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THE EFFECT OF WINDSHEAR DURING TAKEOFF ROLL ON AIRCRAFT STOPPING DISTANCE

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ABSTRACT

A simulation of a Boeing 727 aircraft during acceleration on the runway is used to determine the effect of windshear on stopping distance. Windshears of various magnitudes, durations, and onset times are simulated to assess the aircraft performance during an aborted takeoff on five different runway surfaces. A windshear detection system, active during the takeoff roll and similar to the Honeywell Windshear Detection System is simulated to provide a discrete to activate aircraft braking upon shear detection.

The results of the simulation indicate that several factors affect the distance required to stop the aircraft. Notable among these are gross weight, takeoff flap position, runway characteristics, and pilot reaction time. Of the windshear parameters of duration, onset and magnitude, magnitude appears to have the most significant effect.

INTRODUCTION

Low-level windshears have proven to be one of the most significant threats to aircraft safety. Several aircraft accidents have been directly attributed to the phenomenon, and, as a result, considerable progress has been made in the understanding of the atmospheric mechanisms, methodology of detection, and the control of the aircraft's flight path during a shear encounter.

The research has also resulted in the development of several on-board systems which have been certified by the FAA and are currently in use. These systems have proven effective in detecting the presence of a windshear and, in at least two cases, have been instrumental in the successful escape from an encountered windshear.

One aspect of the windshear problem which has not been adequately addressed, however, is the effect of windshear on the aircraft during takeoff roll: the time between the initial acceleration of the aircraft on the runway and lift off. Several cases of windshear encounters during the takeoff roll are known, the most notable being the incident of United Airlines Flight 663 at Stapleton International Airport on May 31, 1984. In this instance the aircraft, a Boeing 727, encountered the localizer antenna located 1074 feet (327 m) beyond the departure end of the runway. Fortunately, no injuries occurred, but substantial damage was done to the aircraft.

If a flight crew is aware of a windshear condition prior to obtaining the critical engine failure speed, V_1, they may elect to either abort the takeoff or to continue on through rotation and lift off. V_1 is thus a "go,no-go" speed which is generally determined by the aircraft's ability to stop within the remaining runway distance. V_1 is defined as a calibrated airspeed and thus differs from the actual ground speed of the aircraft by the magnitude of the wind. Consequently, the attainment of V_1 in a windshear condition does not necessarily assure that the aircraft can be safely stopped on the runway since the ground speed, and hence the kinetic energy of the aircraft, can be significantly higher than normal. The additional kinetic energy of the aircraft may result in a substantial increase in the required runway to safely stop the aircraft should the flight crew elect to abort the takeoff.

If the windshear is detected after obtaining V_1, the takeoff must be continued in most cases as the available runway to stop the aircraft is usually insufficient.

This paper addresses the problem of windshear occurring during takeoff roll by simulating an aircraft in various magnitudes, durations, and onset times of windshears, at different aircraft weights, and on different runway surfaces.

SIMULATION CONFIGURATION

A Boeing 727 aircraft was simulated on an Epson Equity III+ computer as a three degree of freedom model with an effective one-quarter second computational rate. Lift and drag were computed from curve fits of actual aircraft data with the assumption made that angle of attack, alpha, is constant during the ground roll. Ground effect on lift and drag were included in the simulation.

Thrust was computed from curve fits of Thrust/Delta versus Mach number for a fixed takeoff engine pressure ratio (EPR). The engines simulated were Pratt and Whitney JT8D-15 engines. To simulate engine spool down, a simple lag filter was utilized. Engine thrust reversers were not simulated.

The lift and drag effect of ground speedbrakes was simulated with the assumption that the ground speedbrakes achieve maximum deployment within 1 second.

The aircraft's antiskid system was simulated by assuming 60% efficiency in achieving the maximum coefficient of friction available for the runway surface.

Five runway surfaces were simulated: (a) dry surface; (b) wet, grooved asphalt; (c) wet, grooved concrete; (d) wet, textured asphalt; and (e) wet, textured concrete. The dry surface coefficient of friction was applicable to either asphalt or concrete. Coefficients of friction were derived from curve fits of available data and are shown on Figure 7.

Windshear models available were a linear horizontal shear and a vortex microburst model. The former was used for the simulation runs since it allowed more precise control of shear onset, magnitude, and duration.

The runway altitude was sea level for all cases and the ambient temperature assumed to be standard day, 59 degrees F (15 degrees C). The runway was assumed to have zero slope.

No explicit pilot model was necessary as braking is done by the antiskid system; however, recognition delays were incorporated to approximate pilot response. For all runs except those directed at pilot recognition time, the delay used was 1 second.

AIRCRAFT CONFIGURATION

The simulated flap setting for most takeoffs was 15 degrees, the most common setting for this aircraft. Aircraft weight could be varied, but, as might be expected, the heavy weight aircraft was most severely affected by the shears. To achieve worst case conditions, the aircraft weight was set at 210,000 pounds (95254 Kg). Other runs, not included in this paper, were conducted at 140,000 pounds (63503 Kg) and 175,000 pounds (79378 Kg).

SIMULATION RUNS

The aircraft was initialized at the end of the runway with full takeoff power set and brakes applied. At the start of the run, the brakes were released and the aircraft allowed to accelerate.

The simulated runway was infinitely long to preclude the complexity of altering aircraft weight and flap setting to produce a balanced field length. In this way, the worst case aircraft weight could be used throughout the runs.

To provide baseline data in no shear conditions, an aborted takeoff was performed when the aircraft achieved V_1. Following the recognition delay, the thrust was reduced to idle, the ground speed brakes deployed, and the antiskid system activated to provide braking. The total runway used thus provided a baseline value for comparing the effect of a windshear.

RUNWAY SURFACE TYPES

As windshears may or may not be accompanied by rain, it is important to assess the aircraft's performance on both dry and wet runways. A wet runway is assumed to have from 0 to .5 inch (1.27 cm) of standing water. The type of runway surface can also have significant effects on braking performance. Consequently, the studies used grooved and textured asphalt and concrete runways. For convenience, mnemonics were used for the runway types according to Table 1:

Table 1

Mnemonic	Runway Surface
DRY	Dry Asphalt or Concrete
GVD ASPH	Wet, Grooved Asphalt
GVD CONC	Wet, Grooved Concrete
TEX ASPH	Wet, Textured Asphalt
TEX CONC	Wet, Textured Concrete

EFFECT OF FLAPS ON STOPPING DISTANCE

The flight crew's selection of takeoff flaps significantly alters the amount of runway required to stop the aircraft. The total runway required to accelerate the aircraft to V_1 and then come to a complete stop using the available takeoff flap settings for the Boeing 727 is shown on Figure 1. Clearly, the flap setting of 25 degrees provides the minimum runway usage. This is primarily because V_1 for 25 degrees of flaps is significantly lower than the others. Consequently, the aircraft achieves V_1 with lower runway usage and also has a lower kinetic energy.

However, consideration must be given to aircraft performance once airborne in the event the flight crew elects to continue the takeoff. For the Boeing 727, for example, a flap setting of 15 degrees is preferred for airborne performance and consequently, 15 degrees should be used as a compromise between stopping distance and airborne performance.

As the incremental runway distance between a flap setting of 5 degrees and 15 degrees is significantly more than that between flap settings of 15 and 25 degrees, one must conclude that a flap setting of 5 degrees for takeoff should not be used if windshear is suspected.

EFFECT OF WINDSHEAR ONSET

To assess the effect of shear onset time on stopping distance, a constant shear of 5 knots per second (2.57 m/sec/sec) was introduced at specified points as the aircraft accelerated. The shear, once started, was of infinite duration. Upon detection and recognition of the shear, the takeoff was aborted. As can be seen in Figure 2, the total runway used in most cases was less than or equal to the distance for the no shear case. The times on the Figure indicate the time of shear onset as measured from initial brake release.

In the cases where shear onset occurred slightly before obtaining V_1 speed, the total runway usage was increased, but not dramatically so.

EFFECT OF WINDSHEAR DURATION

The effect of the duration of several shears of different magnitudes was investigated to determine the increase in total runway used in coming to a complete stop. In each case, the onset of the shear was at approximately 10 knots before V_1 speed. Figure 3 illustrates the results. The ordinate axis yields the total runway used in thousands of feet. The magnitude of the shear used was 5 knots per second. For the dry runway or wet, grooved runways the additional runway used is virtually independent of shear duration.

For the wet, textured asphalt or concrete runway, noticeable increases in runway used are evident. However, once the duration of the shear exceeds 15 seconds, the total runway used is approximately constant, leading one to conclude that shear duration is not a prime consideration except on textured surfaces.

EFFECT OF WINDSHEAR MAGNITUDE

A series of runs was conducted in which the shear onset, detection, and reaction coincided with attaining V_1. After onset, the shear was sustained indefinitely. Figure 4 illustrates the results of the simulation runs. The ordinate axis gives runway distance in thousands of feet.

The data indicate that shear magnitude is not of prime concern for the dry or wet, grooved surfaces. Significant increases in total distance used are evident in the wet, textured surfaces, however.

EFFECT OF UNDETECTED WINDSHEARS

As of the time of this writing, no on-board system is available that will detect a shear during takeoff roll, although one such system is now in the certification process. Consequently, it is left to the flight crew to determine whether or not a windshear is present during takeoff roll. The detection of such shears can be difficult since the aircraft is accelerating and the shear may be accompanied by turbulence. In the simulation runs, the magnitudes of the shears were intentionally made small to simulate shears that might go unnoticed by the flight crew. The onset of the shears occurred approximately 10 knots before V_1 speed and the shear was then maintained indefinitely. When the aircraft achieved V_1 speed, it was braked to a full stop and the total runway used noted. A graph of total runway used versus shear magnitude is shown on Figure 5. Undetected shear magnitudes of 2 knots per second or less have profound effects on the total runway used, particularly for the heavy weight aircraft. This is a consequence of shear causing a low air mass acceleration which, in turn, causes V_1 speed to be achieved much further down the runway than normally.

EFFECT OF PILOT RECOGNITION

To assess the effect of a recognition delay in reacting to a detected shear condition, simulation runs were made with reaction delays of 0, 1, 2, 3, 4, and 5 seconds. The results of the runs are shown on Figure 6. In these cases, a 5 knot per second infinite shear began at V_1. The reaction time represents the number of seconds between detection of the shear and the pilot reaction of reducing thrust, braking, and deploying the ground speed brakes. As can be seen, the effects are dramatic, particularly for the longer delay times. On the average, about 4% more runway is used for each additional second of delay, regardless of the surface type.

CONCLUSIONS

The data indicate that flap setting, runway surface type, and pilot recognition time are all prime factors in determining total runway used. A worst case scenario for this aircraft would be heavy gross weight with 5 degree takeoff flaps on a wet, textured concrete runway. A long recognition time further aggravates the situation.

Consequently, one may conclude that the largest possible takeoff flap setting consistent with good airborne performance should be used. For the 727 aircraft, this is a flap setting of 15 degrees.

Timely pilot recognition and reaction to a windshear condition on takeoff should and can be reenforced by simulator training. As mentioned above, approximately 4% more runway is used for each second of pilot reaction time. It is difficult to overemphasize the necessity for rapid response to a windshear condition, particularly if the takeoff is to be aborted.

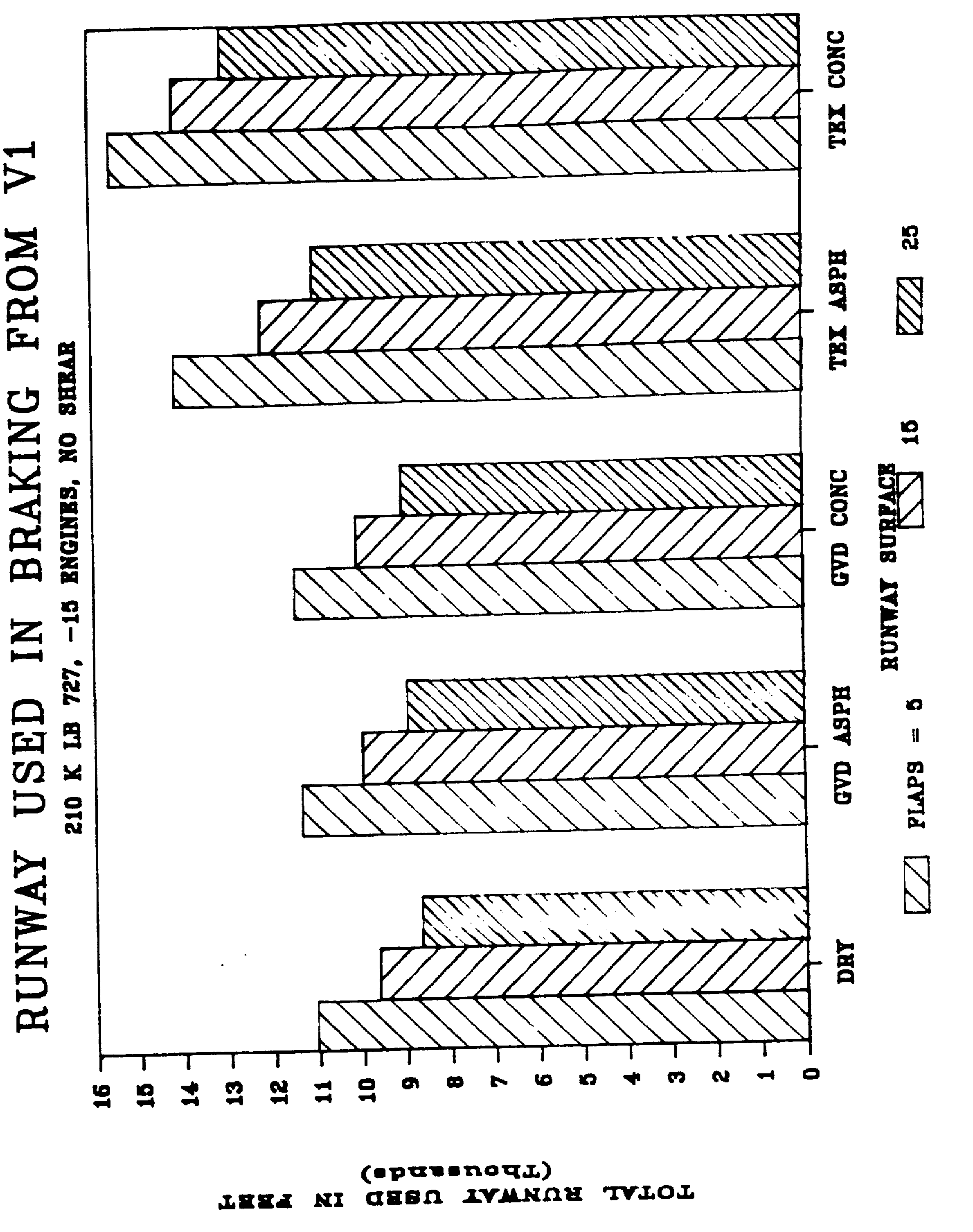
It is interesting that windshears occurring on dry; wet, grooved asphalt; and wet, grooved concrete runways have such a small effect on braking performance. With a shear magnitude of 5 kt/sec occurring at V_1, typical increases in required distance were of the order of 1%.

The effect of ungrooved runway surfaces, however, is significant. A 5 kt/sec shear encountered at V_1 increases the total runway usage by almost 12% for a wet, textured concrete surface. The corresponding number for the asphalt runway is 5.4%. It should be noted also, however, that an aircraft on a wet, textured concrete runway requires about 46% more distance to stop even without a windshear than would be needed if the runway surface were dry.

The effect of shear onset and shear duration did not appear to seriously affect the aircraft's braking performance. Of the detected shears, shear magnitude seemed most significant in terms of braking distance.

Undetected shears resulted in large increases in runway required - up to 56%. However, it is unlikely that the pilot would elect to abort in these cases. It is also unlikely that a low level shear would be sustained for long periods of time. The simulations did provide an indication of the importance of shear detection on the runway, however.

It is important to note that the effect of Windshear Detection System delays were not included in the analysis. Detection delays due to computation and filtering can add appreciably to the total runway used in a windshear condition. The effect of the delays is comparable to the pilot reaction delays discussed in the paper: for each second of delay time, up to 4% more runway may be required to stop the aircraft.


RUNWAY USED IN BRAKING FROM V1
210 K LB 727, -15 ENGINES, NO SHEAR
TOTAL RUNWAY USED IN FEET
(Thousands)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
DRY
GVD ASPH
GVD CONC
TEX ASPH
TEX CONC
RUNWAY SURFACE
FLAPS = 5
15
25

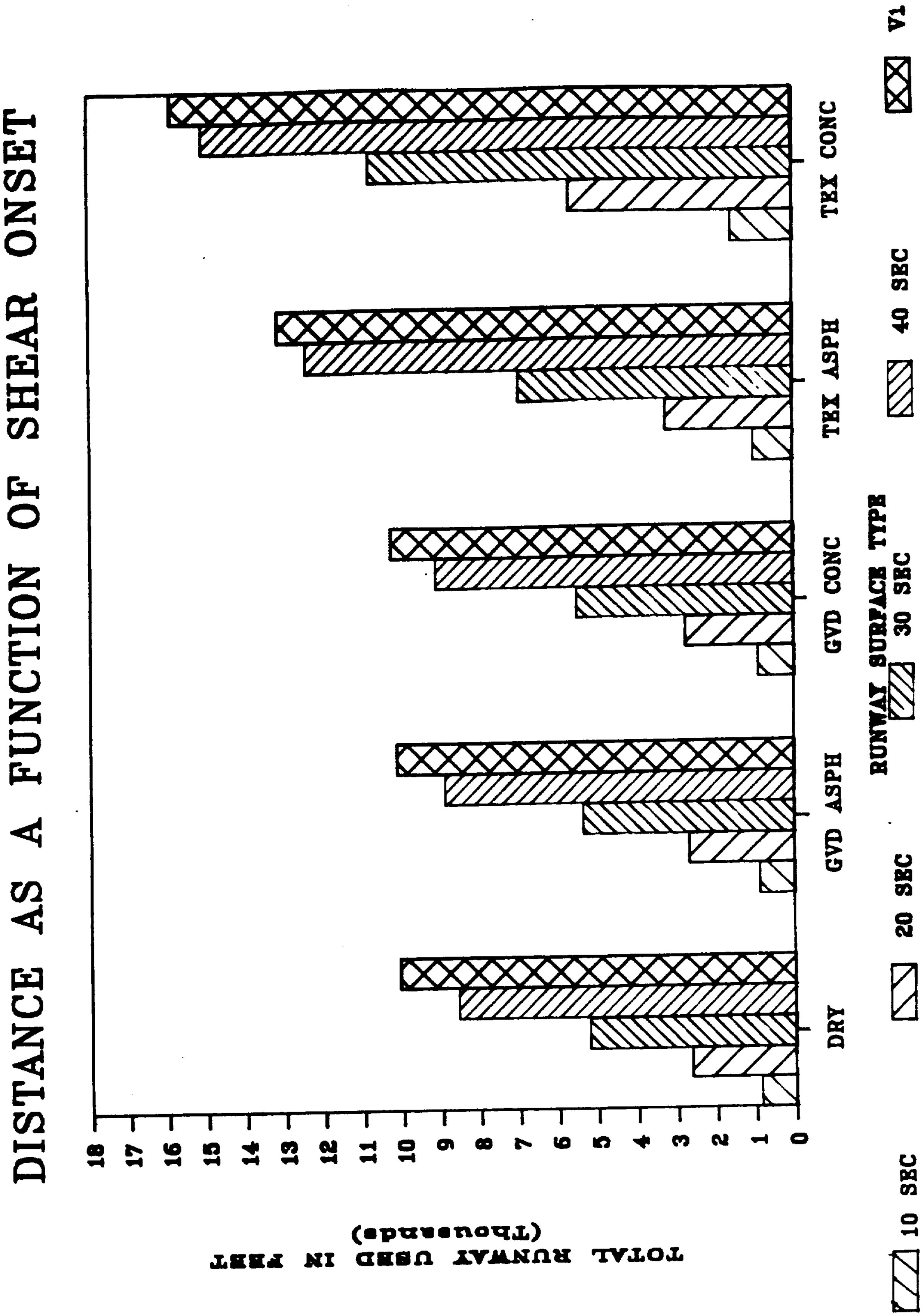

DISTANCE AS A FUNCTION OF SHEAR ONSET
TOTAL RUNWAY USED IN FEET
(Thousands)
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
DRY
GVD ASPH
GVD CONC
TEX ASPH
TEX CONC
RUNWAY SURFACE TYPE
10 SEC
20 SEC
30 SEC
40 SEC
V1

FIGURE 8

EFFECT OF SHEAR DURATION

210 K LB 727, FLAPS 15, 5 KT/S SHEAR

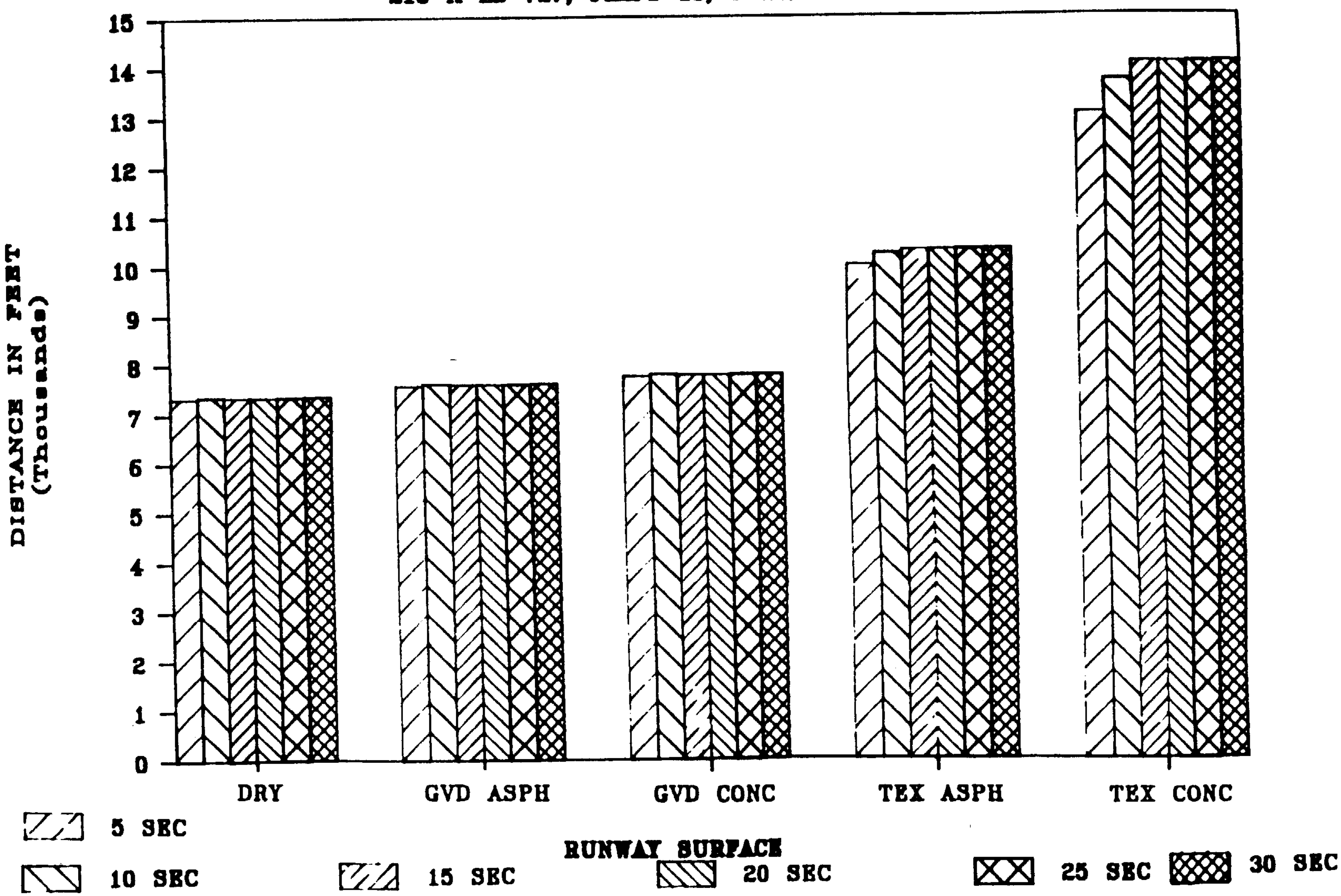
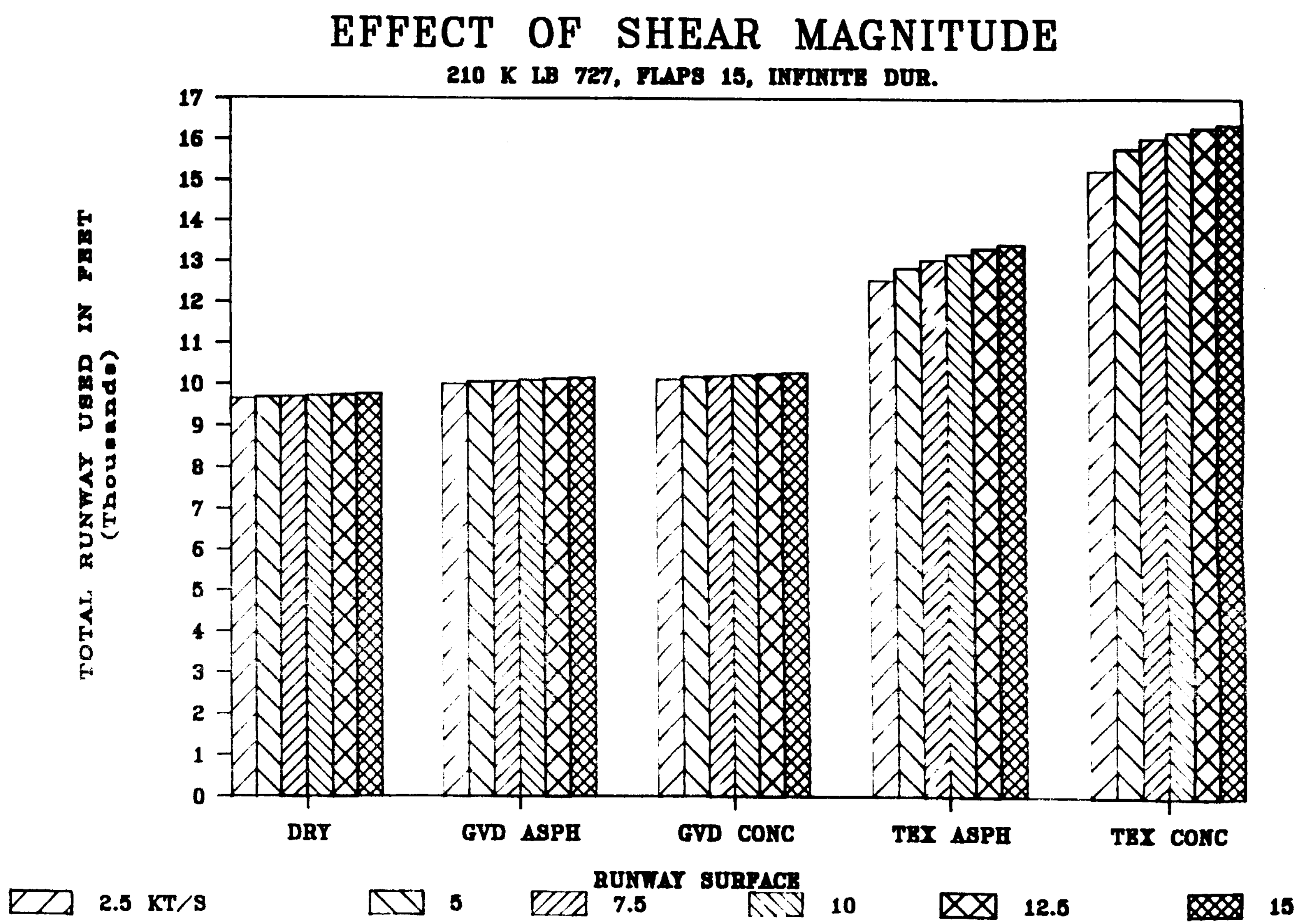


FIGURE 3



EFFECT OF SHEAR MAGNITUDE
210 K LB 727, FLAPS 15, INFINITE DUR.
TOTAL RUNWAY USED IN FEET
(Thousands)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
DRY
GVD ASPH
GVD CONC
TEX ASPH
TEX CONC
RUNWAY SURFACE
2.5 KT/S
5
7.5
10
12.5
15

FIGURE 4

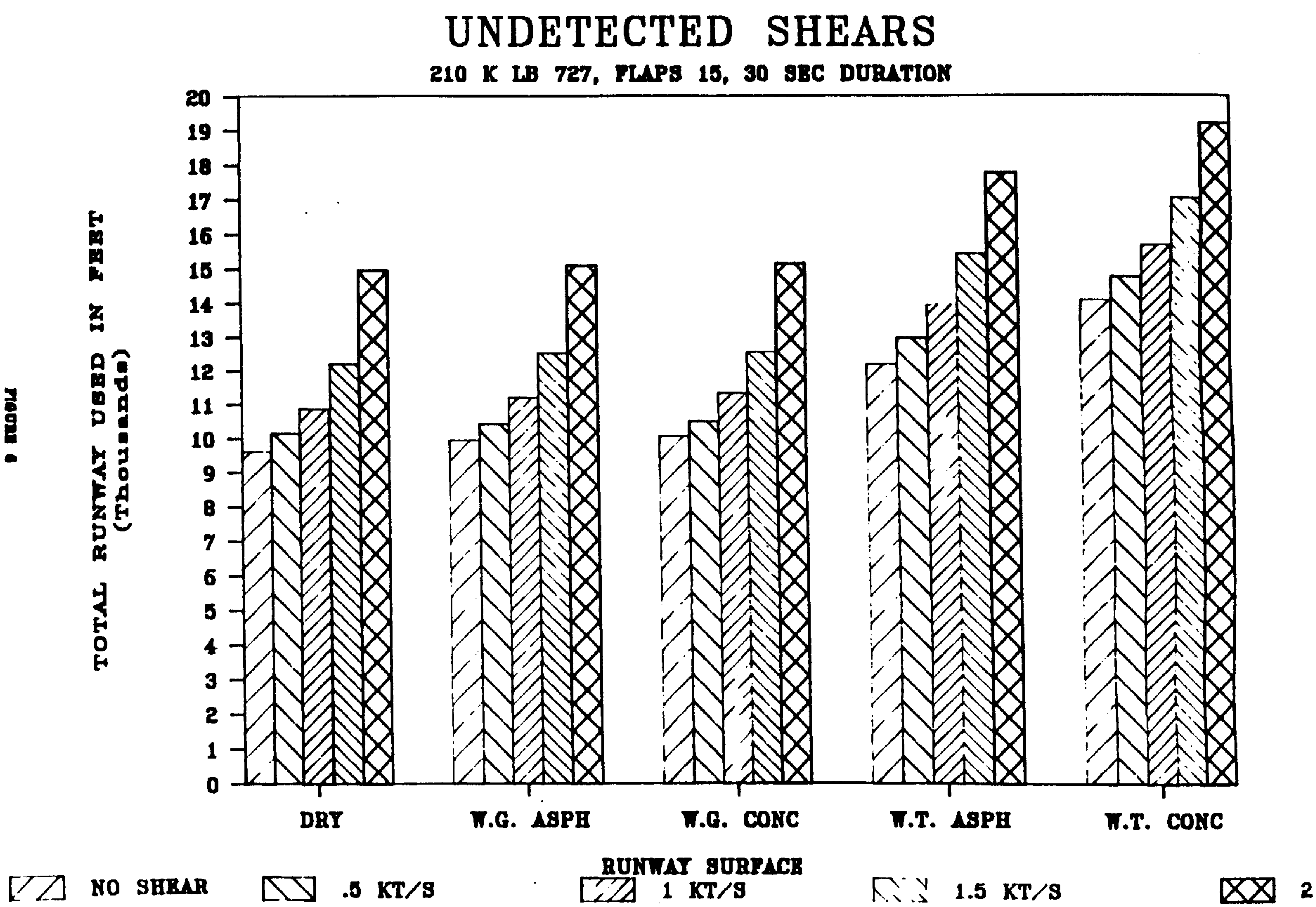

UNDETECTED SHEARS
210 K LB 727, FLAPS 15, 30 SEC DURATION
TOTAL RUNWAY USED IN FEET
(Thousands)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
DRY
W.G. ASPH
W.G. CONC
W.T. ASPH
W.T. CONC
RUNWAY SURFACE
NO SHEAR
.5 KT/S
1 KT/S
1.5 KT/S
2

FIGURE 6

EFFECT OF PILOT REACTION TIME

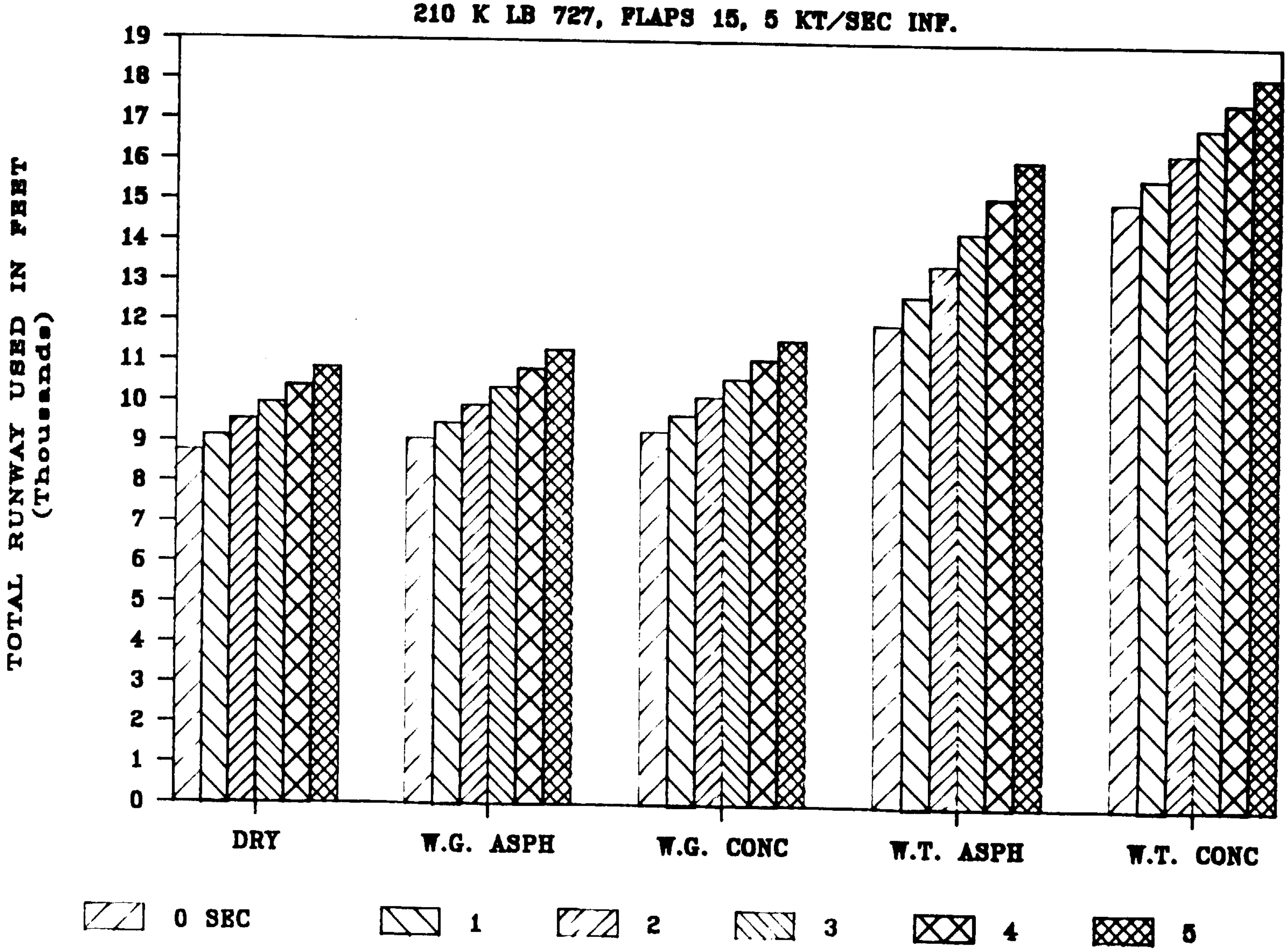


FIGURE [illegible]