000 feet. Grooving these two surfaces by using the landing-research-runway transverse-groove configuration (represented by surfaces B and C) reduces the field-length increase attributable to wetness to approximately 100 feet.

An interesting effect of introducing smooth worn tires to the study is an increase in ungrooved-wet-surface braking distance of approximately 1500 feet on surface D, with no significant change in wet-surface stopping distance for worn tires on a grooved pavement having a texture similar to surface D (represented by surface C). The large increase in the landing distance for a wet and puddled ungrooved surface when worn tires are used emphasizes the importance of tire tread design and particularly the necessity for early replacement of worn tires for ungrooved-runway operations. If the runway is grooved, however, the use of worn tires instead of new tires does not significantly degrade the stopping capability on wet and puddled surfaces.

The wet and puddled ungrooved asphalt surfaces F and I exhibit much higher braking friction coefficients than did the wet ungrooved concrete surfaces A and D; therefore, relatively smaller landing-distance reductions (approximately 1000 feet) result from grooving these surfaces (see results from surfaces F, G, H, and I in fig. 2). Grooving is also effective in reducing landing distances for concrete runway surface D under flooded and slush-covered conditions, as indicated by the reductions in landing field length obtained for similarly textured grooved surface C under both flooded and slush-covered conditions. Slush contamination of the grooves, however, apparently causes a larger reduction in braking efficiency than does the flooded-surface condition.

A brief analytical study of the equations of motion as applied to flooded-runway braking was made for the 990A to determine some effects of cross-wind operations on landing field length. Since reference 3 had shown that negligible side forces were developed by locked wheels on wet surfaces, the flooded-surface locked-wheel 990A airplane braking data obtained on ungrooved surface D (ref. 1) were used to calculate the point of departure from the runway side boundary for assumed cross-wind conditions. Zero wheel side forces were assumed as were the required rudder deflections to maintain $\ddot{\psi} = 0$. Again, the approach-to-brake-engagement conditions of the landings in figure 2 were assumed. Results of this study indicate that a 10-knot direct cross wind could cause the 990A to exit the side boundary of an ungrooved concrete runway, flooded to a depth of from 0.1 inch to 0.3 inch and similar in texture to surface D, at approximately 6000 feet from the 50-foot obstacle clearance height and at a forward velocity of 82 knots. No sustained wheel lockups or directional control losses in cross winds were noted in analyzing the braking data obtained for the 990A on the flooded grooved surfaces of the landing research runway, so it is believed that the transverse-groove configuration did alleviate losses in directional stability and control.

Comparisons of all-weather landing field lengths for the F-4D are presented in figure 3. The allowable reductions in field length as a result of grooving are much more significant for the F-4D than for the 990A, since the braking friction coefficients were lower than for the 990A. For both airplanes, braking was initiated at approximately the same speed (see fig. 1), and the F-4D required 3200 feet to stop from the point of initial brake application as compared with about 1700 feet for the 990A under dry-surface conditions. This result reflects a significant reduction in dry-surface braking effectiveness for the F-4D as compared with the 990A airplane. This minimum dry-surface braking distance (3200 feet) calculated for the F-4D from landing-research-runway test results correlates with demonstrated and flight-manual values obtained for the airplane without parabrake (see fig. 3). Calculated landing field lengths for the wet and puddled ungrooved concrete surfaces A and D are approximately twice the corresponding dry-surface values. Grooving these wet surfaces (represented by surfaces B and C) results in increases of only 700 to 1200 feet over the dry-surface landing distance. For the wet ungrooved asphalt surfaces F and I, landing distances are only 340 to 1700 feet greater than for the wet grooved concrete surfaces tested. Grooving these asphalt surfaces reduces the wet-surface field length to about the dry-surface value. Results obtained for flooded concrete surface D indicate that approximately 11 500 feet would be required to land the F-4D under the assumed conditions. Introduction of grooving reduces this distance by approximately 40 percent. Asphalt surfaces similar to the landing-research-runway surface F provide flooded-surface landing distances of approximately 8700 feet. Grooving surface F (represented by surface G) reduces this flooded-surface field length by approximately 2800 feet.

Take-off Analysis

The definitions used in the take-off (T.O.) analysis are shown in figure 4. Balanced field lengths and critical engine-failure speeds were selected as parameters in comparing adverse-weather take-off performance levels for ungrooved and grooved runways with dry performance of the 990A and F-4D. Standard-day ambient conditions are assumed with no wind and level runway surfaces. The balanced field length is defined herein as the distance required, starting from brake release, to either successfully conduct a take-off or make a stop, with the assumption of a single engine failure at some critical airplane speed (called V, in this paper).

In either case (take-off continued or refused), maximum thrust accelerations are assumed from brake release up to a selected engine-failure speed. For the continued take-off the throttles are retained in maximum thrust settings, with linear thrust decay on the failed engine terminating 3.0 seconds after engine failure. Rotation velocities of 165 and 172 knots were chosen for the 990A and F-4D, respectively, with obstacle clearance heights of 35 feet for the 990A and 50 feet for the F-4D defining the terminal point of the continued take-off field length (see fig. 4). The refused take-off assumptions were a 1.5-second delay from engine failure to pilot recognition, a 0.5-second delay after recognition to apply maximum antiskid braking, a 3.0-second delay for the failed engine to lose thrust linearly, and a 3.0-second delay from the time of pilot recognition to idle thrust on the remaining engines. Spoiler deployment for the 990A and stabilizer deflection for the F-4D to produce maximum positive C_m were assumed complete at 3.0 seconds after the engine failure.

The method used in determining the balanced field lengths and V_1 speeds is shown in figure 5 for some particular all-weather runway condition. Calculated field lengths required for continued and refused take-offs are plotted as functions of engine-failure speed. The intersection indicates the balanced field length and the critical engine-failure speed V_1.

The implication associated with V_1 speed is that the pilot obtain from the flight manual a value of V_1 suitable for the existing runway length, and other conditions, prior to each take-off. A stop should be attempted in the case of take-off emergencies occurring below V_1, since the refusal field length is shorter in this region. Take-off should be continued at speeds above V_1 to utilize the favorable field lengths.

Some examples of the chosen technique are shown in figure 6 wherein balanced field lengths and V_1 speeds are determined for the 990A in the maximum take-off weight condition on wet and dry concrete surfaces. The continued take-off curve shown is representative for all the conditions indicated, since landing-research-runway test results show no appreciable spray drag for either airplane on wet and puddled surfaces. The dry-surface balanced field length is approximately 9600 feet, and the corresponding V_1 speed is 163 knots. Wetting the ungrooved concrete surface A increases the balanced field length to 10 800 feet, and the V_1 speed is reduced by some 20 knots. Establishing the V_1 speed for the wet surface A points out the potential hazards in attempting a refused take-off above this speed. If this same wet runway is, however, grooved (surface B), one might expect to exceed only slightly the dry-surface balanced field length at essentially the dry-surface critical engine-failure speed (see fig. 6). The increase in V_1 speed produced by grooving allows a significant delay in making a continued take-off decision from wet pavements. A similar analysis of F-4D balanced field lengths is shown in figure 7. Refused take-off field length for the wet ungrooved runway surface A is more than doubled at engine-failure speeds occurring at the dry-surface critical value, and the wet-surface V_1 occurs 50 knots below the dry-surface V_1. Grooving wet surface A (represented by surface B) brings the critical engine-failure speed and the balanced field take-off performance up to nearly the dry-surface level.

Figures 8 and 9 present a comparison for both airplanes of the dry and wet, ungrooved and grooved balanced field lengths. Critical engine-failure speeds are listed opposite the corresponding balanced field lengths required. The wet-surface critical engine-failure speeds are included, since they have been shown to be indicative of balanced field performance levels when compared with the dry-surface values. These figures indicate that grooving the runway surfaces of this study would, in essence, allow the use of dry-surface values for V_1 and for balanced field length during wet and puddled operations of both airplanes. All these values are, of course, amendable with the use of auxiliary deceleration aids such as reverse thrust for the 990A in the absence of appreciable cross winds (e.g., see ref. 4) or the F-4D parabrake, which were not included for purposes of this investigation.

Figure 10 shows some predicted results for the 990A regarding balanced field lengths and critical engine-failure speeds for concrete surfaces having a slush covering of 1/2 inch. Also shown are the predetermined dry-surface values for the maximum take-off weight. It is interesting to note the displacement of the take-off curve for grooved and ungrooved surfaces covered by 1/2 inch of slush. This displacement is primarily the result of slush drag on the nose and forward tires of the main gear as determined by the FAA investigation of slush effects in take-off of the Convair 880 (ref. 5), which has similar landing gear and tire configurations. This effect, coupled with reduced accelerations and friction coefficients for the refused take-off, increases the slush-covered ungrooved balanced field length to approximately 12 000 feet. The critical engine-failure speed is, in turn, reduced by approximately 20 knots from the dry-surface value. A reduction in balanced field length of only 500 feet and an increase in V_1 speed of about 10 knots is allowable through grooving of this concrete surface.

CONCLUSIONS

The present study of the effects of transverse runway grooving for the 990A and F-4D airplanes with regard to adverse-weather landing field lengths and balanced take-off field lengths indicates the following conclusions:

1. Transverse runway grooving effectively reduces landing field lengths under adverse weather conditions for a variety of runway surfaces.

2. Essentially dry balanced field take-off performance is attainable for grooved runway surfaces in a wet and puddled condition, since grooving increases the critical engine-failure speed to practically dry-surface values.

3. Only slight reductions in balanced field lengths are provided by grooving for take-off from slush-covered runways.

REFERENCES

1. Yager, Thomas J.: Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 3 herein.)
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3. Byrdsong, Thomas A.: Investigation of the Effect of Wheel Braking on Side-Force Capability of a Pneumatic Tire. NASA TN D-4602, 1968.
4. Horne, Walter B.; and Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.
5. Sommers, Daniel E.; Marcy, John F.; Klueg, Eugene P.; and Conley, Don W.: Runway Slush Effects on the Takeoff of a Jet Transport. Final Report, Project No. 308-3X, FAA, May 1962.

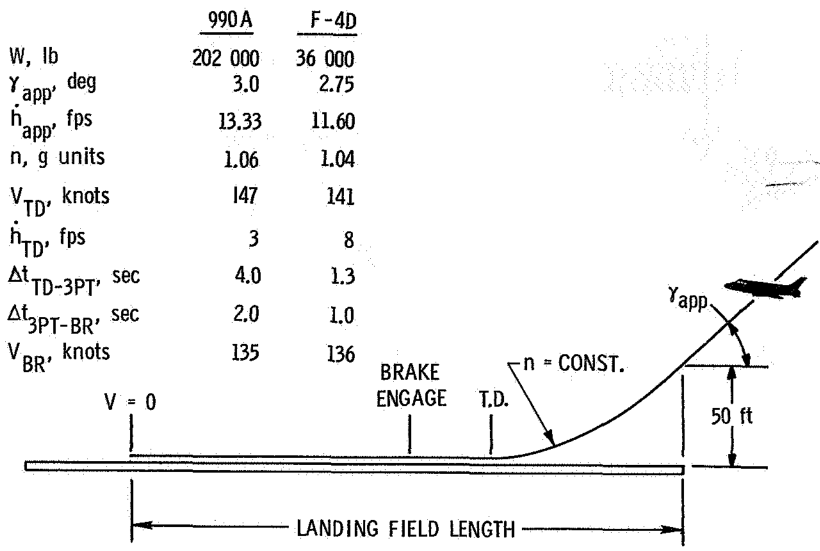

Figure 1.- Landing analysis. Standard day; sea level; no wind.

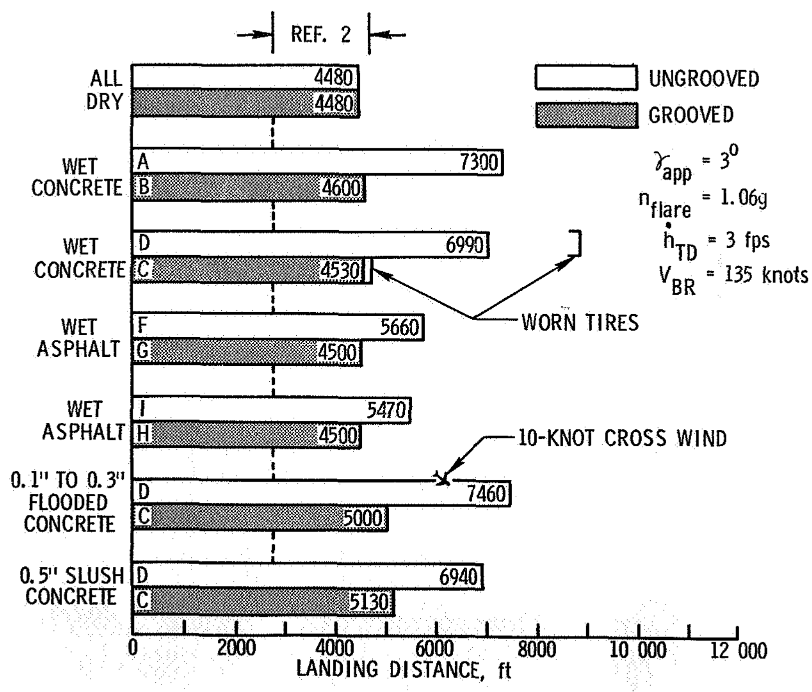

Figure 2.- Landing field lengths for 990A. Standard day; sea level; W = 202 000 lb.

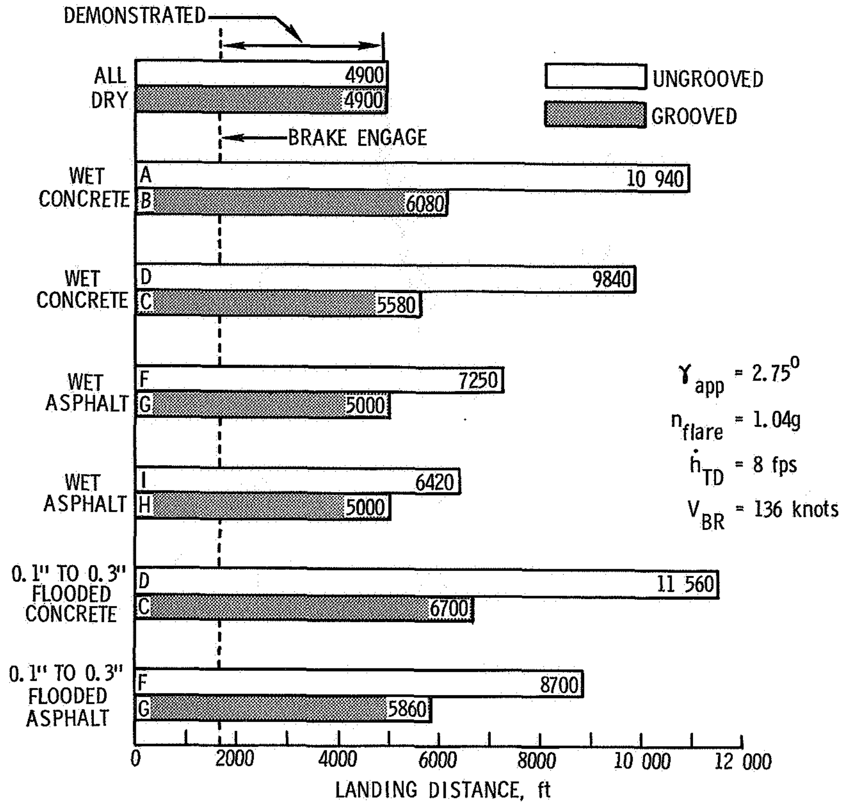

Figure 3.- Landing field lengths for F-4D. Standard day; sea level; W = 36 000 lb.

T.O. CONTINUED

$\Delta t_{T_1 = 0}$ = 3.0 sec

	990A	F-4D
V_r, knots	165	172
h_2, ft	35	50

T. O. REFUSED

Δt, sec	EVENT
0	ENGINE FAILURE
1.5	PILOT RECOGNITION
2.0	BRAKES ON
3.0	SPOILERS OR HORIZONTAL STABILIZERS DEPLOYED (T_1=0)
4.5	IDLE T_R

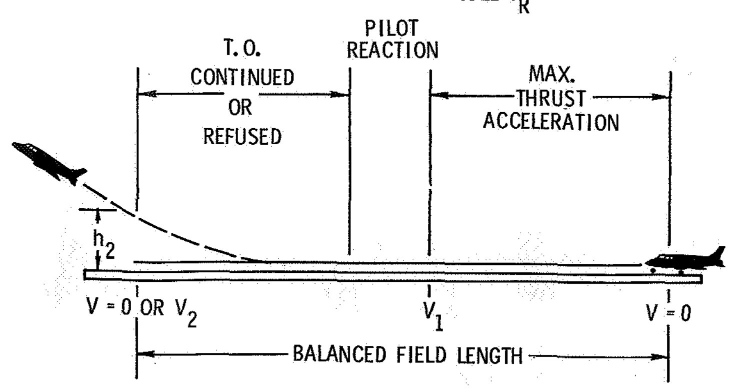

Figure 4.- Take-off analysis. Standard day; sea level; no wind; level runway.

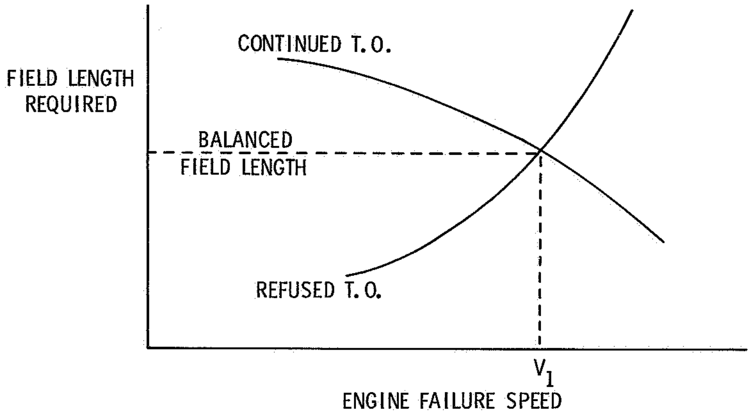

Figure 5.- Take-off balanced field length. Constant weight and ambient conditions.

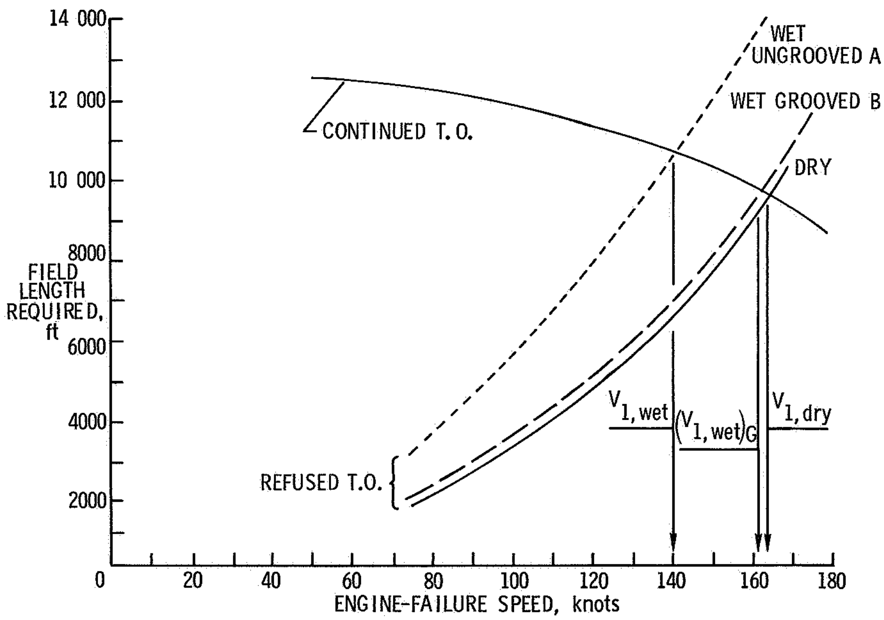

Figure 6.- Dry- and wet-surface balanced field lengths for 990A. W = 246 000 lb; concrete.

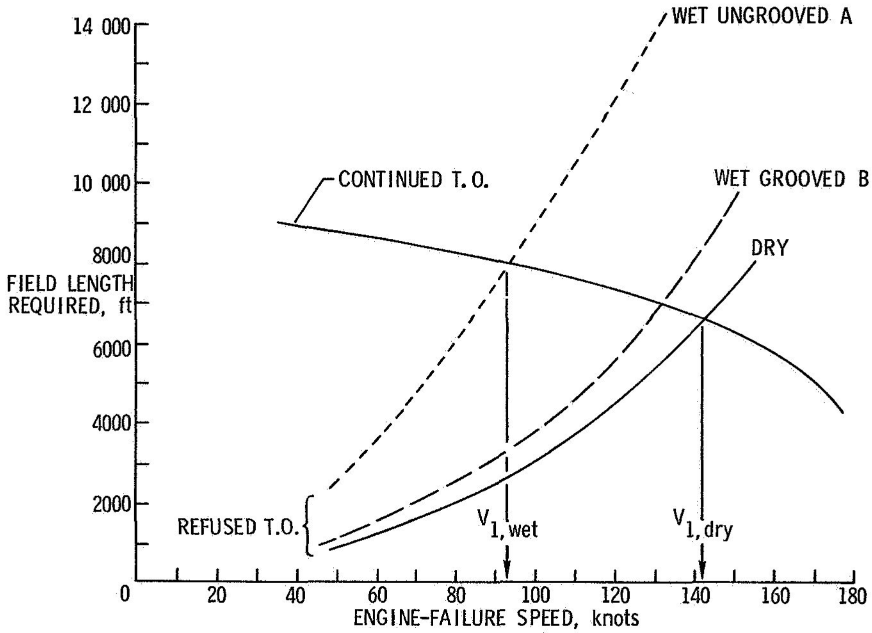

Figure 7.- Dry- and wet-surface balanced field lengths for F-4D. W = 48 000 lb; concrete.

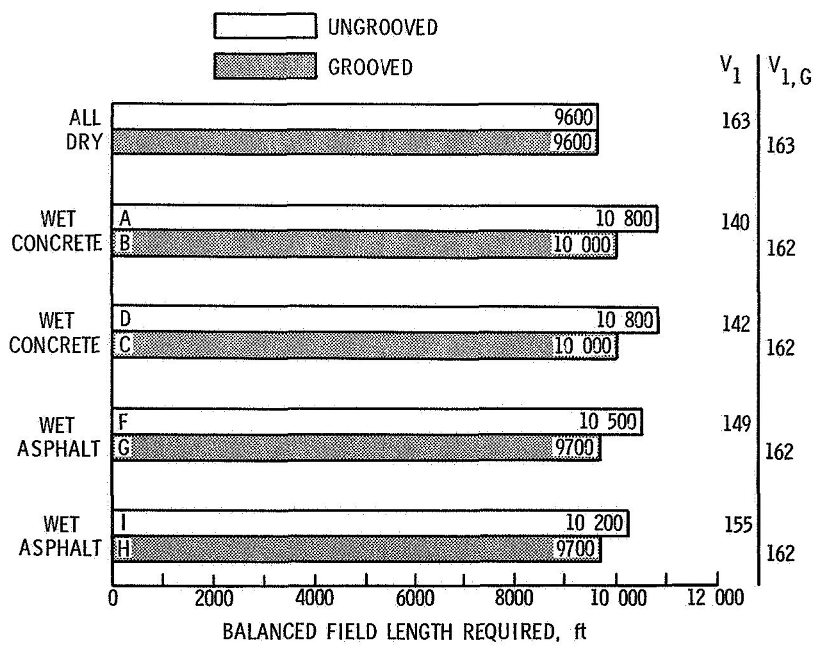

Figure 8.- Effect of grooving on take-off balanced field lengths for 990A. W = 246 000 lb.

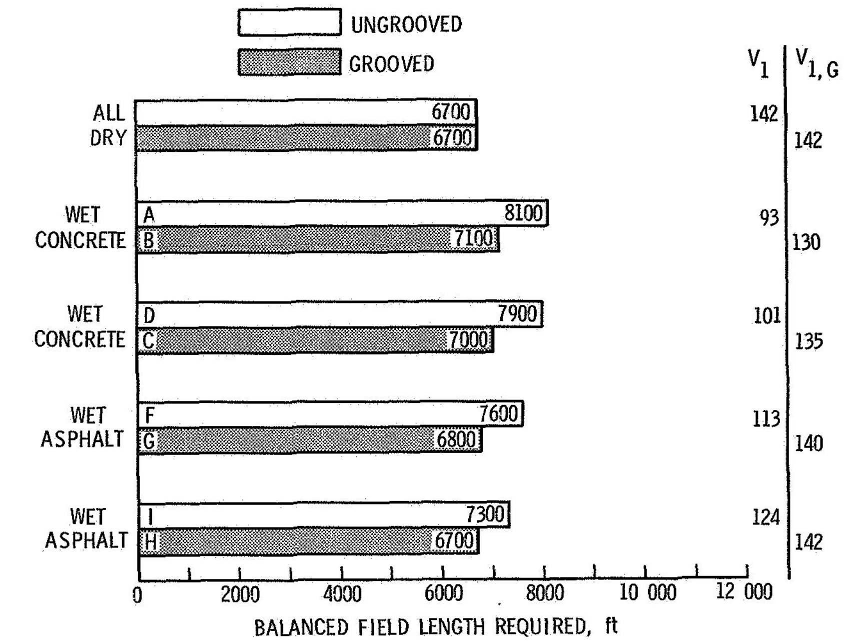

Figure 9.- Effect of grooving on take-off balanced field lengths for F-4D. W = 48 000 lb.

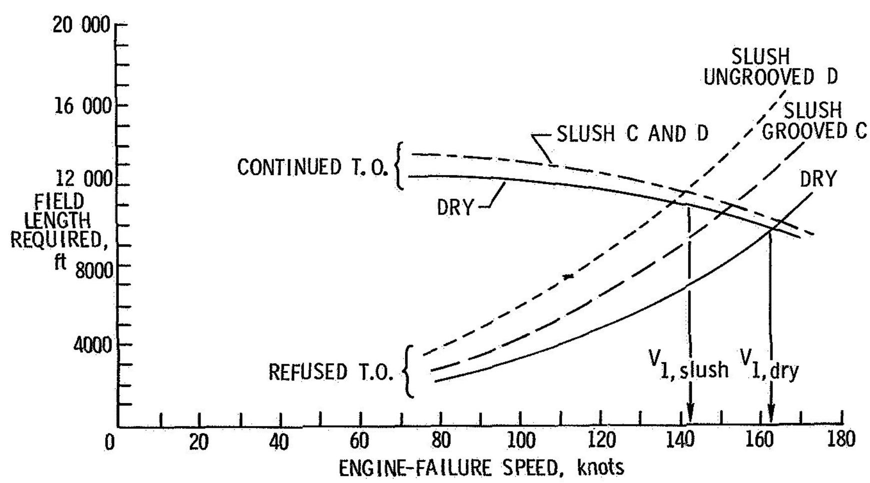

Figure 10.- Balanced field lengths for 990A on dry and slush-covered surfaces. Standard day; sea level; W = 246 000 lb; concrete.