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THE BRAKING PERFORMANCE OF AN AIRCRAFT TIRE ON GROOVED PORTLAND--ETC(U)
JAN 81 S K AGRAWAL, H DAIUTOLO

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THE BRAKING PERFORMANCE OF AN AIRCRAFT TIRE ON GROOVED PORTLAND CEMENT CONCRETE SURFACES

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INTERIM REPORT

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16. Abstract

Introduction of transverse grooves on runways improves braking and cornering performance of aircraft during operations in wet weather conditions and helps to alleviate hydroplaning. The Federal Aviation Administration (FAA) has recommended 1/4-inch square grooves spaced at 1-1/4 inches for installation on runways where the potential of hydroplaning exists. However, a large number of runways remain nongrooved. The major reasons are the high cost of groove installation and limited evidence as to the effectiveness of the grooved surfaces at the touchdown speeds of modern aircraft.

The findings of the research described in this report indicate that by increasing the spacing of the conventional saw-cut grooves (in the portland cement concrete surfaces) up to 3 inches, groove installation cost can be reduced by up to 25 percent compared to the installation cost of grooves spaced at 1-1/4 inches. The results further show that the friction levels available on these grooves under wet operating conditions are not significantly below those attained on grooves spaced at 1-1/4 inches. These results are valid for operating speeds of up to 150 knots. The results also show that a reflex-percussive cutting process is an alternative groove installation technique that produces V-grooves which provide braking performance comparable to that of conventional saw-cut grooves. The installation cost of these alternative grooves can be substanially less than that of saw-cut grooves.

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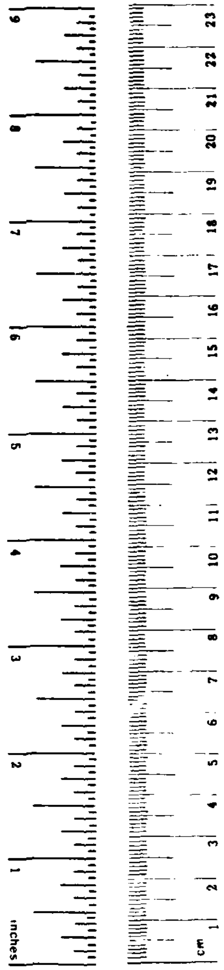
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

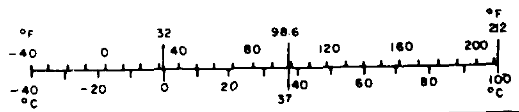
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly) [illegible] Units of Weights and Measures, Price $2.25, SD Catalog No. [illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work described in this report was undertaken and accomplished in response to a request for research, development, and engineering effort from the Office of Airport Standards in the Federal Aviation Administration (FAA). The Airport Development Division of the Systems Research and Development Service provided program direction. The Naval Air Engineering Center, Lakehurst, N.J., provided test facility operation and data acquisition.

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INTRODUCTION

The braking and cornering performance of an aircraft during landing operations depends upon the magnitude of the horizontal forces developed at tire/runway interface. This interface is commonly referred to as the footprint. The ratio of the horizontal forces in the footprint and the vertical force on the tire is defined as the coefficient of friction. The braking performance is controlled by the horizontal force in the direction of tire travel, and the cornering performance is determined by the horizontal force in the direction perpendicular to the direction of tire travel.

The magnitude of the coefficient of friction is influenced by many parameters. The important parameters are: speed of operation, runway surface texture and drainage capacity, contaminants, condition of tire tread, and the braking system characteristics. The presence of water on the runways adversely affects the level of friction available for aircraft speed and directional control (braking and cornering). An extreme case of loss of control is hydroplaning.

Hydroplaning is a peculiar tire-to-runway condition where the physical contact between the tires and the runway is lost, and the tires are supported on the intervening layer of water. The separation of the tire from the runway results when the sum of the forces from the hydrodynamic and the viscous pressures in the footprint exceed the vertical force on the tire. Hydrodynamic forces result from fluid density effects and are predominant where large water depths are present on the runway. Viscous forces result from fluid viscosity effects and are predominant where a thin water film is present on a smooth runway. In all cases, however, both effects are present to some degree. Dynamic hydroplaning and viscous hydroplaning are alternatively used to identify whether the density and viscous effects, respectively, are predominant.

During dynamic hydroplaning, the tire surface in the footprint is deformed by the rapid buildup of hydrodynamic forces; the space so created is filled with water which cannot escape. The rapid buildup of these forces can be eliminated if bulk water is removed from the tire path. Runway grooves provide escape paths for water during the tire passage over the runway. For viscous hydroplaning to be alleviated, sharp runway microtexture that can penetrate through the thin viscous film of water is required.

Introduction of transverse grooves cut into the runway surface was first initiated by British researchers in 1956 (reference 1). Isolated puddles that are likely to be formed on nongrooved surfaces because of uneven surface profile are generally not visible when the same surface is grooved. This is particularly significant where large temperature variations may cause low magnitude undulations in the runway surface.

Grooves are identified by pitch, width, and depth. The pitch is the distance between groove centerlines and is often referred to as groove spacing.

Pavement grooves were extensively studied by the National Aeronautics and Space Administration (NASA) in 1962 and 1964 (reference 2). In 1967, NASA conducted another experimental investigation to determine the groove configuration that provided the best cornering and braking performance under wet operating conditions (reference 3). Three pitches were used: 1 inch, 1-1/2 inches, and 2 inches. Various groove widths and depths were included in the test program. NASA concluded that all groove configurations provided improved cornering and braking performances relative to nongrooved surfaces; however, the 1-inch by 1/4-inch by 1/4-inch groove configuration provided the greatest increase in available friction (reference 3). Based on these and further tests by NASA (references 4 and 5), the Federal Aviation Administration (FAA) has recommended (reference 6) a standard 1-1/4-inch by 1/4-inch by 1/4-inch groove configuration and has encouraged airport operators, managers, and owners to groove runways where the potential of hydroplaning exists.

Regardless of the fact that runway grooves improve braking and cornering performance of aircraft and help alleviate hydroplaning, a large number of runways have not been grooved. The major deterrents to the use and acceptability of runway grooves are the high installation cost and only limited evidence as to the effectiveness of grooved surfaces at the touchdown speeds of air-carrier jet aircraft.

The cost of groove installation can be substantially reduced (reference 7) by increasing the groove spacing beyond the currently recommended (reference 6) value. However, the effectiveness of these grooves in terms of braking performance of the aircraft/tire/runway system may also be affected. This relationship between cost and effectiveness is not known. The research described in this document attempts to provide information about the cost-effectiveness of grooves of various pitches on the portland cement concrete (pcc) surfaces. The research effort is limited to evaluation of the braking performance on water-covered surfaces; operation on dry surfaces is relatively safer even when the surfaces are not grooved. As an alternative to the conventional saw-cutting technique, other groove installation methods were also investigated as part of this research.

OBJECTIVES

There are three objectives of this test program. They are:

1. Determination of a cost-effective configuration for the conventional saw-cut grooves on pcc.

2. Evaluation of alternative groove installation techniques competitive to saw-cutting; and

3. Evaluation of the performance of alternative grooves relative to saw-cut grooves on pcc.

SCOPE OF THE INVESTIGATION

Low grooving cost and acceptable braking performance are the two key factors in determining a cost-effective configuration for the saw-cut grooves. The term "acceptable braking performance" is subjective and is so treated in this study. As such, the acceptable performance is defined as follows:

The available friction levels on water-covered surfaces which have grooves installed at pitches in excess of 1-1/4 inches are significantly higher than on the nongrooved surfaces and are not significantly lower than on the 1-1/4-inch pitch grooves currently recommended (reference 6).

The groove configurations which satisfy the above definition are then evaluated in terms of grooving costs. The configurations which provide acceptable performance and low grooving cost will be identified as cost-effective. In this evaluation process, it is possible that more than one configuration may be identified as cost-effective.

A new groove configuration can be obtained by changing the pitch, the width, or the depth of the groove, and the braking performance of each new groove configuration could then be evaluated. However, the cost of such a vast program would be prohibitive. Therefore, in order to rationalize the basis on which to choose the groove dimension or dimensions that should be varied in the experimental program, a construction cost consultant was contracted to examine the cost savings available on different groove sizes and pitches. Grooving costs were sampled in the Northeastern, Midwestern, and Southwestern United States by the firm of Edward Sharf and Sons of Washington, D.C. (reference 7). Their investigation concluded that increasing the groove pitch has significantly more cost-saving potential than changing the groove size. Their results are valid for both the pcc surfaces and the asphaltic concrete surfaces. The experimental program described in this document, therefore, included the groove pitch as the major test variable. Various groove pitches between 1-1/4 inches and 4 inches were included in the program. Nongrooved surfaces were also included for determining the relative improvement in performance available as a result of grooving. A machine for installing saw-cut grooves was developed by the U.S. Navy for the test program and is shown in figure 1, which also shows the 3-inch by 1/4-inch by 1/4-inch groove configuration.

Evaluation of alternative grooving techniques is limited to a reflex-percussive cutting process. The reflex-percussive method of controlled concrete removal was recognized by the Concrete Society of Great Britain in 1972. This method was first developed to obtain a very rough finish on the pavement. When the cutting head strikes the surface of the concrete, it causes the material directly under the area of impact to deflect downward, thus creating a momentary and localized compression. The compressive strain is mainly elastic, and it is almost immediately given up in generating a rebound and causes the concrete to attempt to pass through its relaxed state into one of tension nearly equal to the initial compression. However, being very weak in tension, the concrete fractures and elastic energy is given up as kinetic energy of the flying fragments. The great advantage of this method of cutting is its ability of not loosening the aggregate particles within the matrix or creating micro fractures in the undamaged surrounding concrete. This technique provides a nonsymmetrical V-shaped groove cross section. The grooving machine is shown in figure 2.

The inclusion of these grooves in the experimental program was based on two factors. First, the cost-saving potential of this process was high because of the high operating speed of the machine and the longer life of replacement parts. Furthermore, the Canadian manufacturer, who held the patent for the application of the percussive cutting process for grooving, had demonstrated the economics associated with the process during resurfacing of part of an operating runway. Second, the evaluation of two other potential grooving techniques showed them to be unsatisfactory for further consideration either because of the nonuniformity of the grooves so produced or because of chipping and spalling of the surface resulting from the process. Figure 3 shows the groove configuration obtained by one of these techniques — a high speed water jet cutting technique (reference 8). For comparison, saw-cut grooves and V-grooves are also shown in this figure. The other technique, which uses the principle of vibration kerfing, was found not to be a viable cost competitive method for grooving because of inherent weaknesses in obtaining perfect alignment of the kerfing tool which resulted in a bush hammer effect (reference 9).

This program considered only the pcc surfaces. Testing on asphaltic concrete

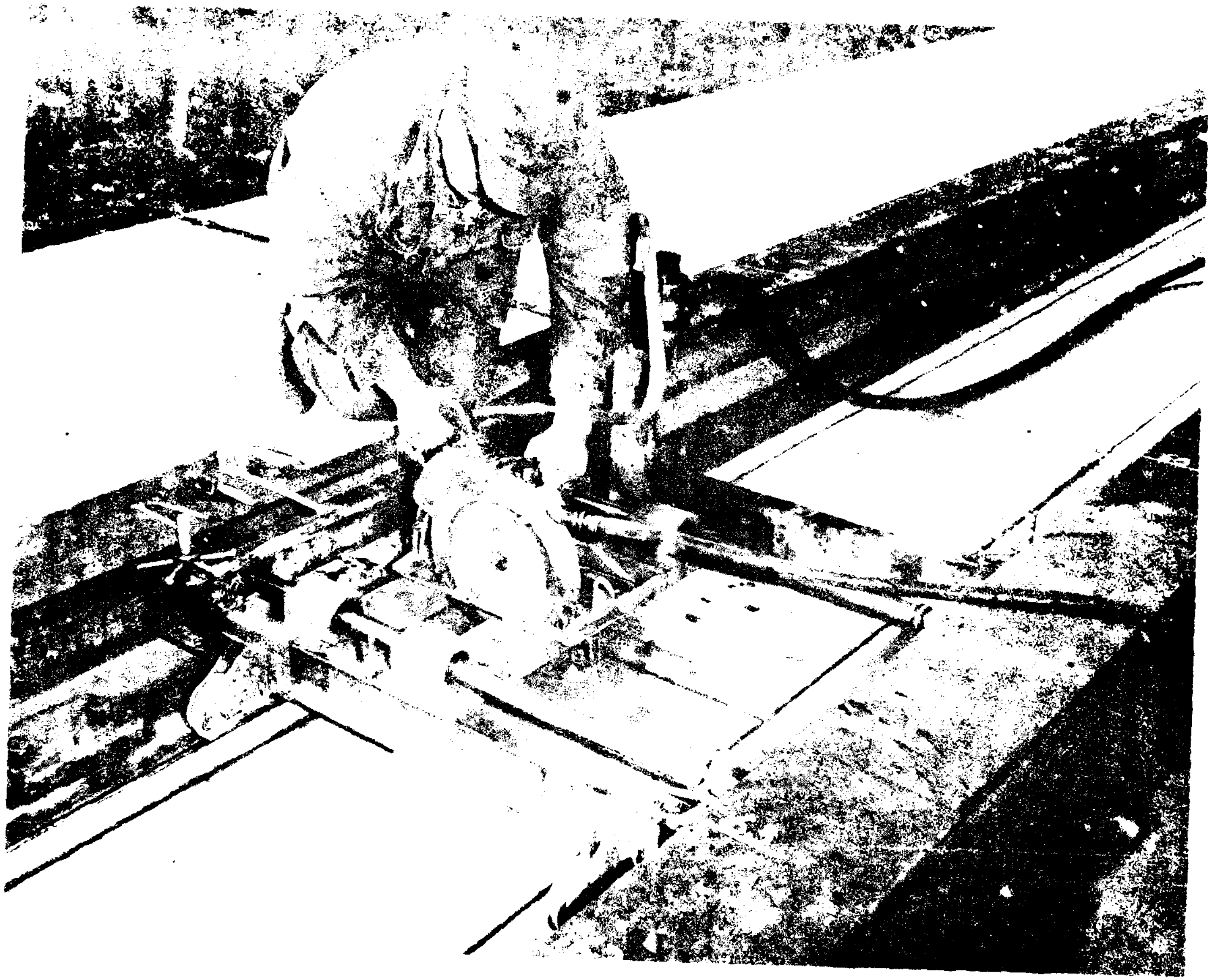


FIGURE 1. GROOVING MACHINE USED FOR CUTTING 1/4-IN. WIDE BY 1/4-IN. DEEP GROOVES AT VARIOUS PITCHES IN THE TEST SECTIONS

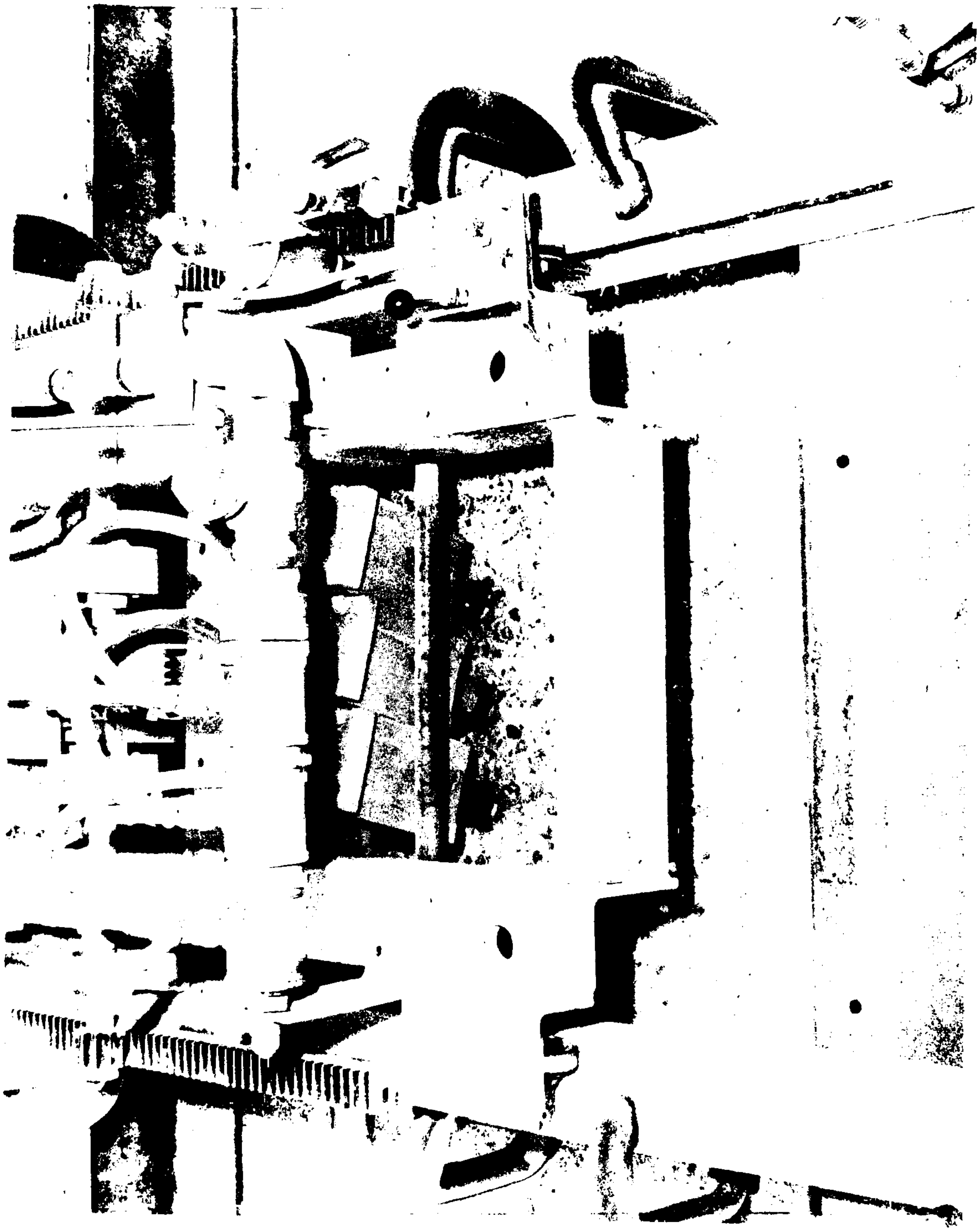
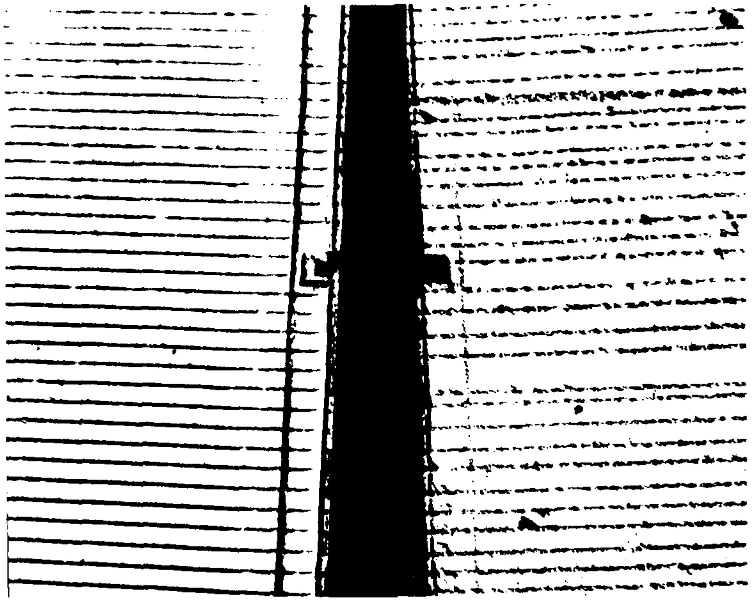


FIGURE 2. MACHINE FOR CUTTING REFLEX-PERCUSSIVE GROOVES IN THE TEST SECTIONS



1
GROOVES PRODUCED
BY SAW CUTTING

2
GROOVES PRODUCED
BY WATER-JET CUTTING

3
GROOVES PRODUCED BY
REFLEX-PERCUSSIVE PROCESS

80-35-3

FIGURE 3. COMPARISON OF GROOVES PRODUCED BY HIGH-SPEED WATER JET TECHNIQUE, BY SAW-CUTTING TECHNIQUE, AND BY REFLEX-PERCUSSIVE PROCESS

surfaces will be accomplished in a subsequent program. The terms "conventional saw-cut grooves" or "saw-cut grooves" and "reflex-percussive V-grooves" or "V-grooves" will frequently be used in the remainder of this report to identify the two distinctly different types of grooves investigated in this study.

EXPERIMENTAL PROGRAM

TEST FACILITY AND EQUIPMENT.

The test program was conducted at the Naval Air Engineering Center, Lakehurst, N.J. Track No. 1 at this facility was jointly developed by the FAA and the U.S. Navy and has the capability of simulating a jet transport tire-wheel assembly under touchdown and rollout conditions. Test speeds of up to 150 knots can be attained on this test track. The track is 1 mile long with guide rails spaced 52-1/2 inches apart. Reinforced concrete strips extend beyond the rails to a width of 28 feet. A four-wheeled jet car, powered with J48-P-8 aircraft engines (total thrust of 24,000 pounds), is used to propel test equipment along the track from the launch end at a preselected speed. The jet car is disengaged when the test speed is attained, and the test equipment is allowed to coast at this speed into the test sections. The last 200 feet of the track are used for installing the test bed. The pcc test bed is 30 inches wide and 5 inches thick. An aircraft arresting system is located beyond the test bed to recover the test equipment at the completion of a test run. Figure 4 shows part of the jet car and guide rails and components of the test equipment.

The major components of the test equipment are: the dynamometer and wheel assembly, the dead-load carriage which supports the dynamometer assembly, and the measuring system. The dynamometer is similar in design to the one developed by NASA for the Langley test facility (reference 10). Figure 5 shows the dynamometer and wheel assembly and the details of the instrumentation for measuring vertical and horizontal loads at the axle. The assembly is pivoted about an axis contained in the dead-load carriage. The carriage weighs 60,000 pounds. Figure 6 shows the hydraulic system for applying vertical load on the test tire. The hydraulic fluid in this system is forced into the cylinders by pressurized nitrogen; the braking system is also activated by pressurized nitrogen. In each system, pressurized nitrogen is released by the action of a solenoid.

The dynamometer is instrumented to measure the vertical load on the tire, the horizontal force developed at the tire/pavement interface, the angular velocity of the test tire, and the vertical motion of the dynamometer assembly relative to the dead-load carriage. The water depth on the test bed was measured by the use of a NASA water level depth gage.

TEST SECTIONS.

The 200-foot test bed (figure 7) at the recovery end of the mile-long test track was divided into five sections. The first section was 20 feet long and was intended for ensuring proper approach of the test wheel into the test section; the remaining 180 feet were divided into four 45-foot sections. The dimensional tolerance of the test surface was held within ± 1/8 inch from horizontal level throughout the test bed. The test sections were numbered from 0 to 4 with 0 representing the 20-foot section. The last section remained nongrooved throughout the test program; sections 1 through 3 were grooved. Thus, it was possible to compare the performance of three differently-grooved surfaces and the nongrooved surface in one test run. Figure 8 shows the schematic of grooved and nongrooved sections on each test bed. Testing was completed on bed number 1 before proceeding to bed number 2 and to subsequent beds. Since the same 200

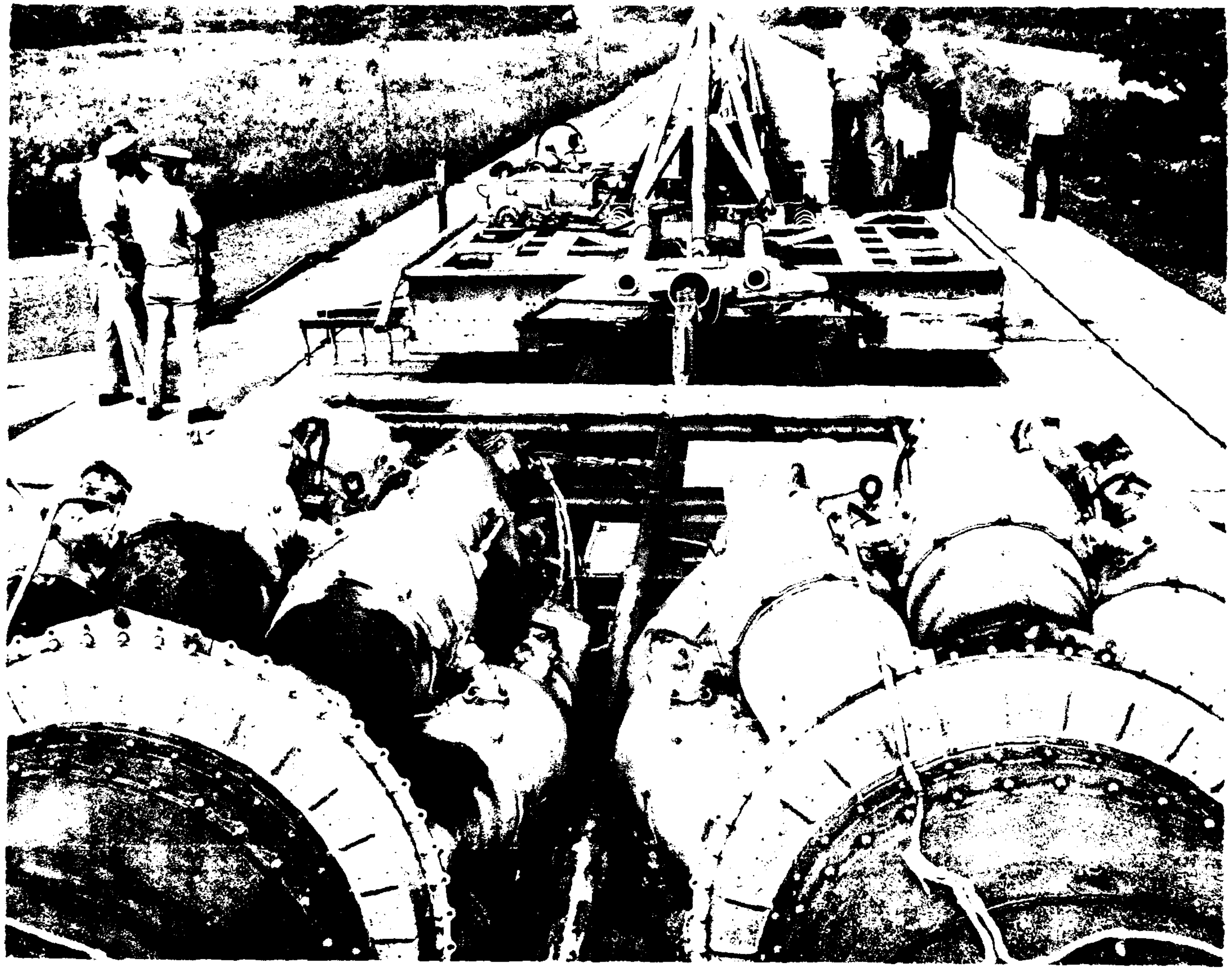


FIGURE 4. JET-POWERED PUSHER CAR FOR PROVIDING PRESELECTED SPEEDS TO TEST EQUIPMENT

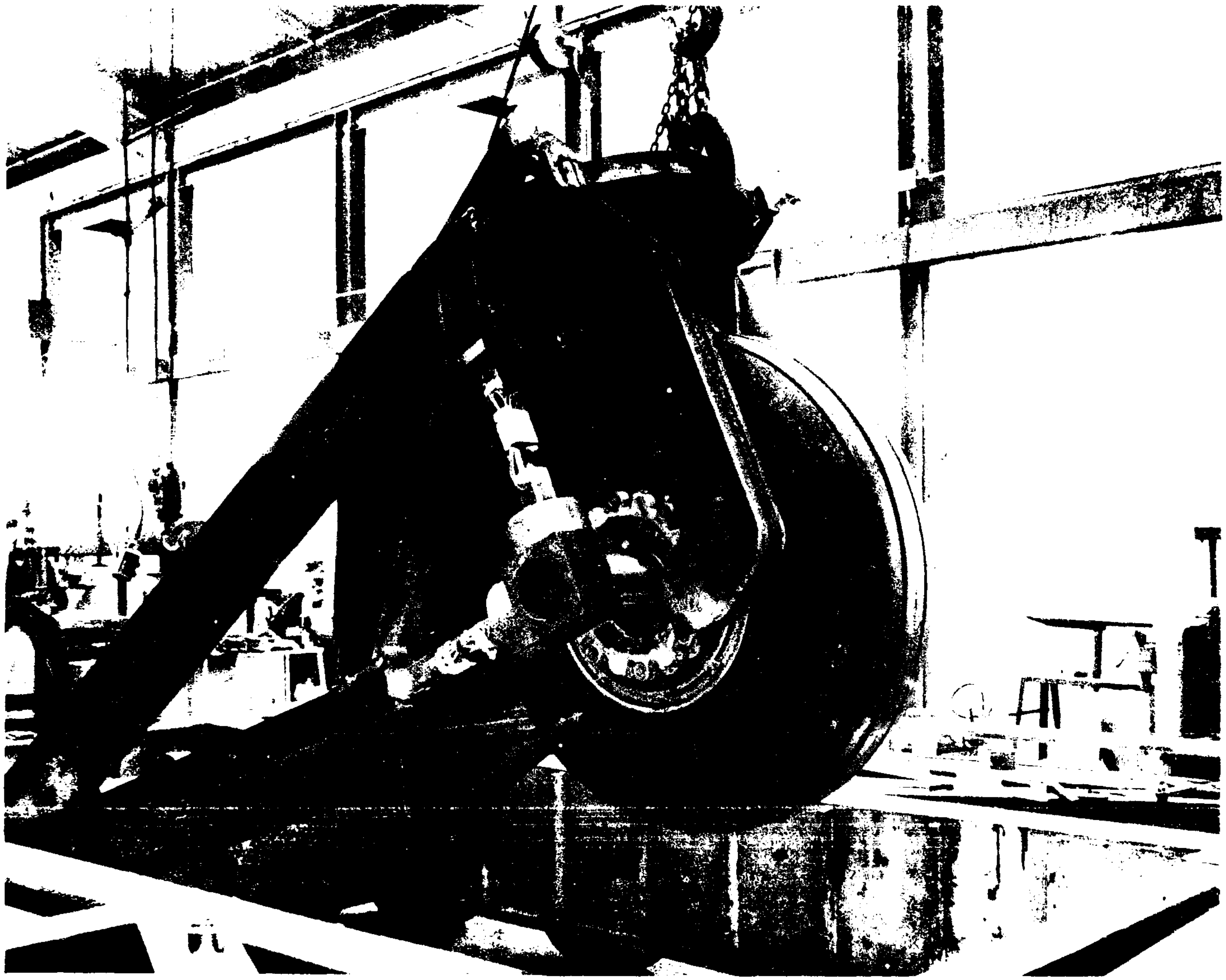


FIGURE 5. DYNAMOMETER AND WHEEL ASSEMBLY SHOWING VERTICAL AND HORIZONTAL LOAD LINKS

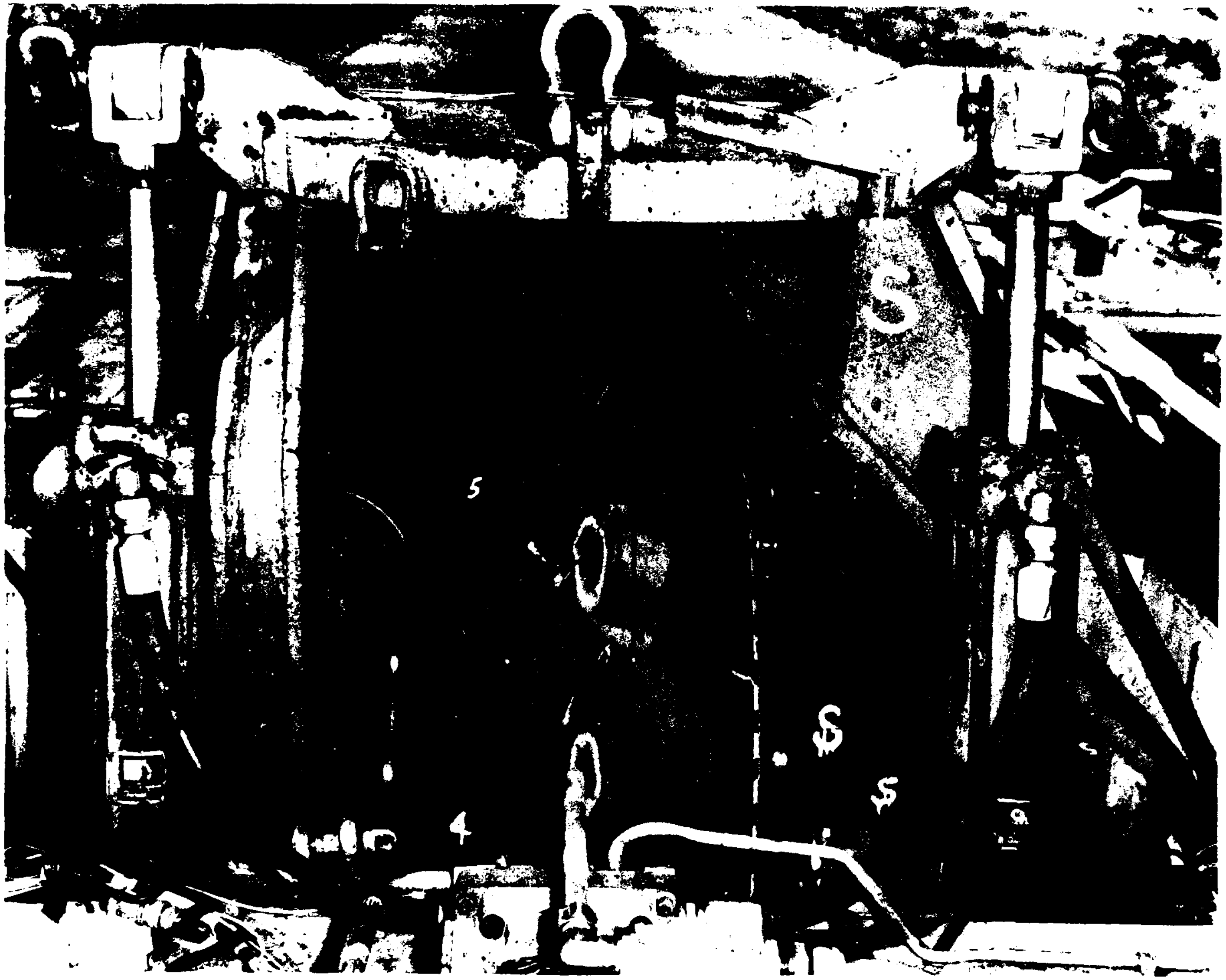


FIGURE 6. HYDRAULIC SYSTEM FOR APPLYING VERTICAL FORCE ON THE TEST TIRE

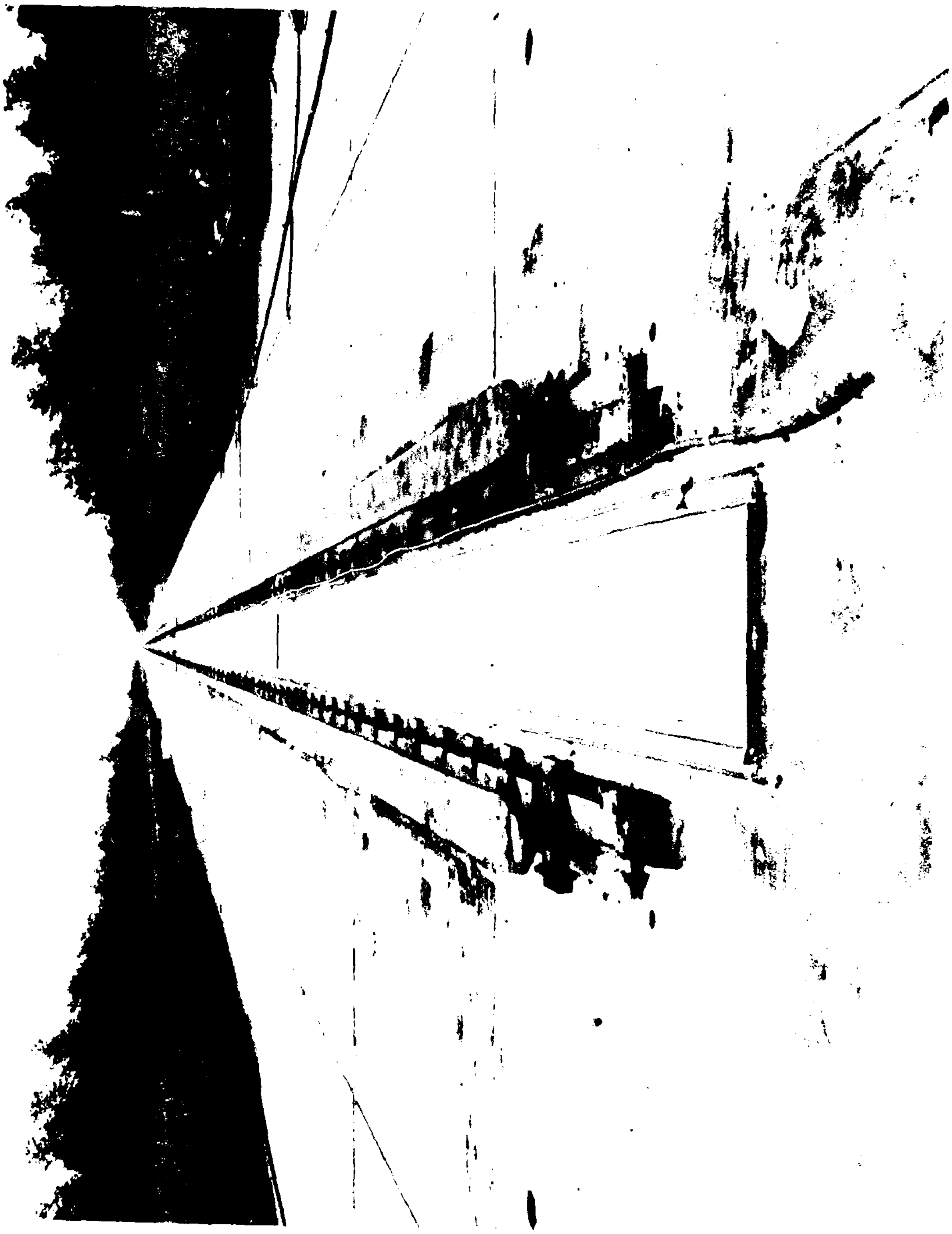


FIGURE 7. FOUR SECTIONS OF THE 200-FT TEST BED

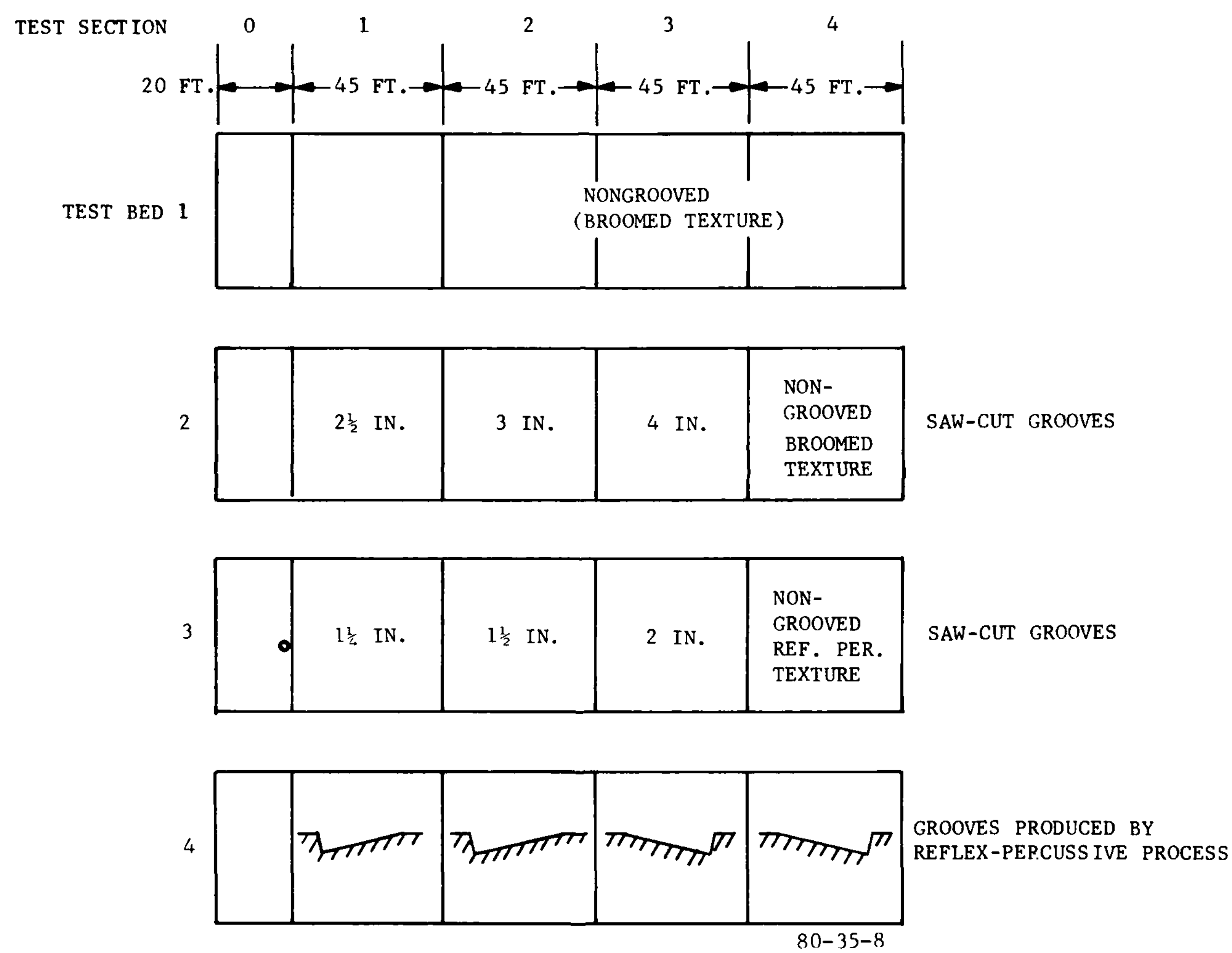


FIGURE 8. SCHEMATIC OF GROOVED AND NONGROOVED SECTIONS

feet of the track were used for all the test beds, the configuration shown for bed number 4 was obtained after removing the grooves shown for bed number 3. The grooves were removed by the reflex-percussive process.

TEST PARAMETERS.

Four types of parameters were investigated in the test program: tire, pavement, environmental, and operational. The magnitudes of these parameters were carefully selected. The primary criterion was to choose a value for a given parameter such that it represented a value widely used or encountered by airlines or aircraft.

Among the various tire parameters, the important ones are: the size, the vertical load, the inflation pressure, and the tread design. All the test tires were 49x17, 26-ply rating, type VII. These tires are used on both the Boeing-727 and the Boeing-747 aircraft and represent a large population of the tires used by the airline industry. To include the effects of tire tread design in terms of tread wear, two extremes were selected — a completely worn tire and a fully treaded tire. Both the tires were recapped except that the tread rubber was completely worn out on one. The total vertical load on the tire in these tests was 35,000 pounds, a value representing the average load on each landing wheel of a Boeing 727-200 aircraft. The tire inflation pressure was maintained at 140 pounds/square inch, which represents the lower limit of the operational range of the Boeing-727 aircraft tires. With this lower inflation pressure, it was possible to initiate hydroplaning at relatively lower speeds.

The pavement parameters included the type of surface, the groove spacings, and the microtexture of the surface. Only one type of surface — the pcc — was employed in this study. Spacings for transverse, saw-cut grooves were 1-1/4 inches, 1-1/2 inches, 2 inches, 2-1/2 inches, 3 inches, and 4 inches. The cross-sectional dimensions of these grooves were 1/4 inch wide and 1/4 inch deep (figure 9). The geometry and dimensions of the percussive V-grooves are also shown in figure 9. Nongrooved concrete surfaces provided the baselines for performance comparison of each of the two types of grooves. The texture depth of the base surface for the saw-cut grooves and the V-grooves was 0.007 inch and 0.021 inch, respectively. The increased texture depth for the latter was a result of resurfacing by the percussive process.

Water depth was the only enviromental parameter applied in the study for performance comparison. The average water depths on the test sections ranged from the "wet" condition to the "flooded" condition. For the purposes of this study, a flooded condition indicates average water depths between 0.17 inch and 0.32 inch; average water depths between 0.02 inch and 0.16 inch are classified as puddled condition; and average water depths below 0.02 inch are referred to as the wet condition.

The operational parameters included the test speed and the mode of wheel operation. The tests were run at speeds between 70 and 150 knots. The wheel was braked for all the tests but generally held in the rotating mode. Where wheel-lock occurred, the data were not used.

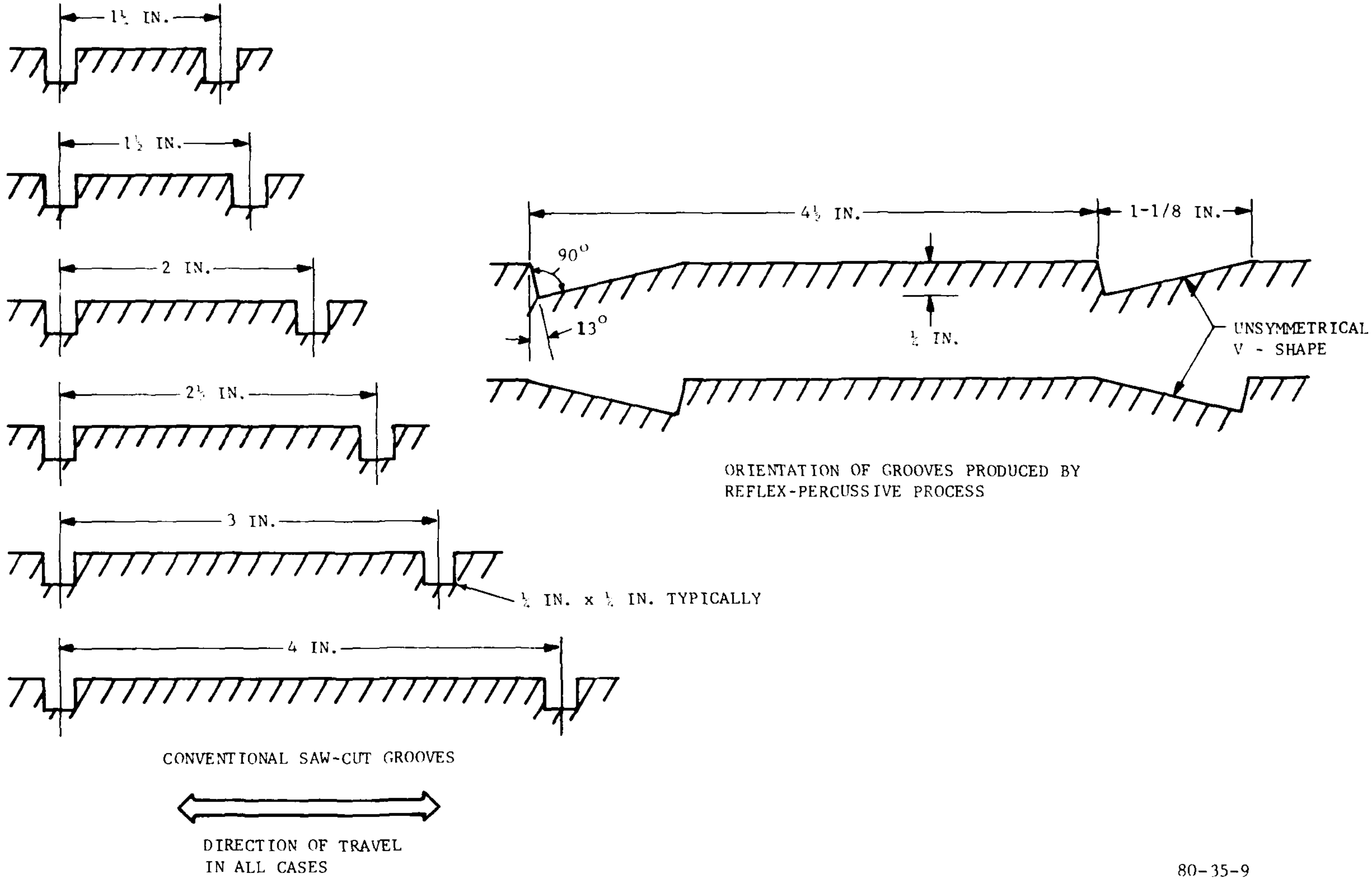


FIGURE 9. GEOMETRY AND DIMENSIONS OF VARIOUS GROOVES TESTED

The following is a summary of all the test parameters investigated in this research:

Tire Parameters -

Vertical Load	:	35,000 lbs.
Inflation Pressure	:	140 psi
Tread Design	:	Worn and fully treaded (six grooves)
Tire Size/Type	:	49x17, 26-Ply, type VII
Static Tire Footprint	:	Worn 13 in. wide x 22 in. long
	:	Fully treaded 13 1/2 in. wide x 24 in. long

Pavement Parameters -

Type of Surface	:	pcc
Microtexture (inches)	:	0.007 (broomed texture) 0.021 (reflex-percussive texture)
Types of Grooves	:	Conventional saw-cut and percussive V-grooves
Groove Spacings (Saw-Cut only)	:	1-1/4 in., 1-1/2 in., 2 in., 2-1/2 in., 3 in., 4 in.

Environmental Parameters -

Water Depths	:	Less than 0.02 in. Wet 0.02-0.16 in. Puddled 0.17-0.32 in. Flooded

Operational Parameters -

Wheel Operation	:	Rolling to locked
Brake Pressure	:	300 psi — 1,800 psi
Speeds	:	70 knots — 150 knots

TEST PROCEDURE.

Since the test bed contained four sections (not counting the initial 20-foot section), four data points were collected during each test run. The vertical load on the tire and tire inflation pressure were held constant for all tests.

One complete braking test consisted of the following steps:

1. Test tire was selected and checked for inflation pressure.

2. Desired water depth was obtained on the test sections.

3. Jet engines were started at the launch end of the track and set at the performance level to provide the preselected speed in the test section.

4. Jet car was released to propel the test equipment (dead load and dynamometer). The test tire remained in a free-rolling state during this maneuver.

5. Jet car was braked and separated from the test equipment several hundred feet ahead of the test section. This allowed the dead load and dynamometer to enter the first test section at the preselected speed. The test speeds in the remaining sections were within 1 to 2 knots of the speed in the first section as computed from the analog traces.

6. Before entering the first test section, the hydraulic systems were activated to apply the vertical load and the brake pressure on the tire. (The magnitude of each was preselected.) Thus, the wheel entered the sections at preselected test conditions.

7. As the wheel left the test bed, unloading and brake release were initiated and the test equipment was recovered by the use of arresting cables.

Various steps of the complete test run were accomplished by different personnel. Two persons were responsible for obtaining desired water depths in the test sections. At the launch end, two persons were responsible for starting the engines and releasing the jet car. One more person was responsible for setting the engine performance level, the vertical load level, and the brake pressure level. On the recovery end, additional persons were responsible for the safe operation of the arresting cable system to recover and return the test equipment to the launch end for the next run. Data were transmitted from the dynamometer to the instrumentation room (located near the track) by the use of telemetry; three technicians collected the data. The entire operation was under the control of the program manager and the site officer.

In order to obtain the maximum friction level available at each speed, multiple tests were conducted with gradually increasing brake pressure. The speeds were kept constant in these multiple tests, and the brake pressure was increased until wheel-lock occurred.

DATA COLLECTION AND ANALYSIS.

The data were collected in the form of analog traces. Typical data collected in a test are shown in figure 10. This figure shows two traces each for horizontal force and vertical load on the tire. The coefficient of friction was computed from these four traces by dividing the horizontal force by vertical load. The coefficient of friction trace is also shown in figure 10. Wheel revolutions were measured at two sensitivities to monitor the wheel spin-down and to measure wheel slip if desired. The test speed was computed from time/distance traces.

The results on pcc surfaces with and without grooves are shown in tables A-1 through A-3 in the appendix. The coefficients of friction in these tables represent the maximum available under each set of operating conditions; many more tests were conducted to obtain the maximum. A least-square fit was obtained

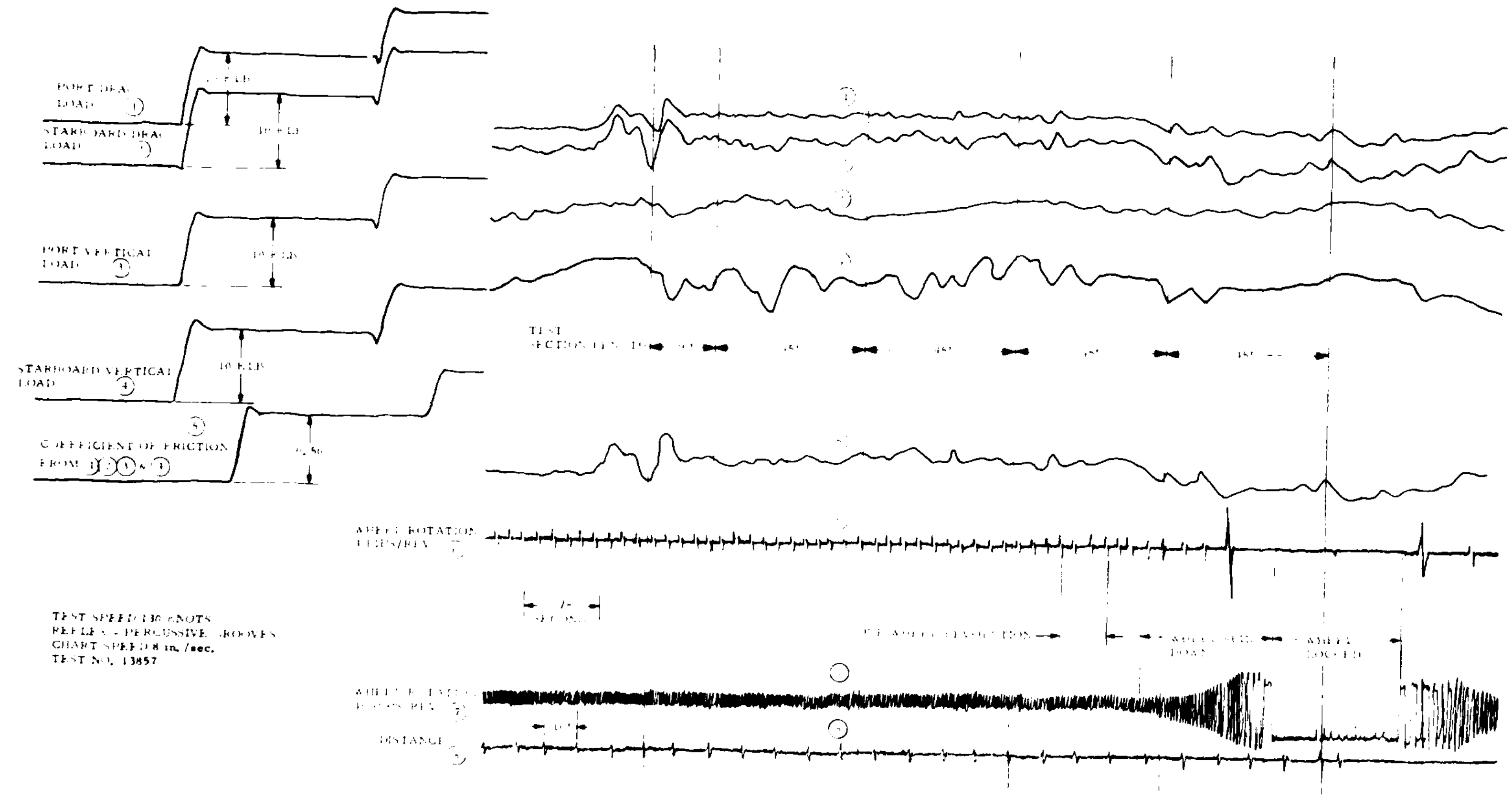


FIGURE 10. A TYPICAL DATA TRACE FOR A BRAKING TEST

between speed and coefficient of friction. The equation ($\mu = AV^{-B}$) for the fit was considered appropriate because a majority of the data showed a linear relationship on the logarithmic scale on both the speed and the friction coefficient axes. Table A-4 in the appendix shows the functional relationships between the coefficient of friction (μ) and speed (V).

Figure 11 shows the coefficient of friction as a function of speed for the puddles and the flooded conditions on saw-cut grooves and on nongrooved surfaces, and figure 12 shows similar relationships for tests on V-grooves. Figure 13 shows results on wet surfaces. Data from figures 11 and 12 are replotted in figure 14 to show the relative performance of the saw-cut grooves and the V-grooves. Limited data on nongrooved surfaces are also included in this figure.

DISCUSSION OF RESULTS

CONVENTIONAL SAW-CUT GROOVES.

The basic characteristics of the friction speed relationships in figures 11 through 13 indicate a drop in friction with increasing speeds — a trend which has been well documented in the past (reference 3). These results verify the validity of the experimental procedures of this research and complement the findings of the past research.

Wet runway surfaces are normally encountered during or after a light or moderate rain. These surfaces may be saturated with water but would not have measurable water depth present on them. A worn tire operating on a wet, nongrooved surface represents a situation where predominantly viscous hydroplaning may occur. Even when hydroplaning does not occur, the viscous pressures in the contact are high and remain high even at a relatively low speed. The result is low available friction levels. Broken-line curves in figure 13 plots (a) and (c) show the friction levels obtained under these conditions.

When a new tire is operated on wet, nongrooved surfaces, a more complex mechanics takes place under the tire. The viscous pressure under the tire groove is lower than under the rib. This results in a lower integrated pressure under the tire and provides more contact between the tire and the concrete surface. The friction levels available are significantly increased (over those obtained with a worn tire) as shown by broken-line curves in figure 13 plots (b) and (d).

When the concrete surfaces are grooved, the performance of a worn tire under wet conditions improves significantly when compared with nongrooved surfaces, as shown in figure 13 plots (a) and (c); the performance of a new tire is also improved under similar conditions. However, the introduction of grooves on the surfaces renders the performance of a worn tire comparable to that of a new tire as shown by the solid-line curves in figure 13 plots (a) and (b) or in figure 13 plots (c) and (d).

The data scattered around the solid-line curves in figure 13 are not indicative of the effect of groove pitch or shape on the available friction levels. Rather, they show the sensitivity of the coefficient of friction to changes in the water depth. It is relatively more difficult to control small water depths (0.0 to 0.02 inch) on the surfaces precisely; therefore, it is likely that the water depths are varying slightly from these limits.

An overall observation from figure 13 can be summarized as follows:

Where predominantly wet surfaces are encountered during aircraft operations, the introduction of grooves on the concrete surfaces will render the braking performance of a worn tire comparable to

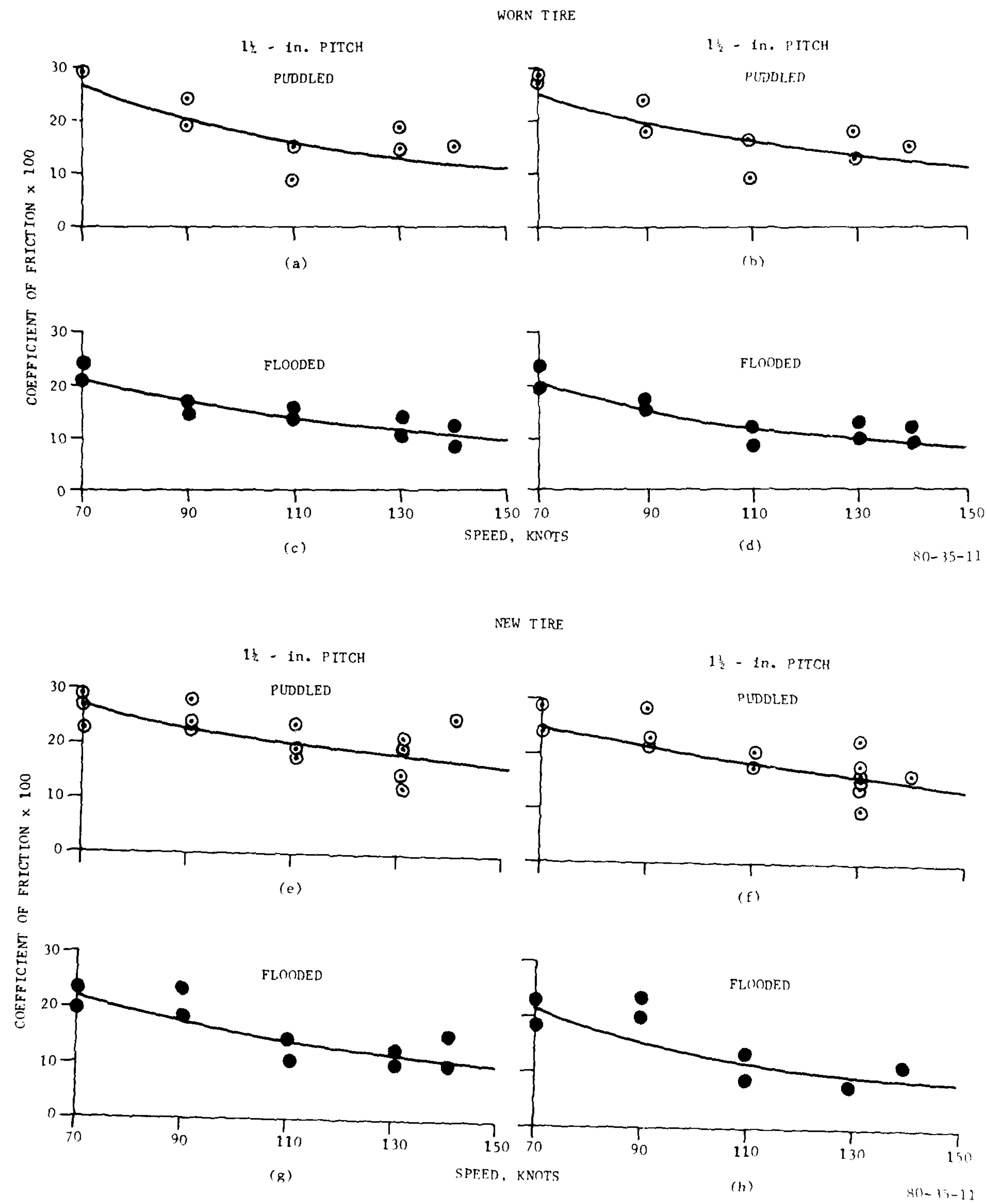


FIGURE 11. COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED UNDER VARIOUS TEST CONDITIONS ON SAW-CUT GROOVES AND NONGROOVED CONCRETE (Sheet 1 of 4)

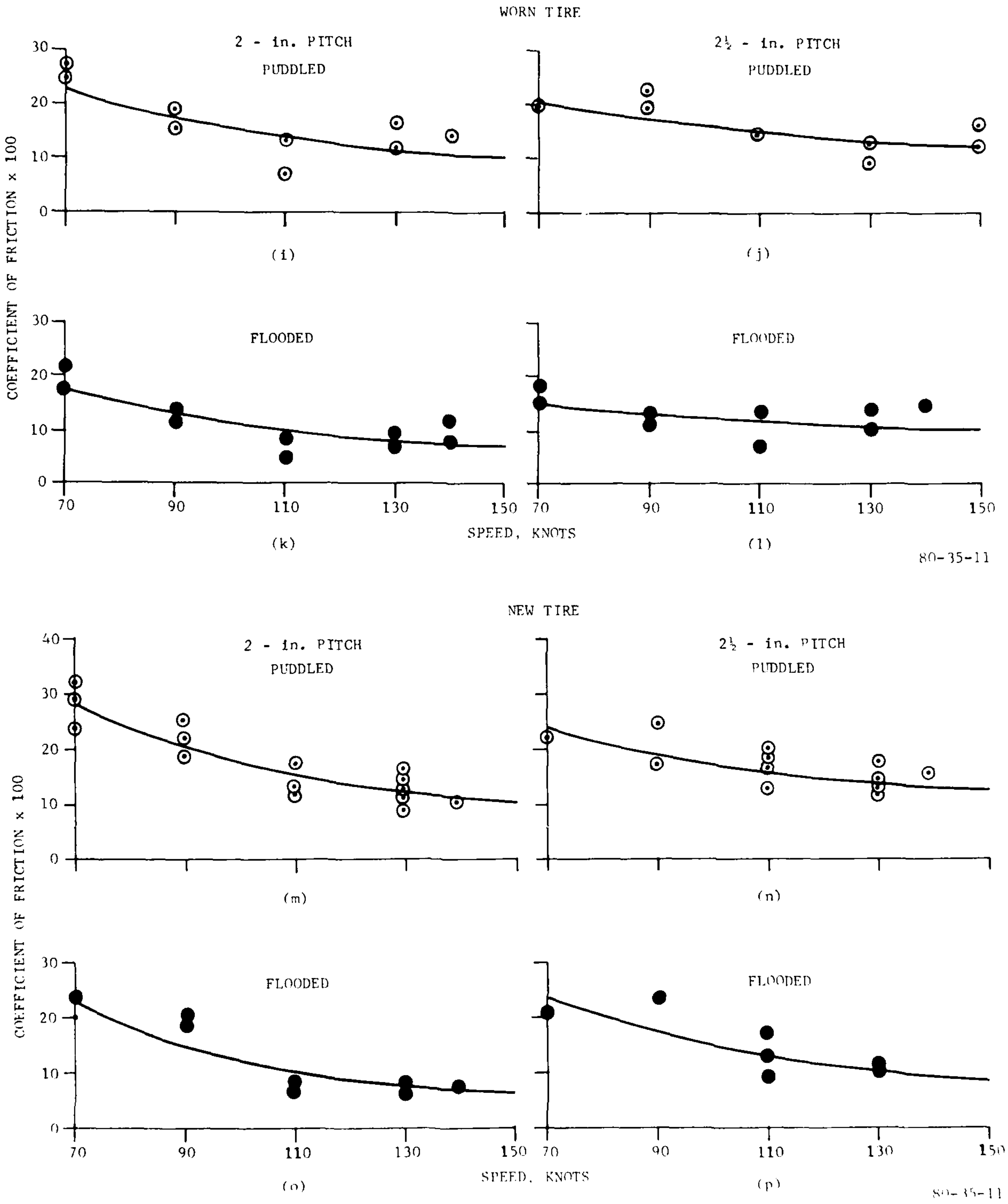


FIGURE 11. COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED UNDER VARIOUS TEST CONDITIONS ON SAW-CUT GROOVES AND NONGROOVED CONCRETE (Sheet 2 of 4)

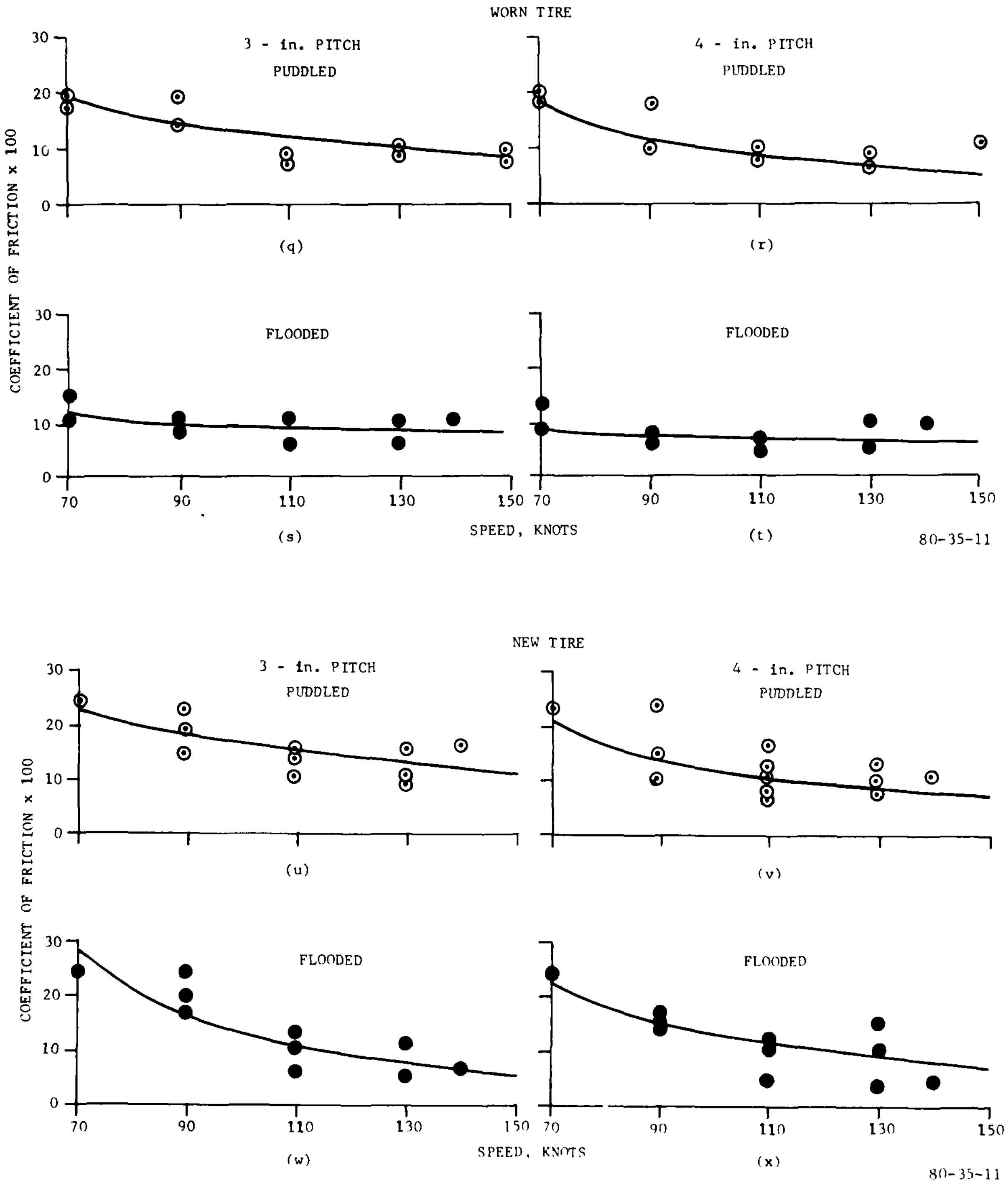


FIGURE 11. COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED UNDER VARIOUS TEST CONDITIONS ON SAW-CUT GROOVES AND NONGROOVED CONCRETE (Sheet 3 of 4)

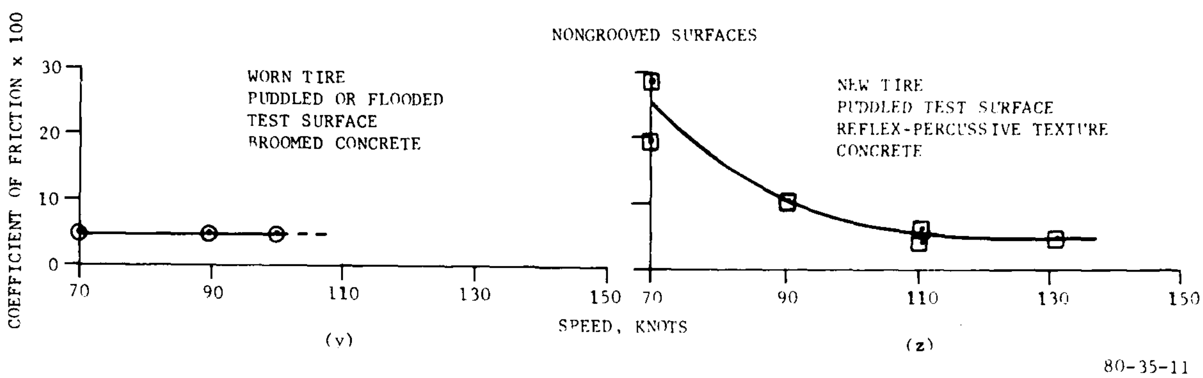


FIGURE 11. COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED UNDER VARIOUS TEST CONDITIONS ON SAW-CUT GROOVES AND NONGROOVED CONCRETE (Sheet 4 of 4)

the braking performance attainable with a new tire. The available friction levels with both a new and a worn tire are insensitive to changes in the pitch of saw-cut grooves or the orientation of V-grooves.

The puddled surfaces are representative of conditions that can be expected immediately after heavy rains of short duration. Puddles can also form on poorly drained runways or where large temperature variations produce undulations in the runway surface. In any event, the puddles are generally not continuous in either the longitudinal or the lateral direction. The flooded runway conditions can be expected as a result of continuous, heavy rainfall. Braking performance on grooved surfaces when puddled and flooded conditions are encountered are shown in figure 14; the results on V-grooves and on nongrooved surfaces are also shown.

Comparison of figure 14 plots (a) and (c) shows that for all groove spacings, the braking performance on puddled surfaces is improved with a new tire over a worn tire. This improvement is available over the entire range of operating speeds. On the other hand, when flooded conditions are present, the new tire provides gradually improving braking performances as the operating speeds are reduced. Tire wear is, thus, an important factor during low-speed operations (70-90 knots) on grooved, flooded surfaces.

The braking performance on nongrooved surfaces is poor under puddled and flooded conditions, and the probability that hydroplaning may occur is always high. The results on nongrooved surfaces under puddled and flooded conditions with a worn tire are shown in figure 14 plots (a) and (b). A coefficient of friction of only 0.05 was available when operating speeds were below 100 knots. Above 100-knot operating speeds, the wheel was locked at all the braking pressures. A friction coefficient of 0.05 is generally accepted as a level representing hydroplaning. The friction force corresponding to a coefficient of friction of 0.05 is 5 percent of the vertical load on the tire. The introduction of grooves on the surface has increased the available friction from 0.05 to a maximum of 0.29. The smallest increase occurs for a worn tire operating on a flooded surface; the largest increase occurs for a new tire operating on a puddled surface.

While the use of new tires and grooved runways will shift the onset of hydroplaning to a higher speed, they cannot, in all cases, completely eliminate it. As the operating speeds increase, the time available for the fluid particles to

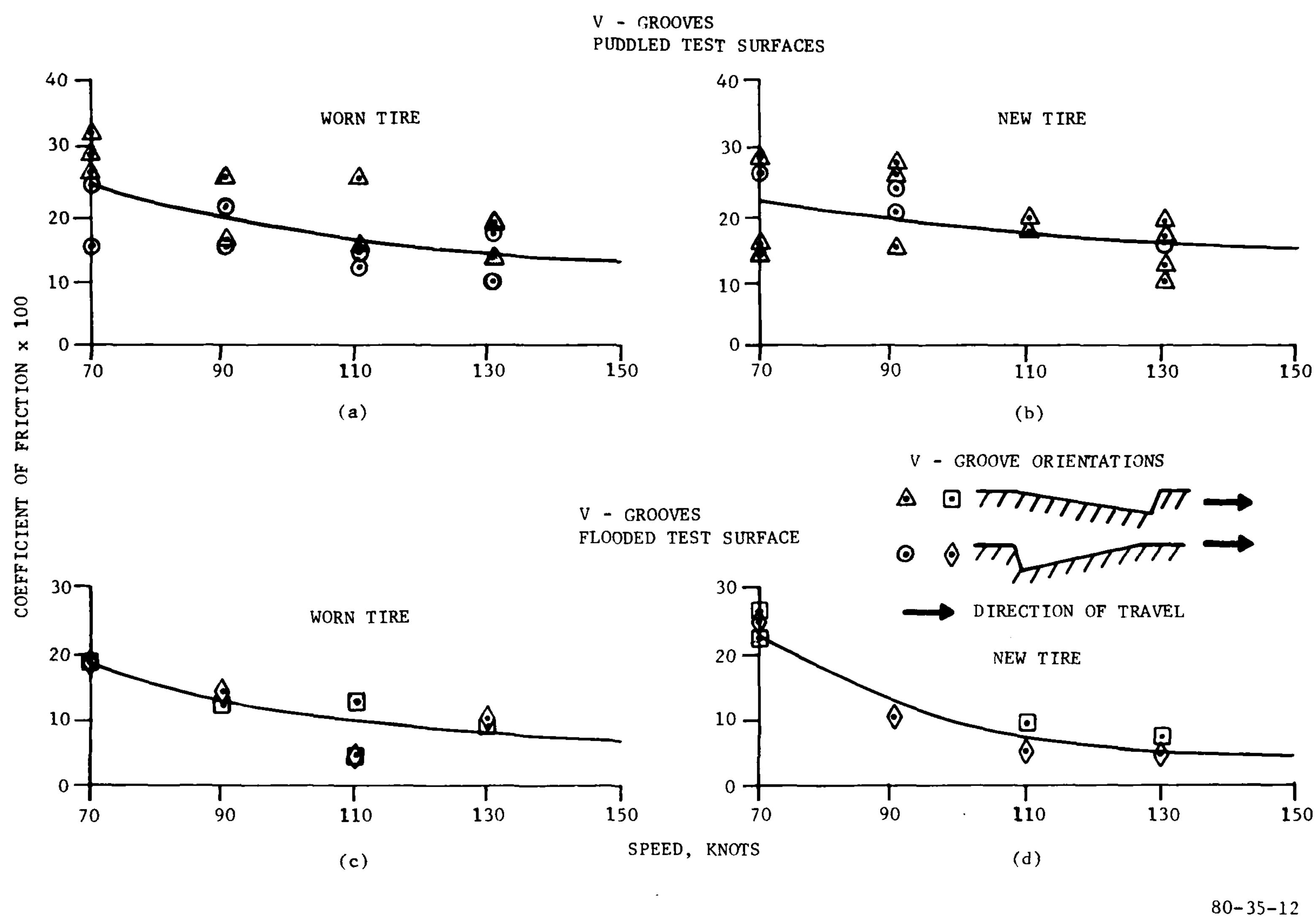


FIGURE 12. COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED UNDER VARIOUS TEST CONDITIONS ON V-GROOVES

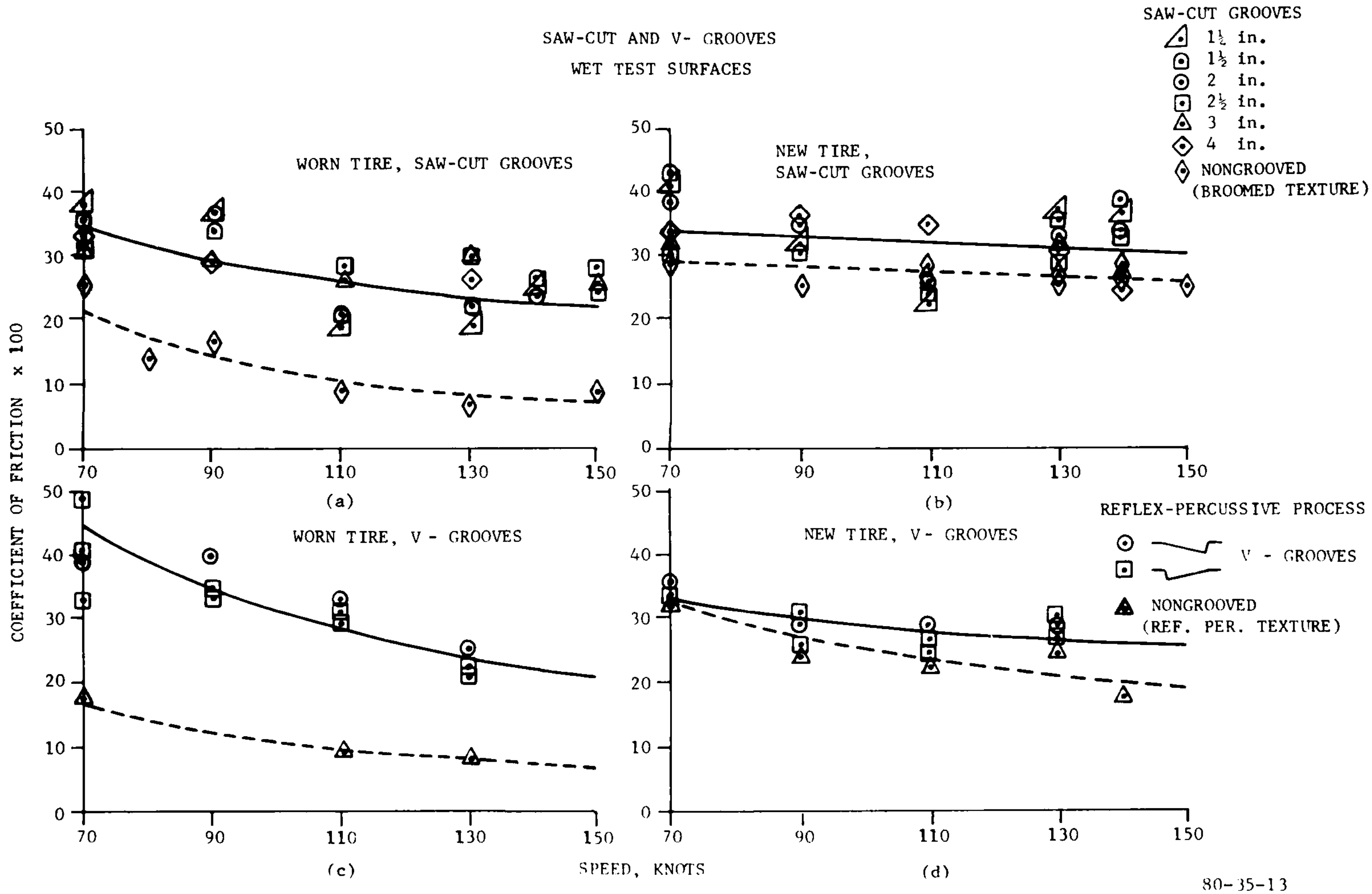


FIGURE 13. PERFORMANCE OF WORN AND NEW TIRES ON SAW-CUT GROOVES AND V-GROOVES UNDER WET CONDITIONS

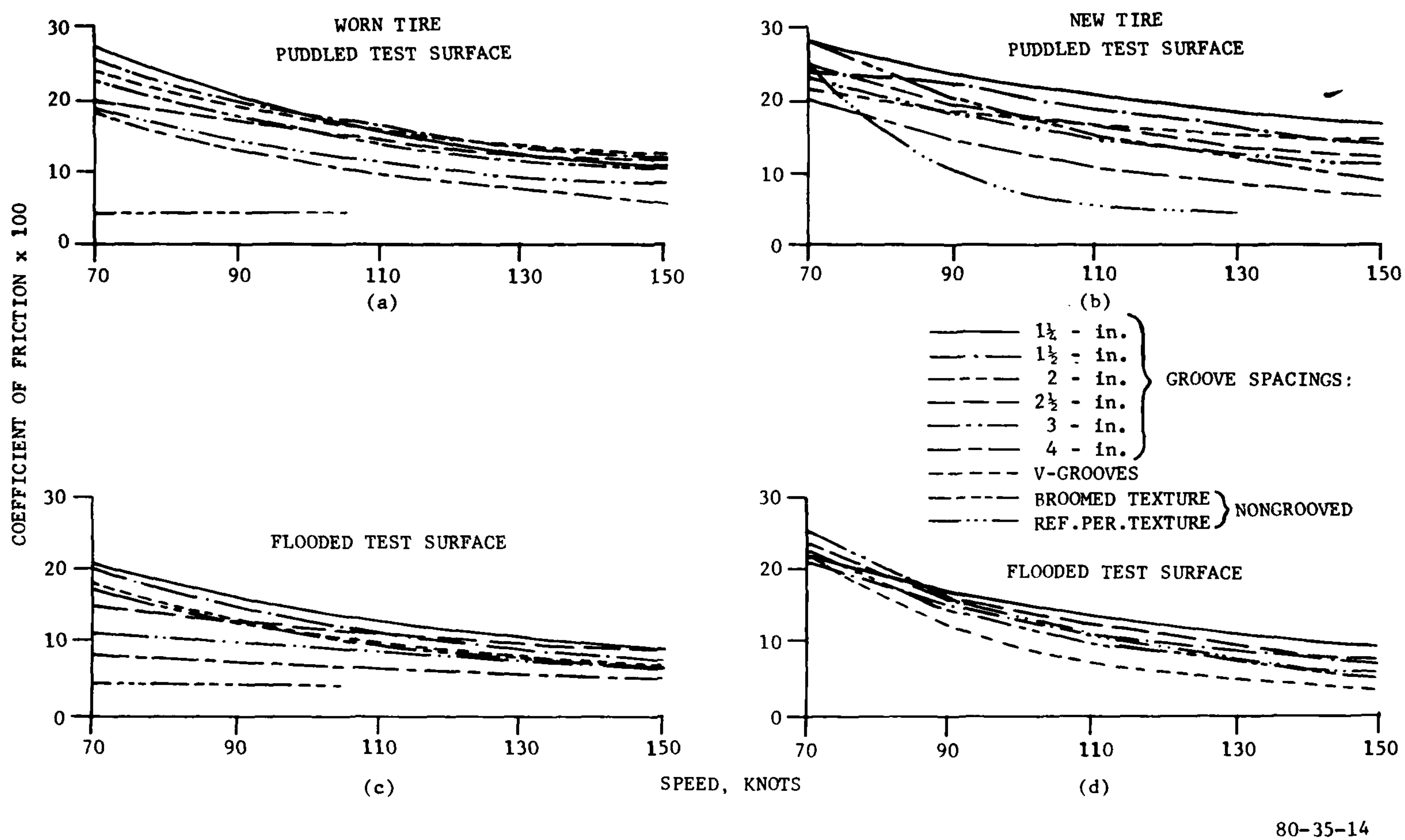


FIGURE 14. COMPARISON OF THE BRAKING PERFORMANCE OF WORN AND NEW TIRES ON ALL GROOVES TESTED

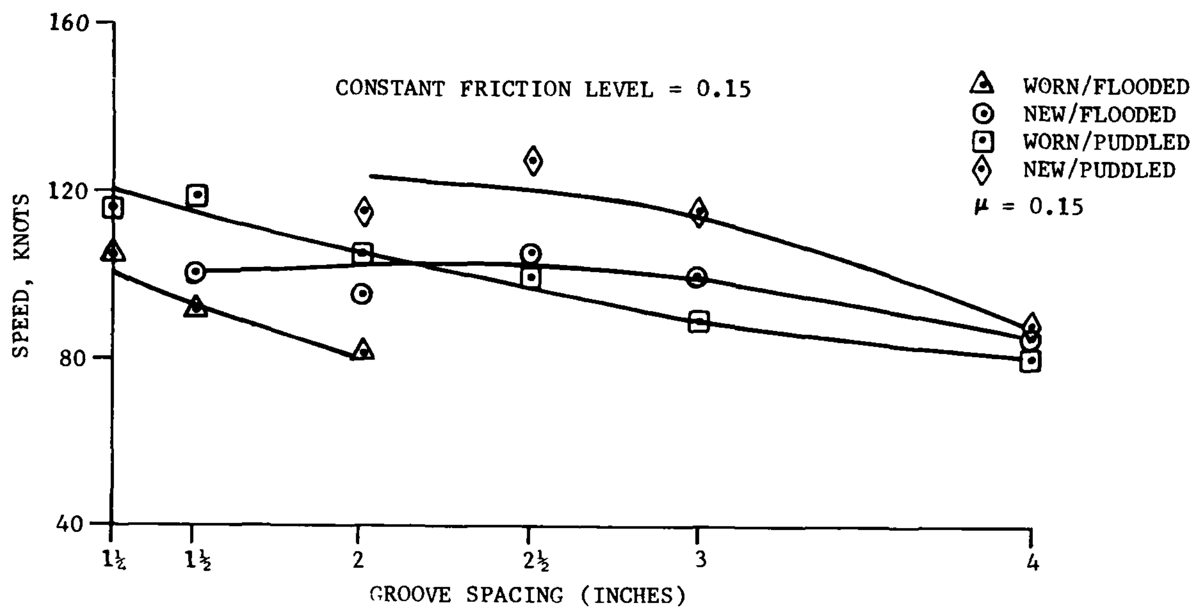
escape from the tire/runway contact area decreases. Any increase in the number of escape paths, either by providing patterns in the tire tread or grooves in the runway surface, cannot totally compensate for the reduction in available time brought about by higher operating speeds. Closer spacings between the grooves, however, will provide more discharge outlets to the water entrapped in the contact area. Although the number of discharge outlets will thus be increased, total surface area resisting the water flow will also be increased. The reduction in time available for a fluid particle to go from one discharge outlet to another when the groove spacing is reduced from, for example, 3 inches down to 1-1/4 inches will be 0.00087 second at 100 knots operating speed. The question, therefore, arises as to whether the entrapped mass of water, owing to its inertia, can respond rapidly enough to show any significant changes in braking performance on the two spacings used in the above example. Clearly, much larger spacings will have adverse effects on the braking performance at higher operating speeds and when runways are flooded. Figure 14 plot (d) seems to verify the above argument. The figure shows a small drop in coefficient of friction for 3-inch groove spacing over 1-1/4-inch groove spacing. However, no definite trend is identifiable for the direction in which the friction force is changing when the entire spectrum of groove spacings is considered.

If a coefficient of friction (μ) of 0.15 is arbitrarily chosen as a performance level that is expected from any of the groove configurations included in the test program, it is possible to compare the braking performance on these grooves in terms of attainable speeds under various operating conditions. The data from figure 14 are replotted in figure 15 for a constant friction level of 0.15. Certain observations can be made from figure 15. Under flooded conditions, the grooves spaced beyond 2 inches cannot provide a μ of 0.15 with worn tires even at low operating speeds (below 80 knots). This can be expected as the only channels for water to escape from the contact area are provided by the grooves, and there are not enough of them. In this situation, the smaller the groove spacing the better the braking performance. However, the consequence that groove spacings beyond 2 inches cannot sustain a friction level of 0.15 is of little importance. The worn tire condition and the flooded runway surface represent two extremes of tire wear and runway contamination, respectively. The likelihood of this combination being present at runways is very small because the tire tread would have to be completely worn, and the runway would have to be fully covered with standing water. If the grooved surfaces were puddled, the same worn tire could attain a friction level of 0.15 and provide an operating speed range of 120 knots to 80 knots between the groove spacings of 1-1/4 inches and 4 inches, respectively.

In general, as the groove spacing is increased, the operating speed needed to maintain a constant friction level of 0.15 decreases. The rate of decrease is smaller with a new tire. At any groove spacing, the operating speed can be increased by replacing the worn tire with a new tire.

The effect of groove spacing on the braking performance of a worn or a new tire on puddled and flooded surfaces can also be evaluated from figure 16. This figure shows the data from figure 14 replotted in an alternative manner; the effect of groove spacing is compared in terms of maximum available coefficient of friction under various test conditions.

In all cases, the friction coefficient decreases as the speed increases for all the groove spacings. The friction levels attainable on nongrooved surfaces with worn tires approach the



80-35-15

FIGURE 15. COMPARISON OF ATTAINABLE SPEEDS FOR A CONSTANT FRICTION LEVEL ON SAW-CUT GROOVES

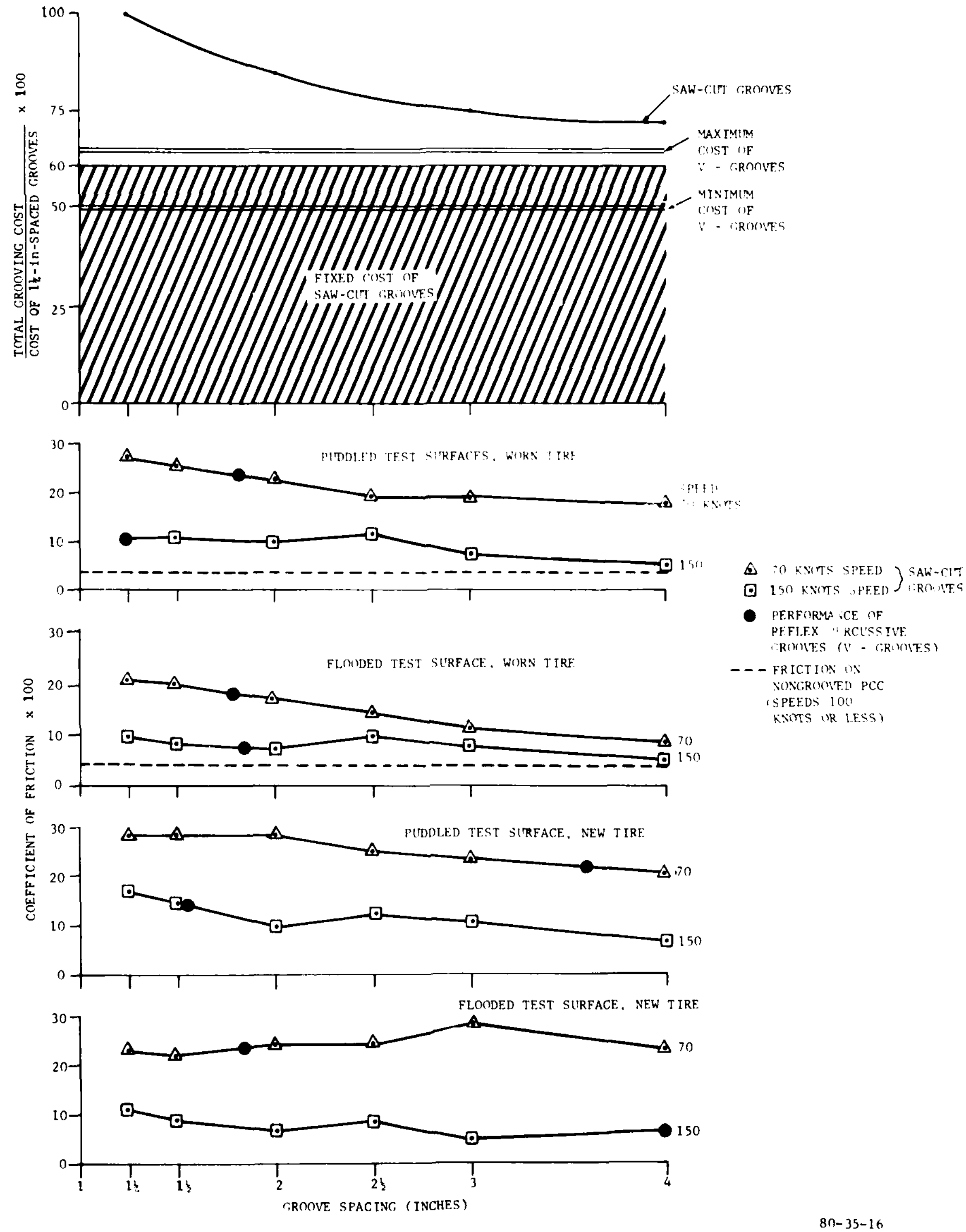


FIGURE 16. BRAKING PERFORMANCE AND ESTIMATED GROOVING COST AS A FUNCTION OF GROOVE SPACING

hydroplaning level (μ = 0.05) at operating speeds of 100 knots or less, while the introduction of grooves increases both the level of friction available and the attainable speeds — the lower the operating speeds, the higher the available friction level. The use of new tires provides an additional increase in the available friction levels.

When the effects of increasing the groove spacings under constant operating conditions are compared, the overall effect is a decrease in friction level with increasing spacings; however, the decrease cannot be classified as significant. If the operation with new tires is considered, increasing the spacing from 2 inches to 3 inches does not change the friction force at 150 knots. In fact, the decrease in friction coefficient when the groove spacing is increased from the current recommended value of 1-1/4 inches to 2 inches or 3 inches is a maximum of 0.06 with new tires operating on puddled or flooded surfaces. A slightly greater decrease occurs with worn tires under similar operating conditions.

REFLEX-PERCUSSIVE V-GROOVES.

The test results on the V-grooves are shown in figures 12, 13, 14, and 16. Since the V-grooves have an unsymmetrical cross section, the tire encounters different flow conditions on the leading edge of the groove depending upon the groove orientation (figure 9). This, however, did not seem to affect the braking performance as shown in figure 12.

Figure 12 shows the results on puddled and flooded surfaces. The general characteristics of the friction-speed relationships for the V-grooves follow the same trends as for the saw-cut grooves. The new tire shows a significant improvement in braking performance on a puddled, grooved surface (figure 12 plot (b)) compared to a nongrooved surface. Also, a worn tire performs better on a grooved, puddled surface than a new tire on a nongrooved surface.

The braking performance of the V-grooves on wet surfaces is shown in figure 13, which also shows the braking performance of saw-cut grooves. In general, the braking performance on these two types of grooves is comparable. In addition, the braking performance of a worn tire is significantly improved by the introduction of grooves (figure 13 plot (c)). In fact, the performance of a worn tire and a new tire are comparable on grooved surfaces as shown by solid-line curves in figure 13 plots (c) and (d).

The friction-speed curves from figure 12 were redrawn in figure 14 for direct comparison of the braking performance on the saw-cut and the V-grooves. It can be seen that the performance on V-grooves is comparable to the performance of saw-cut grooves in most cases (figure 14 plots (a) through (c)). The only exception is the performance of a new tire on a flooded surface (figure 14 plot (d)).

Figure 16 shows the relative position of the V-grooves in terms of the braking performance of the saw-cut grooves. Generally, the performance of the V-grooves corresponds to that of the saw-cut grooves spaced at 2 inches or less.

COST AND PERFORMANCE ANALYSIS.

The total cost of grooving is a function of many variables; groove spacing is one of them. The investigation by the Washington, D.C., firm concluded that fixed and variable construction costs for grooving the runways are 60 percent and 40 percent, respectively, of total cost and that the variable cost savings increase with groove spacing nonlinearly. For example, by cutting grooves at 2-inch spacing, the cost savings over 1-1/4-inch groove spacing are 15 percent (out of the total available of 40 percent). The cost savings for 3-inch and 4-inch spacings over 1-1/4-inch spacing are 25 percent and 28 percent, respectively (figure 16).

As pointed out earlier in this report, the cost-effective groove configuration must meet certain criteria. It has been shown (figure 14) that the overall effect of increasing the groove spacings is a decrease in available friction. However, the decrease is not significant. In addition, the braking performance on all the grooved surfaces tested is significantly higher than on nongrooved surfaces. Friction levels representing a hydroplaning condition were observed on both puddled and flooded nongrooved surfaces (figure 14 plots (a) and (b)). If performance alone were a factor for selecting a groove configuration, 1-1/4-inch spaced grooved runways will provide maximum friction levels under all operating conditions included in this study. However, in the majority of cases, both the cost and the performance are considered to be important when installing grooves on runways. In these cases, the groove spacings of 2 inches or 3 inches will provide sufficient braking to allow a gradual reduction in the speed of an aircraft and thus develop further braking. In addition, savings of up to 25 percent in groove installation cost (compared to installation cost for 1-1/4-inch spaced grooves) are available.

The V-grooves installed by the reflex-percussive technique offer even higher cost savings than the savings offered by 3-inch or 4-inch spaced grooves. In fact, the V-grooves have a potential of costing even less than the fixed cost for saw-cut grooves (figure 16); however, realistic cost estimates and full savings potential can only be affirmed after application of these grooves on an operating airport.

CONCLUSIONS

The following conclusions are drawn from the findings of this research and are valid for portland cement concrete surfaces:

1. The conventional saw-cut grooves spaced at 3 inches or less will provide acceptable braking performance to an aircraft tire on water-covered surfaces. Installation cost of 3-inch spaced grooves is 25 percent less than that of the grooves spaced at 1-1/4 inches.

2. The reflex-percussive cutting process is an alternative groove installation technique competitive with the conventional saw-cutting method. The reflex-percussive cutting process produces unsymmetrical, V-shaped grooves. Installation cost of these grooves can be significantly less than that of the conventional saw-cut grooves.

3. The braking performance provided by the V-grooves on water-covered surfaces is comparable to that provided by the 2-inch pitch, conventional saw-cut grooves.

4. The conventional saw-cut grooves spaced at 1-1/4 inches, although costing the most, do provide maximum friction levels under all operating conditions included in this study.

REFERENCES

1. Judge, R.F.A., A Note on Aquaplaning and Surface Treatments Used to Improve the Skid Resistance of Airfield Pavements, 8556/PS Min. Public Bldg. Works (Britain), October 1965.

2. Horne, Walter B.; Yeager, Thomas J.; and Taylor, Glenn R.; Review of Causes and Alleviation of Low Tire Traction on Wet Runways, National Aeronautics and Space Administration, Langley Station, Hampton, Virginia, NASA TN D-4406, April 1968.

3. Horne, Walter B. and Brooks, George W., Runway Grooving for Increasing Traction - The Current Program and an Assessment of Available Results, Paper Presented at the 20th Annual International Air Safety Seminar, Williamsburg, Virginia, December 4-7, 1967.

4. Yeager, Thomas J., Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station, Paper No. 3, Conference on Pavement Grooving and Traction Studies, Langley Research Center, Hampton, Virginia, NASA SP-5073, November 18-19, 1968.

5. Byrdsong, Thomas A.; McCarty, John Locke; and Yeager, Thomas J.; Investigation of Aircraft Tire Damage Resulting from Touchdown on Grooved Runway Surfaces, National Aeronautics and Space Administration, Washington, D.C., NASA TN D-6690, March 1972.

6. Method for the Design, Construction and Maintenance of Skid Resistant Airport Pavement Surfaces, Advisory Circular No. 150/5320-12, Department of Transportation, Federal Aviation Administration, Washington, D.C., June 30, 1975.

7. Costs of Runway Grooving, Naval Air Test Facilty, Report Job No. 75-119, Edward Galura Scharf and Sons, Washington, D.C., June 25, 1975.

8. Labus, Thomas J. and Khan, Mohamed S., Runway Grooving Using High Pressure Water Jets, IIT Research Institute, Chicago. Final Report No. D6112, January 1976.

9. Schmid, W. E., Experiments for Vibratory Kerfing of Concrete Pavements, Final Report, Contract No. 68335-76-C-4408, Department of Civil Engineering, Princeton University, Princeton, New Jersey, December 1978.

10. Joyner, Upshur T.; Horne, Walter B.; and Leland, Trafford, J.W.; Investigation on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag, Report 429, Advisory Group for Aeronautical Research and Development, Paris, January 1963.

11. Yeager, Thomas J.; Phillips, W. Pelham; Sparks, Howard C.; and Horne, Walter B.; A Comparison of Aircraft and Ground Vehicle Stopping Performance on Dry, Wet, Flooded, Slush-, and Ice-Covered Runways, National Aeronautics and Space Administration, Washington, D.C.; NASA TN D-6098, November 1970.

APPENDIX A

LIST OF TABLES

TABLE A-1. TEST RESULTS ON PCC SURFACES WITH WORN TIRE

Test Speed Knots	Coefficient of Friction, x100																				
	Nongrooved Surface (Broomed)			Groove Spacings, Inches																	
				1-1/4			1-1/2			2			2-1/2			3			4		
	Average Water Depth, Inches																				
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
70	26	4	4	38	29 29	21 24	36	27 28	19 23	36	27 25	18 22	31	19 19 19	16 18	31	20 19 19	15 10	33	20 19 19	13 8
90	17	4	-	37	24 19	17 15	34	24 18	15 17	37	19 15	12 14	29	19 22	13 11	29	15 20	9 10	29	10 18	7 6
100	14	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
110	9	-	-	18 19	15 9	14 15	19 21	16 9	8 12	19 21	13 7	9 5	28	13 14	13 6	27	9 8	11 6	20	8 10	6 4
130	7	-	-	18 19	15	14 11	19 22	18 13	12 9	20 22	16 12	9 7	30	9 12	13 10	30	9 10	10 6	26	7 8	9 4
140	-	-	-	25	15	12 8	26	15	11 8	25	14	12 8	-	-	14	-	-	11	-	-	9
150	9	-	-	-	-	-	-	-	-	-	-	-	27	16 12	-	24	10 8	-	24	11	-

Note:
A = 0-0.02 inches - Wet
B = 0.02-0.16 inches - Puddled
C - 0.17-0.32 inches - Flooded
35,000 lbs Vertical load, 140 psi tire inflation pressure

TABLE A-2. TEST RESULTS ON PCC SURFACES WITH NEW TIRE

Test Speed Knots	Coefficient of Friction, x100																				
	Nongrooved Surface (Broomed)			Groove Spacings, Inches																	
				1-1/4			1-1/2			2			2-1/2			3			4		
	Average Water Depth, Inches																				
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
70	30	29 19 31	-	41	30 28 24	20 24	43	29 29 24 24	24 19	39	32 29 24	25 21	31	22	21	32	24	24	32	23	24
90	26	-	-	32	29 25 24	24 19	31	29 22 23	24 21	35	25 22 19	20 21	-	17 24 24	24 11	-	23 15	17 20 24	35	24 15 15 10	14 15 16
110	29 28	17	-	23	25 19 20	15 11	24	18 21 18	14 9	26	13 17 12	9 8	-	16 18 19 12	9 17 13	-	16 14 15 11	6 13 11	34	17 11 8 12 7	10 12 5
130	26 28	-	-	37	22 21 15 15 13	13 11	36	13 17 18 14 10 15	8 8	33	16 13 14 14 9 11	7 9	29	17 14 12 11 12	10 12	33	16 11 11 10	11 5	30	13 10 10 8	10 15 4
140	28 28	-	-	37	26	16 10	39	17	12 12	34	10	8 8	33	15	-	28	17	7	24	11	4
150	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note:
A = 0-0.02 inches - Wet
B = 0.02-0.16 inches - Puddled
C - 0.17-0.32 inches - Flooded
35,000 lbs Vertical load, 140 psi tire inflation pressure

TABLE A-3. TEST RESULTS ON REFLEX — PERCUSSIVE GROOVES

Test Speed Knots	Coefficient of Friction, x100															
	Worn Tire							New Tire								
	Non-grooved Surface	Groove Orientation						Nongrooved Surface			Groove Orientation					
	Average Water Depth, Inches															
	A	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
70	18	49 41 40	15 24	19 19	41	32 29 27	19 19	33	28 19	20 20	34 34	20 26	26	36	14 15 29	27 23
90	-	34 35 40	21 15	14	40	26 15	13	26 20	10	-	31 25	24 20	11	30	26 27 15	
110	10	31 30	14 12 14	5	33	26 14	13 5	23	4 6	-	24 26	-	6	28	19 18	10
130	9	22 21 25	17 10	10	25	19 14	9	26	5	-	27 30	15	6	28	16 19 12 10	6 8
150	-	-	-	-	-	-	-	18	-	-	-	-	-	-	-	-

Note:
A = 0.0-0.02 inches - Wet
B = 0.02-0.16 inches - Puddled
C - 0.17-0.32 inches - Flooded
35,000 lbs Vertical load, 140 psi inflation pressure

TABLE A-4. LEAST SQUARE RELATIONSHIP BETWEEN SPEED AND COEFFICIENT OF FRICTION ($\mu = AV^{-B}$)

Coefficient of Friction on:	Wet Surface		Puddled Surface		Flooded Surface	
	Worn Tire	New Tire	Worn Tire	New Tire	Worn Tire	New Tire
Nongrooved Concrete	$26566V^{-1.650}$	$43V^{-0.093}$	-	-	-	-
1-1/4-in. Pitch Grooved Concrete	↑	↑	$4934V^{-1.197}$	$464V^{-.659}$	$2069V^{-1.072}$	$1484V^{-0.980}$
1-1/2-in. Pitch Grooved Concrete			$1948V^{-1.018}$	$1306V^{-.901}$	$3844V^{-1.233}$	$4610V^{-1.253}$
2-in. Pitch Grooved Concrete	$414V^{-.587}$	$70V^{-.166}$	$1955V^{-1.049}$	$10657V^{-1.392}$	$3245V^{-1.230}$	$46466V^{-1.755}$
2-1/2-in. Pitch Grooved Concrete			$355V^{-0.680}$	$1520V^{-0.967}$	$133V^{-0.518}$	$9091V^{-1.392}$
3-in. Pitch Grooved Concrete			$267V^{-1.160}$	$924V^{-0.878}$	$91V^{-0.492}$	$327748V^{-2.195}$
4-in. Pitch Grooved Concrete	↓	↓	$13531V^{-1.553}$	$10643V^{-1.470}$	$99V^{-0.578}$	$31173V^{-1.689}$
Reflex-Percussive Grooves	$2611V^{-.957}$	$156V^{-.366}$	$1049V^{-0.889}$	$255V^{-0.577}$	$2629V^{-1.174}$	$279450V^{-2.2207}$
Reflex-Percussive Textured Concrete	$2056V^{-1.139}$	$521V^{-.655}$	-	-	-	-

V= Test speed in knots.

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