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FACTORS INFLUENCING AIRCRAFT GROUND HANDLING PERFORMANCE

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FACTORS INFLUENCING AIRCRAFT GROUND HANDLING PERFORMANCE

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Abstract

Problems associated with aircraft ground handling operations on wet runways are discussed and major factors which influence tire/runway braking and cornering traction capability are identified including runway characteristics, tire hydroplaning, brake system anomalies, and pilot inputs. Research results from studies conducted at the Langley Aircraft Landing Loads and Traction Facility, tests with instrumented ground vehicles and aircraft, and a recent aircraft wet runway accident investigation are summarized to indicate the effects of different aircraft, tire, and runway parameters. Several promising means are described for improving tire/runway water drainage capability, brake system efficiency, and pilot training to help optimize aircraft traction performance on wet runways.

Introduction

Research findings and technological advances in recent years have helped alleviate, but not eliminate, the hazards associated with adverse weather aircraft operations. Conversely, better avionics, growth in aircraft fleet, airport/runway congestion, and economics are factors which have increased the frequency of aircraft ground operations during inclement weather. However, to a pilot, happiness is still landing into the wind on a long, clean, dry runway keeping to a minimum the number of challenging situations which can arise during operations on slippery runways with fluctuating crosswinds. Improvements in aircraft braking systems, pilot simulator training programs, and runway surface treatments have tended to increase safety margins but weather-related aircraft accidents still occur such as those last year at Washington, D.C., Boston, and New Orleans. Unpredictable and rapidly

changing weather conditions that may be encountered at a given airport further complicate the problems associated with aircraft takeoff and landing maneuvers. For ground operations under varying rainfall conditions, a large number of interacting runway, aircraft, and atmospheric variables, along with pilot technique, combine to influence the level of aircraft runway performance. A need exists for timely recognition and proper assessment of these parameter combinations that can produce inadequate aircraft braking and directional control performance for a given wet runway situation.

With the introduction of large and fast jet transports into airline service in the late 1950's, various research efforts [1 to 27] have been directed towards evaluating the effects on aircraft runway performance due to different rainfall rates, runway characteristics, tire features, and brake system operational modes. Findings from studies conducted at the Langley Aircraft Landing Loads and Traction Facility, tests with instrumented aircraft and ground vehicles, and a recent aircraft wet runway accident investigation are discussed in the following sections of this paper. In addition to showing the effects of several pavement factors and defining the principal causes of wet pavement tire friction degradation and brake system performance anomalies, several promising approaches are identified to help retain adequate tire/ pavement friction and brake system efficiency during aircraft ground operations on wet runways.

Pavement Factors

Water Depth

The major factors affecting aircraft wet runway performance are identified in figure 1. This figure indicates that runway water depth and tire/pavement drainage capability combine to define the friction coefficient available to help meet the aircraft stopping and steering requirements. For low rainfall

rates and good drainage conditions this available tire/pavement friction coefficient may remain high; however, for high rainfall rates and poor drainage conditions, the available friction coefficient can drop drastically, especially at the higher aircraft ground speeds. To help promote water drainage, most runways are constructed with a cross slope or crown and coarse, highly textured surface finishes are applied. In general, runway water buildup or surface flooding that occurs during periods of precipitation is directly related to the rainfall intensity, the surface macrotexture (coarse, large-scale, surface roughness), the runway cross slope, and to some extent, the magnitude and direction of surface winds. Pavement flooding is defined as the depth of water that completely covers the top of all surface asperities. Surface winds have been found to affect water drainage path lengths in the flooded portions of the runway and, depending upon the wind magnitude and direction, the amount of surface water can change from that occurring on a calm day. [13] From data collected during a comprehensive Texas Transportation Institute study described in reference 10, a relationship was established between rainfall intensity, surface macrotexture, pavement cross slope, and water drainage path length without the presence of surface winds. This relationship, given in figure 2, can be used to calculate the rainfall intensity required to initiate flooding in typical aircraft tire paths on a runway surface for a calm day.

The data shown in figure 2 represent the calculated variation in rainfall rate required to flood to within 4.57 m (15 feet) of the runway centerline. The main gear tires of a B-767 transport airplane would be near this distance from the runway centerline if the airplane was traveling directly down the centerline. Calculations were made for five different cross slopes each having a similar range of macrotexture depths. In general, the figure shows

the increase in rainfall rate needed to flood the surface as a function of cross slope and macrotexture depth. If the depth of pavement macrotexture is small, such as observed in some rubber-coated runway touchdown areas, rainfall intensity required for flooding is low despite appreciable cross slope values. Similarly, the chance of reaching flooded surface conditions for a given rainfall intensity increases with decreasing cross slope. In addition, it can be shown that as the distance from the runway centerline (apex of crown) increases, lower rain rates may produce surface flooding.

Texture

Various research studies [28-30] have identified two distinct texture classifications, namely, micro- and macrotexture. In general, microtexture consists of the fine, small-scale, surface features such as those found on individual stone particles, whereas macrotexture encompasses the coarse, large-scale roughness of a pavement surface-aggregate matrix. Under rainfall conditions sufficient to initiate flooding on runway surfaces, the bulk water drainage effectiveness of the surface is dependent on macrotexture characteristics. Based on numerous macrotexture depth measurements taken during several research programs [9 and 28] on a wide variety of runway pavement types and conditions using both the grease sample and sand patch measurement methods, surfaces have been classified into the five major pavement groups or classes shown in the table of figure 3. A general description of the different categorized pavement types is given with class I pavement surfaces having the highest macrotexture depth values and class V surfaces having the lowest macrotexture depth values. Since the potential for dynamic hydroplaning, which is described in the tire friction performance section, varies inversely with surface macrotexture, class I pavements are identified as having the least hydroplaning potential whereas class V

pavements are considered to be the most susceptible. Using this pavement

classification system as a guide for runway surfaces, airport operators should

be encouraged to install class I or II pavement surfaces on runways and if

periodic macrotexture depth measurements indicate the runway surface is

approaching the class IV category, corrective surface treatments, such as

grooving or rubber removal programs, should be implemented. It is also

recommended that if a runway or portion of a runway surface is determined

to be within class IV or V, adequate and timely notification should be given

to pilots particularly during wet weather aircraft landing and takeoff

operations.

Although class I pavements have been proven to minimize wet runway

friction problems, one recent runway installation created another problem

under dry surface conditions which has since restricted aircraft operations

to takeoffs only. The photographs in figure 4 illustrate the extent of a

tire tread abrasion problem which occurred during three aircraft landing

tests on an asphalt-rubber chip seal overlay surface. This operational prob-

lem is attributed to the sharp, multi-edged, exposed, stone chips used in

the overlay mix combined with the relatively low dry surface friction

capability.

Contaminants

The effect of surface water and rubber contaminants on vehicle stopping

capability and tire friction performance is shown in figure 5. This eval-

uation was performed with the NASA-developed diagonal-braked vehicle (DBV)

shown in the photograph in figure 5. The brake system diagram illustrates

the modification made to implement stable and controlled vehicle perform-

ance during the friction measurements at high speed with two diagonal wheels

locked and the remaining pair free rolling (unbraked). The DBV wet/dry

stopping distance ratios depicted in the bar graphs for different rainfall

rates and surface types were obtained from test runs conducted at the same distance off runway centerline with brake application speed from 98 km/h (60 mph) down to a complete stop. Measurements of surface water depth and DBV stopping distance during different periods of rainstorm activity on an ungrooved concrete runway with a 1 percent crown reveal a direct relationship between average water depth and stopping distance. As rainfall rates increase, greater water buildup on the runway surface occurs which decreases tire friction performance as reflected in the increased DBV wet/dry stopping distance ratios. A further increase in runway slipperiness was found near the end of the runway which was contaminated by rubber deposited during aircraft tire spin-up following touchdown. The buildup of the rubber coating on runway surfaces tends to reduce pavement texture and hence, degrade tire friction particularly under wet conditions. The cross-hatched DBV stopping distance increment shown in figure 5 illustrates the effects of rubber contamination on the ungrooved concrete runway slipperiness measurements for different rainfall rates. Also included in the figure are comparable DBV measurements made on other grooved and ungrooved runways under artificially wetted (truck) conditions where the average water depth was 0.5 mm (0.02 in.). The longer DBV wet/dry stopping distance ratios measured on the ungrooved asphalt runways compared to the concrete surfaces are the result of lower surface macrotexture. Fortunately, successful methods [31] have been developed to remove the rubber deposits on runway surfaces using high pressure water and now many major airports regularly schedule runway rubber removal treatments.

Tire Friction Performance

Viscous and Dynamic Hydroplaning

During aircraft ground operations in wet weather, a water removal or drainage problem is created at tire/pavement interfaces. The runway surface

water encountered by the moving aircraft tires must be rapidly expelled from the tire/pavement contact area or the viscous and dynamic water pressures that build up with increasing ground speed will significantly reduce tire friction performance. Research studies [28-30] have shown that the slope of a tire friction-speed gradient curve is primarily a function of the surface macrotexture, and the magnitude of the friction at a given speed is related to the surface microtexture. Hence, an assessment of both surface micro- and macrotexture characteristics is necessary to fully relate tire friction performance to pavement texture.

The principal forms of these wet pavement tire friction losses, namely, viscous and dynamic hydroplaning and reverted rubber skidding, are illustrated in figure 6. The speed regime, pavement and tire condition, and tire operating mode that contribute to loss in tire friction are identified together with the factors that tend to alleviate their occurrence. Viscous hydroplaning or thin-film lubrication results from the inability of the tire to penetrate and disrupt the very thin residual fluid film left on the pavement after the majority of the trapped water has been displaced from the tire footprint. In this case, the pressure buildup within the tire/pavement interface is due to fluid viscous properties. Smooth tires operating on wet smooth pavements are particularly susceptible to this type of tire hydroplaning.

During dynamic hydroplaning, a buildup of hydrodynamic pressure between tire and flooded pavement occurs as the square of vehicle speed. [2] When this hydrodynamic pressure exceeds the tire-pavement bearing pressure, a wedge of water penetrates the tire contact area and the tire footprint is partially or totally detached from the pavement surface. Under total dynamic hydroplaning conditions, tire friction capability is reduced to near zero because of the inability of the fluid to support significant shear forces. It should

be noted that for many wet pavement aircraft operations, reduced tire friction performance may occur from both viscous and dynamic fluid pressure buildup resulting in combined viscous/dynamic hydroplaning. [13]

The contact pressure developed between tire tread and pavement establishes the escape velocity of bulk water drainage from beneath the tire footprint. High pressure tires can expel surface water more readily from the footprint that low pressure tires. When the aircraft ground speed equals or exceeds the escape velocity of water drainage from the footprint, choked water flow occurs. The tire has now reached the state of total dynamic hydroplaning. Test results [2, 12, and 13] indicate that the critical aircraft ground speeds required for this total hydroplaning condition to occur on flooded (runway water depth is greater than tire tread goove depth) pavements with an unbraked tire are approximately:

Spin-down (Rotating tire) speed, knots = 9 $\sqrt{\text{Infl. pressure, psi}}$

and

Spin-up (Nonrotating tire) speed, knots = 7.7 $\sqrt{\text{Infl. pressure, psi}}$

For the nonrotating tire case (as at aircraft touchdown), Langley track test results shown in figure 7 illustrate the delay in tire spin-up following touchdown on a flooded surface until the test carriage speed decreased to approximately 93 knots. It is important that pilots be aware that the lower hydroplaning spin-up speed, rather than the high hydroplaning spin-down speed, represents the actual tire situation for aircraft touchdown on flooded runways.

Reverted Rubber Skidding

The third form of tire friction loss, reverted-rubber skidding, is named for the appearance of the tire tread skid patch after a prolonged locked-wheel skid. It is believed that friction-generated heat within the skidding tire/pavement contact area is sufficient to produce steam and cause the tire

tread rubber to revert back to its uncured state. [12 and 18] The soft gummy

reverted rubber forms a seal around the tire footprint periphery and the

entrapped steam and water significantly reduce braking and cornering capabili-

ty. This hypothesis would also explain the distinctive (steam cleaned) mark

left on the pavement in the tire path as shown in the aircraft accident

photographs in figure 8. Evidence from this aircraft wet runway skidding

accident as well as several others indicates that once started, reverted

rubber skidding results in very low tire/pavement friction which persists

down to very low speeds. With tire operation in a nonrotating mode, the loss

of tire cornering capability for directional control is possibly a greater

problem, considering runway geometry, for pilots to overcome than the low

braking performance. Providing and maintaining runway surfaces with high

macrotexture and good drainage characteristics is very important in allevi-

ating the occurrence of this aircraft tire friction loss as well as those

associated with tire hydroplaning.

Aircraft Landing Performance

During aircraft ground operations, pilot techniques and control inputs

together with certain aircraft parameters including aerodynamics, engines,

brake system, and landing gear configuration interact to determine how much

of the available tire pavement traction is utilized for stopping and direc-

tional control purposes. The influence of speed, tire tread condition, and

pavement surface macrotexture on aircraft braking performance is illustrated

in figure 9. These data were obtained during instrumented CV990 aircraft

braking tests [8] conducted at NASA Wallops Flight Center on a unique research

runway which features a variety of pavements selected to provide a wide range

of surface macrotextures. A portion of each of these different pavements

was modified with installation of 6 x 6 x 25 mm (0.25 x 0.25 x 1-in. pitch)

transverse grooves. For dry concrete conditions, the measured aircraft

effective braking friction coefficient level indicated in figure 9 did not
vary significantly with tire tread design or surface configuration but some
decrease was observed with increasing speed. The effect of speed was much
more pronounced on the wet ungrooved surface and these data indicate that
the rib-tread design provided a significant improvement compared with the
smooth tire data. The calculated hydroplaning spin-down speed of 114 knots
noted in figure 9 is based on a tire inflation pressure of 1103 kPa (160 lb/in^2).
On the similarly wetted grooved concrete, the transverse runway grooves pro-
duced substantially greater aircraft braking friction levels with both tire
treads than were shown by the wet ungrooved surface data. These aircraft
braking performance data on wet runways also suggest that the effects of tire
tread wear are secondary to the effects of surface grooving because of the
greatly enhanced tire/pavement water drainage capability available on grooved
runways.

Antiskid Behavior

The brake system is the primary means for stopping the aircraft. The
development and use of antiskid control systems designed to minimize
tire skidding and prevent wheel lockups during braking has substantially
enhanced aircraft braking performance and stopping capability. Most antiskid
systems employ touchdown and locked-wheel protection features in the brake
control logic circuits to prevent brake pressure application to a nonrotating
wheel as at touchdown or as the result of low tire/pavement friction conditions
causing wheel lockup. The proper performance of these systems, however,
depends on accurate inputs of aircraft ground speed and instantaneous braked
wheel angular velocity data coupled with efficient mechanisms for reducing
and reapplying hydraulic pressure to each wheel brake unit. Effective
antiskid brake control operation also requires positive wheel spin-up

accelerations after tire touchdown and following brake pressure release during antiskid cycling. Since wheel spin-up characteristics are directly influenced by the friction generated between the tire and the runway, brake control behavior can be significantly compromised during aircraft operations under adverse weather conditions and at high ground speeds. The precision of braked wheel control by the antiskid deteriorates when low tire traction causes low wheel spin-up accelerations. Certain pilot inputs, such as full brake application before the wheels reach synchronous aircraft speed, can also adversely affect brake control because the logic circuits do not receive the correct aircraft ground speed reference value. [14]

Aircraft Test Results

An example of such anomalous antiskid brake control operation following touchdown is given in figure 10. These time history data collected during wet runway tests with a large jet transport aircraft [32] illustrate the antiskid brake control response of the inboard wheels on a four-wheel bogie main landing gear to brake applications that occurred prior to and after full wheel spin-up during landings. For brake application prior to full wheel spin-up, it is apparent from figure 10 that the ground speed reference assumed by the skid-control logic circuit for the front wheel is well below the actual aircraft speed. The low wheel spin-up accelerations following brake pressure release during each braking cycle, combined with the low ground speed reference, prevented the front wheel from attaining synchronous aircraft speed until approximately 30 seconds into the landing rollout. By that time, the aircraft speed had decreased sufficiently to cause high wheel spin-up acceleration and the proper ground speed reference signal was acquired. Subsequently, braked wheel motion was satisfactorily controlled down to the aircraft stop point. The much faster recovery of aircraft synchronous speed

by the rear tandem wheel (Figure 10) reflects the benefit of path clearing
by the front tandem wheel which produces a less slippery surface for the
trailing wheel.

Figure 10 also includes wheel angular velocity data obtained during a
second aircraft landing in which brakes were applied after the wheels
reached full spin-up. These braked wheel responses suggest that the pilot
should delay brake application during landings on wet runways to allow the
skid-control logic system sufficient time to acquire an accurate ground
speed reference. The considerably reduced tire skidding experienced during
this landing compared to the data collected when brakes were applied early
suggests improved aircraft stopping performance and reduced tire wear.
should be noted that a comparison of the braking effect   emonstrated
by the two landings is not justified because the t. s were made at different
aircraft gross weights and brake application speeds.

Comparative aircraft braking effectiveness data is presented in figure
11 for three landing tests conducted with a B-727 aircraft equipped with an
antiskid brake system. These test results,[22] which show the variation in
effective braking friction coefficient with speed for one dry and two wet
runway landing cases, illustrate the significant effect that tire/runway
friction and braked wheel control have on aircraft braking performance. For
the dry and wet runway landings (cases 1 and 2) conducted with sufficient
tire/runway friction to permit braked wheel control without locking the wheel,
a continuous increase in friction was measured as the aircraft speed decreased.
As expected, significantly higher aircraft braking effectiveness was obtained
during the dry runway landing compared to the wet runway landing. The
second wet runway landing, case 3, was made with an average surface water
depth about twice that measured for case 2. This greater runway water depth

resulted in much lower tire/runway friction and all four main gear wheels locked following brake application. The subsequent skidding produced a reverted rubber patch on the tire such as shown in the photograph in figure 11. With the development of reverted rubber skidding, the aircraft braking effectiveness was substantially reduced with little change in friction throughout the landing speed range. The calculated aircraft stopping distance for case 3 is approximately twice that found for case 2. Of equal concern, a locked (nonrotating) wheel cannot provide stabilizing forces necessary for directional control. Analogous low tire friction results were also obtained during Langley track tests [6] when prolonged tire skidding on a wet surface produced reverted rubber in the tire contact patch.

Additional insight into the lack of directional control as well as reverted rubber skidding caused by nonrotating tires was obtained during a recent investigation of a T-38 aircraft landing veeroff accident which occurred at night during a moderate rainstorm. A left-to-right crosswind component caused the pilot to land the aircraft at a crab angle slightly right of runway centerline. The accident aircraft landing runout track, identified by white marks visible on the runway surface, is shown in figure 12 together with photographs of the ungrooved, low textured (class V), concrete runway surface, the main landing gear (MLG) tire skid patches, and the damaged aircraft. Fortunately, the pilot escaped injury even though the nose and right main landing gear failed and the right wing tip was sheared off subsequent to the aircraft leaving the right shoulder of the runway, traversing a relatively soft soil surface, and coming to rest on an intersecting paved taxiway. During the investigation which followed the accident, the estimated aircraft touchdown point near the runway intersection was found to be a water ponding area with water depths measured up to 13 mm (0.5 in.). Additional evidence

and factors which tend to support the belief that possibly the MLG tires did
not spin up following touchdown include the fact that the aircraft touchdown
speed was significantly higher than the calculated tire hydroplaning spin-up
speed of 119 knots, the surface white marks from the MLG tires commenced
when the aircraft exited the deeply flooded portion of the runway and con-
tinued to the runway shoulder edge, and only one skid patch, showing evidence
of tread rubber reversion in the aft portion, was found on each MLG tire.
Knowing that he was landing on a wet runway, the pilot did not apply wheel
braking during the aircraft runout on the paved runway and yet, reverted
rubber skidding evidently occurred. Inspection of the aircraft wheel brake
assemblies revealed no abnormalities and no indication of dragging brake
operation. In all other documented aircraft accident/incident cases involving
reverted rubber skidding, the pilot had employed wheel braking during the
aircraft runout which contributed to locked wheel operation.

Concluding Remarks

The principal weather, aircraft, runway, and pilot factors which combine
to affect aircraft ground handling performance during wet runway operations
have been reviewed. This review included: identifying a relationship estab-
lished between rainfall rate and runway water depth; defining the major forms
of tire friction losses; classifying pavement surfaces by macrotexture depth
and hydroplaning potential; and evaluating antiskid brake system performance.
Research results from studies conducted at the Langley Aircraft Landing Loads
and Traction Facility, tests with instrumented ground vehicles and aircraft,
and a recent aircraft wet runway accident investigation were presented to
illustrate the effects of various parameters on aircraft braking effectiveness.
These findings underscore the complexity and variability which characterizes

aircraft wet runway operations. Research efforts, however, have revealed several promising means, such as the use of runway grooving and frequent rubber removal treatments, which offer improved tire/runway water drainage capability and hence, contribute to safer aircraft operations. In reviewing the factors influencing aircraft wet runway performance, several approaches or needs have also been recognized to alleviate the severity of the problem including: continued updating of pilot education and training procedures; implementation of procedures for monitoring slippery runway conditions and identifying severity to the pilot; improvement in antiskid brake system performance; and prompt remedial treatment of runway surface drainage problems.

References

1. Horne, Walter B.; and Leland, Trafford J. W.: Influence of Tire Tread Pattern and Runway Surface Condition on Braking Friction and Rolling Resistance of a Modern Aircraft Tire. NASA TN D-1376, 1962.

2. Horne, Walter B.; and Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.

3. Joyner, Upshur T.; Horne, Walter B.; and Leland, Trafford J. W.: Investigations on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag. AGARD Rept. 429, Jan. 1963.

4. Leland, Trafford J. W.; and Taylor, Glenn R.: An Investigation of the Influence of Aircraft Tire-Tread Wear on Wet-Runway Braking. NASA TN D-277ᷓ, April 1965.

5. Horne, Walter B.: Skidding Accidents on Runways and Highways Can Be Reduced. Astronautics and Aeronautics, vol. 5, no. 8, Aug. 1967, pp. 48-55.

6. Horne, Walter B.; Yager, Thomas J.; and Taylor, Glenn R.: Review of Causes and Alleviation of Low Tire Traction on Wet Runways. NASA TN D-4406, 1968.

7. Leland, Trafford J. W.; Yager, Thomas J.; and Joyner, Upshur T.: Effects of Pavement Texture on Wet-Runway Braking Performance. NASA TN D-4323, January 1968.

8. Anon.: Pavement Grooving and Traction Studies. NASA SP-5073, 1969.

9. Yager, Thomas J.; Phillips, W. Pelham; Horne, Walter B.; and Sparks, Howard C. (Aeronautical Systems Div., WPAFB): A Comparison of Aircraft and Ground Vehicle Stopping Performance on Dry, Wet, Flooded, Slush-, and Ice-Covered Runways. NASA TN D-6098, Nov. 1970.

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

11. Yager, Thomas J.: Progress in Airport Pavement Slipperiness Control. Air Line Pilots Association 18th Air Safety Forum, Dallas, TX, July 20-22, 1971.

12. Horne, Walter B.: Wet Runways. NASA TM X-72650, April 1975.

13. Horne, Walter B.: Status of Runway Slipperiness Research. NASA SP-416, October 1976, pp. 191-245.

14. Horne, Walter B.; McCarty, John L.; and Tanner, John A.: Some Effects of Adverse Weather Conditions on Performance of Airplane Antiskid Braking Systems. NASA TN D-8202, July 1976.

15. Merritt, Leslie R.: Impact of Runway Traction on Possible Approaches to Certification and Operation of Jet Transport Aircraft. Paper 740497, Soc. Automotive Engineers, April-May, 1974.

16. Horne, Walter B.; and Joyner, Upshur T.: Determining Causation of Aircraft
Skidding Accidents or Incidents. Paper presented at the 23rd Annual
International Air Safety Seminar, Flight Safety Foundation, Inc.
(Washington, DC), October 1970.

17. Horne, Walter B.: Elements Affecting Runway Traction. (Preprint)
740496, Soc. Automotive Engineers, April-May, 1974.

18. Lander, F. T. W.; and Williams, T.: The Skidding Resistance of Wet
Runway Surfaces with Reference to Surface Texture and Tyre Conditions.
RRL Rep. LR 184, Road Res. Lab., British Ministry of Transportation, 1968.

19. Smiley, Robert F.; and Horne, Walter B.: Mechanical Properties of
Pneumatic Tires With Special Reference to Modern Aircraft Tires. NASA
TR R-64, 1960. (Supersedes NACA TN 4110).

20. Horne, Walter B.; and Joyner, Upshur T.: Pneumatic Tire Hydroplaning
and Some Effects on Vehicle Performance. SAE International Automotive
Engineering Congress (Detroit, Michigan), SAE 970C, Jan. 11-15, 1965.

21. Yager, Thomas J.; and White, Ellis J.: Recent Progress Towards Predicting
Aircraft Ground Handling Performance. NASA TM 81952, March 1981.

22. Horne, Walter B.; Yager, Thomas J.; Sleeper, Robert K.; and Merritt,
Leslie R. (Federal Aviation Administration): Preliminary Test Results
of the Joint FAA-USAF-NASA Runway Research Program, Part I - Traction
Measurements of Several Runways Under Wet and Dry Conditions with a
Boeing 727, a Diagonal-Braked Vehicle, and a Mu-Meter. NASA TM X-73909,
1977.

23. Horne, Walter B.; Yager, Thomas J.; Sleeper, Robert K.; Smith, Eunice G.;
and Merritt, Leslie R. (Federal Aviation Administration): Preliminary
Tests Results of the Joint FAA-USAF-NASA Runway Research Program, Part
II - Traction Measurements of Several Runways Under Wet, Snow-Covered,
and Dry Conditions with a Douglas DC-9, a Diagonal-Braked Vehicle, and

a Mu-Meter. NASA TM X-73910, 1977.

24. Stubbs, Sandy M.; and Tanner, John A.: Review of Antiskid and Brake

    Dynamics Research. Aircraft Safety and Operating Problems, NASA CP-2170,

    1981, pp. 555-568.

25. McCarty, John L.; Yager, Thomas J.; and Riccitiello, S. R.: Wear,

    Friction, and Temperature Characteristics of an Aircraft Tire Undergoing

    Braking and Cornering. NASA TP 1569, 1979.

26. Yager, Thomas J.; and Dreher, Robert C.: Traction Characteristics of a

    30x11.5-14.5, Type VII, Aircraft Tire on Dry, Wet, and Flooded Surfaces.

    NASA TM X-72805, 1976.

27. Tanner, John A.: Review of NASA Antiskid Braking Research. Paper 821393,

    Soc. Automotive Engineers, Oct. 1982.

28. Yager, Thomas J.; and Buhlman, F.: Macrotexture and Drainage Measurements

    on a Variety of Concrete and Asphalt Surfaces. ASTM STP 763, 1982, pp.

    16-30.

29. Ludema, K. C.; and Gujrati, B. D.: An Analysis of the Literature on

    Tire-Road Skid Resistance. ASTM STP 541, 1973.

30. Henry, J. J.; and Hegmon, R. R.: Surface Texture Versus Skidding:

    Measurements, Frictional Aspects, and Safety Features of Tire-Pavement

    Interactions. ASTM STP 583, 1975, pp. 3-17.

31. Horne, Walter B.; and Griswold, Guy D. (USAF, Langley AFB): Evaluation of

    High Pressure Water Blast with Rotating Spray Bar for Removing Paint

    and Rubber Deposits from Airport Runways, and Review of Runway Slipperi-

    ness Problems Created by Rubber Contamination. NASA TM X-72797,

    November 1975.

32. Model L-1011 (Base Aircraft) Landing Performance Report for FAA Evaluation

    of Concorde SST Special Condition 25-43-EU-12. Rep. No. LR 26267

    Lockheed Aircraft Corp., Jan. 14, 1974.
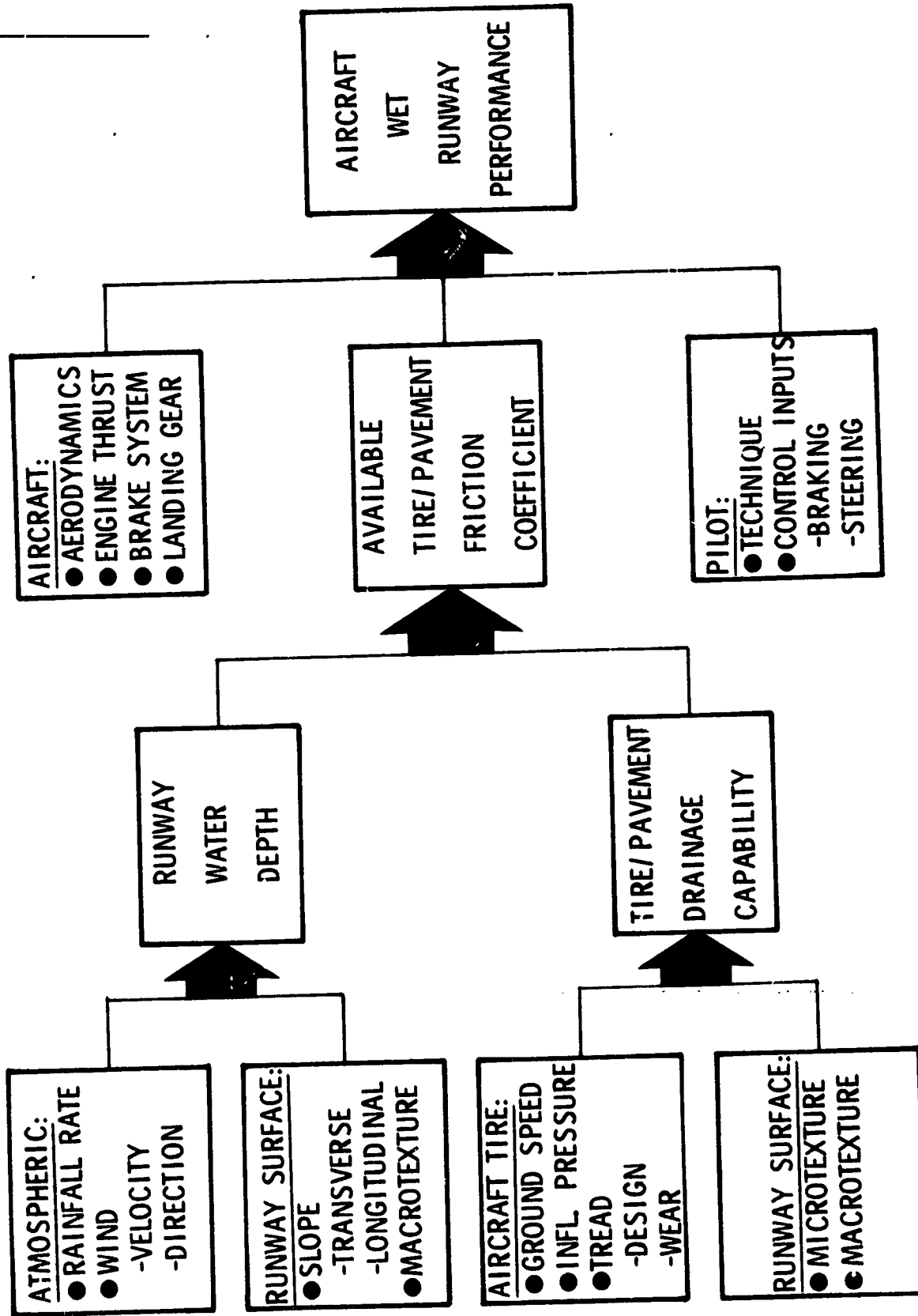
Figure 1.- Factors affecting aircraft wet runway performance.

$$\text{RAINFALL RATE} = K \left[\frac{(\text{MACROTEXTURE DEPTH})^{.89}}{[(\text{DISTANCE FROM RUNWAY } \text{\textcentoblique})]^{.43} \left(\frac{1}{\text{CROSS SLOPE}} \right)^{.42}} \right]^{1.695}$$

(FROM REF. 10)

WHERE:

K = 1253 for metric units; 15430 for U.S. Customary units

4.57M (15 FT) FROM RUNWAY CENTERLINE; CALM WINDS
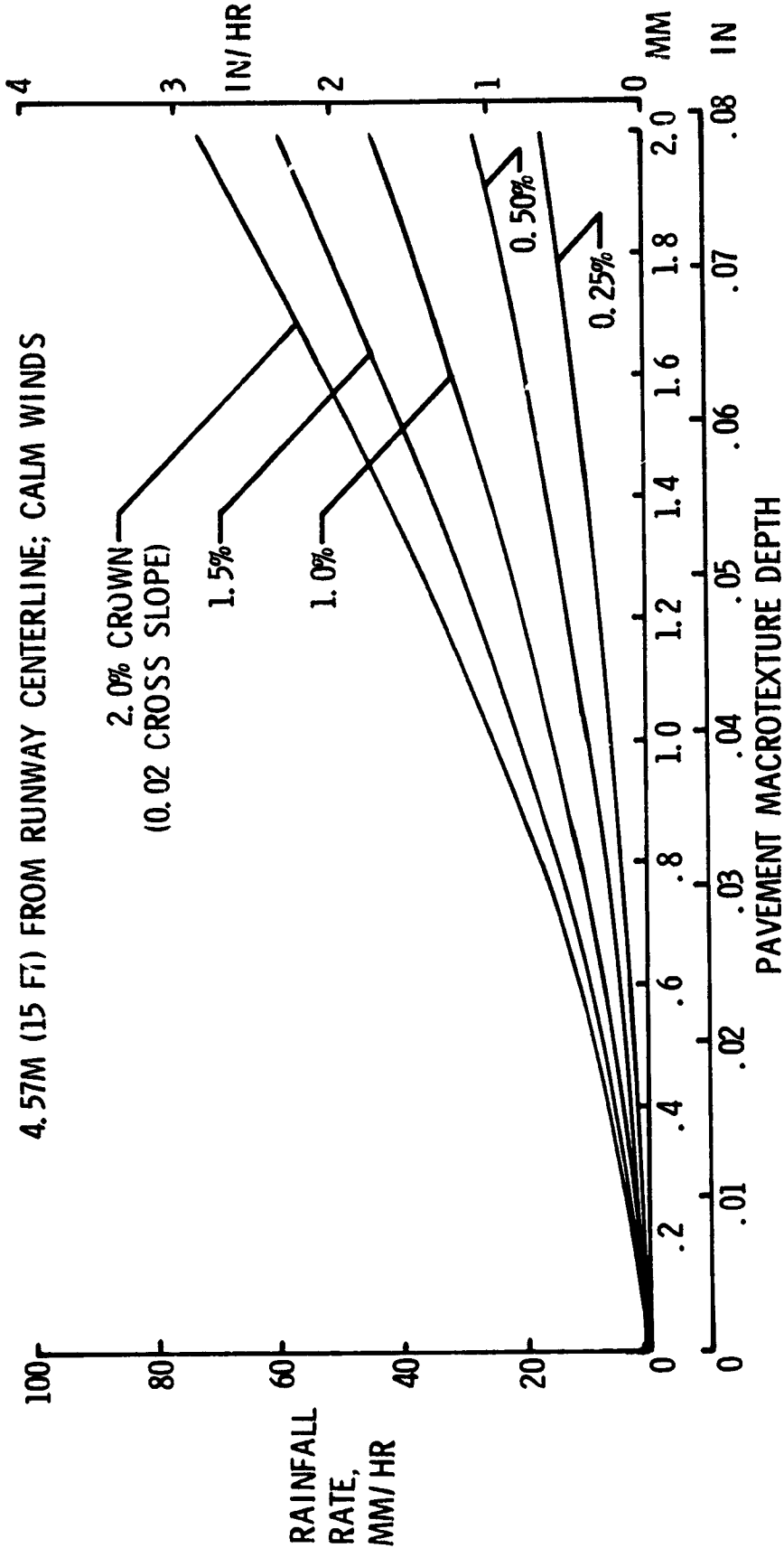
Figure 2.- Calculated rainfall rate required for flooding runway surfaces in typical transport aircraft main gear tire path.

CLASS	TYPE OF SURFACE	HYDROPLANING POTENTIAL	MACROTEXTURE DEPTH, MM (IN.)	
			GREASE SAMPLE METHOD	SAND PATCH METHOD
I	DEEP GROOVING OPEN TEXTURE POROUS FRICTION COURSE	LOW	>1 (0.04)	>1.8 (0.07)
II	SHALLOW GROOVING SCORING AND WIRE COMBING SOME LARGE AGGR. ASPHALT	POOR	1 (0.04) TO 0.5 (0.02)	1.8 (0.07) TO 0.9 (0.035)
III	HEAVILY TEXTURED CONCRETE SOME MIXED-GRADATION AGGREGATE ASPHALT	FAIR	0.5 (0.02) TO 0.3 (0.01)	0.9 (0.035) TO 0.6 (0.024)
IV	LIGHTLY TEXTURED CONCRETE SOME WORN AND TRAFFICKED MOST SMALL AGGR. ASPHALT	GOOD	0.3 (0.01) TO 0.1 (0.004)	0.6 (0.024) TO 0.25 (0.01)
V	VERY LITTLE TEXTURE PAINTED AND RUBBER COATED SOME HEAVILY TRAFFICKED	HIGH	<0.1 (0.004)	<0.25 (0.01)

Figure 3.- Classification of pavement surfaces by hydroplaning potential and macrotexture depth.
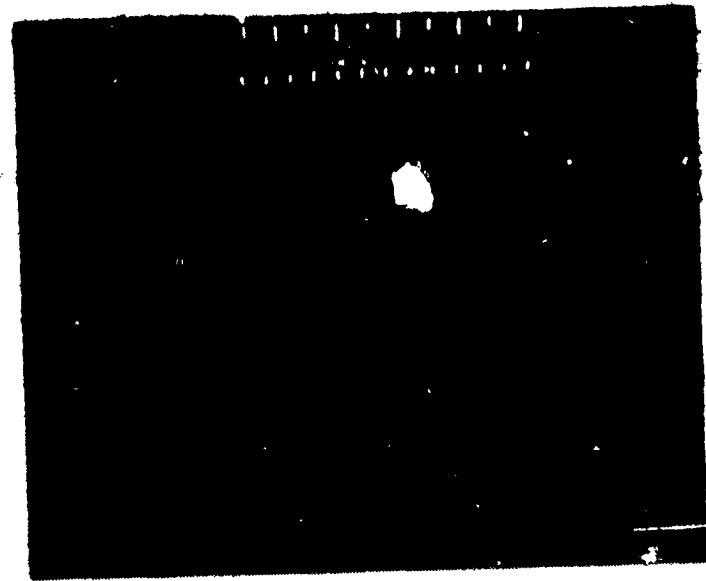
TREAD ABRASION FOUND ON
B-737 AIRCRAFT MAIN GEAR TIRE
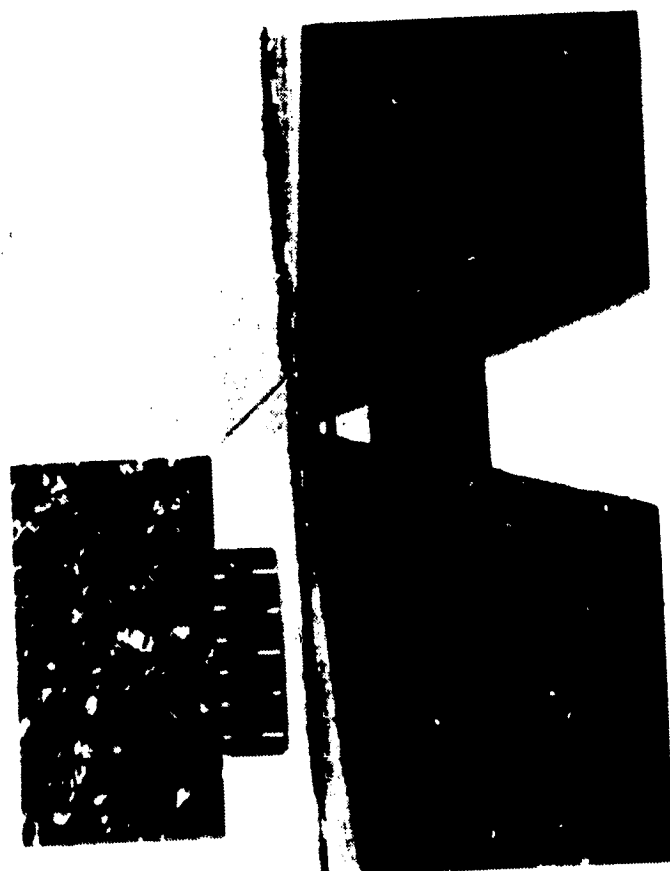
ASPHALT-RUBBER CHIP SEAL OVERLAY SURFACE

Figure 4.- Example of high macrotexture runway surface causing aircraft tire tread abrasion problem.
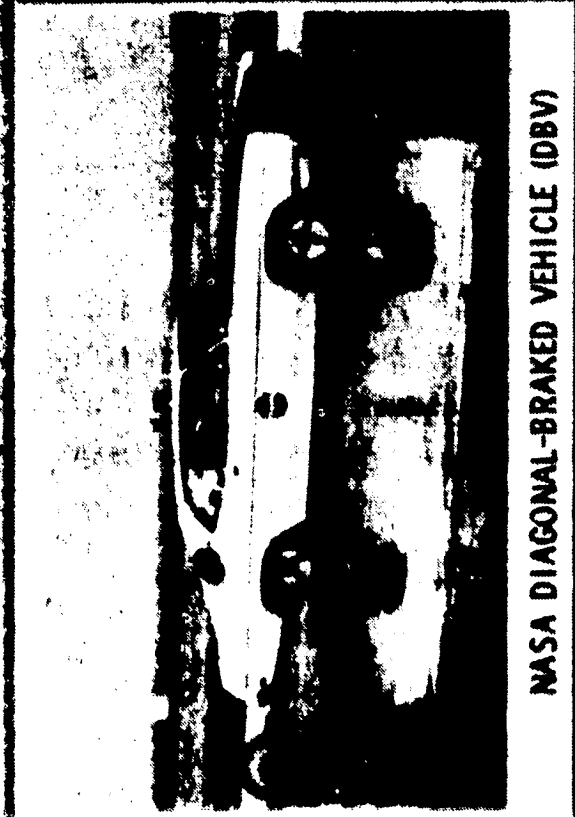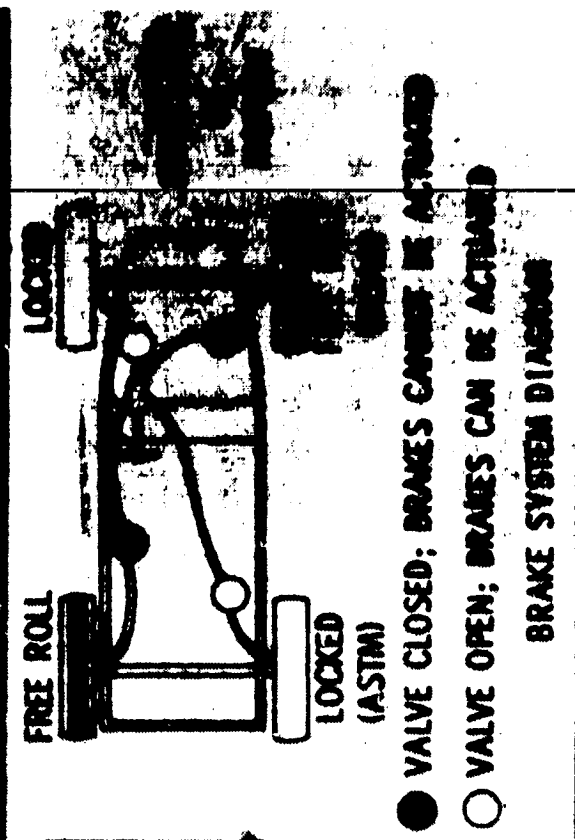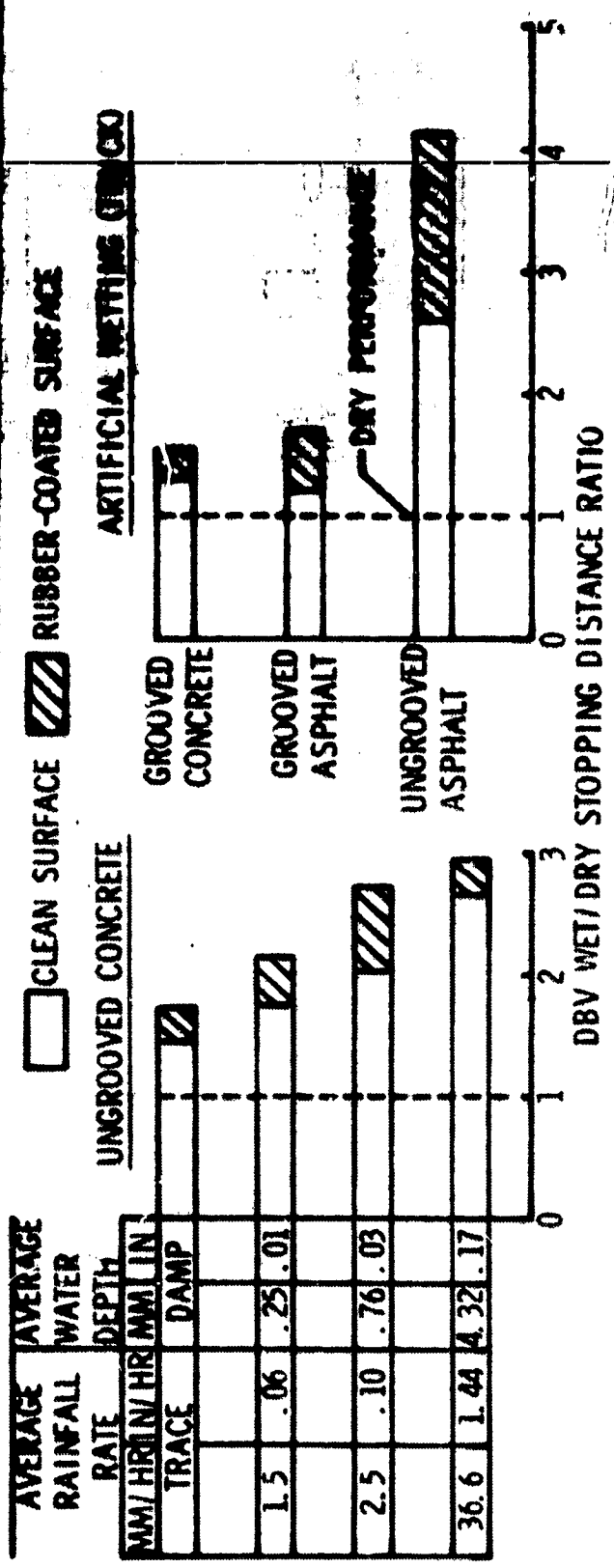
Figure 5.- Effect of surface contaminants on diagonal-braked vehicle stopping performance.
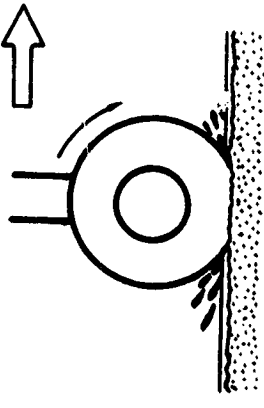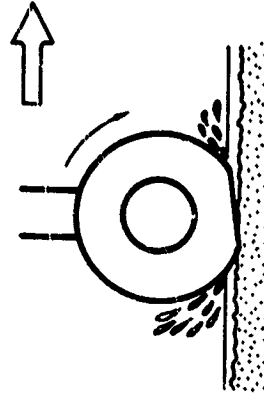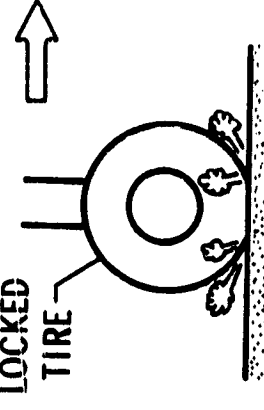
CAUSES	HYDROPLANING		REVERTED RUBBER SKIDDING
	VISCOUS	DYNAMIC	
CONTRIBUTING FACTORS	DAMP OR WET PAVEMENT MEDIUM TO HIGH SPEED POOR PAVEMENT TEXTURE WORN TIRE TREAD	FLOODED PAVEMENT HIGH SPEED LOW TIRE PRESSURE WORN TIRE TREAD	WET OR FLOODED PAVEMENT HIGH SPEED POOR PAVEMENT TEXTURE DEFICIENT BRAKE SYSTEM
ALLEVIATING FACTORS	PAVEMENT MICROTEXTURE PAVEMENT GROOVING GOOD TREAD DESIGN	PAVEMENT MACROTEXTURE PAVEMENT GROOVING INCREASED TIRE PRESSURE GOOD TREAD DESIGN	GOOD PAVEMENT TEXTURE PAVEMENT GROOVING IMPROVED ANTISKID

(Diagram labels: LOCKED TIRE, under REVERTED RUBBER SKIDDING)

Figure 5.- Principal causes of wet pavement tire friction losses.

DC-9 MAIN GEAR, RIB-TREAD TIRE; INFLATION PRESSURE, 965 KPA (140 LB/IN²)
AVERAGE WATER DEPTH, 5 MM (0.2 IN.)

TIRE HYDROPLANING SPIN-UP SPEED = 91 KNOTS
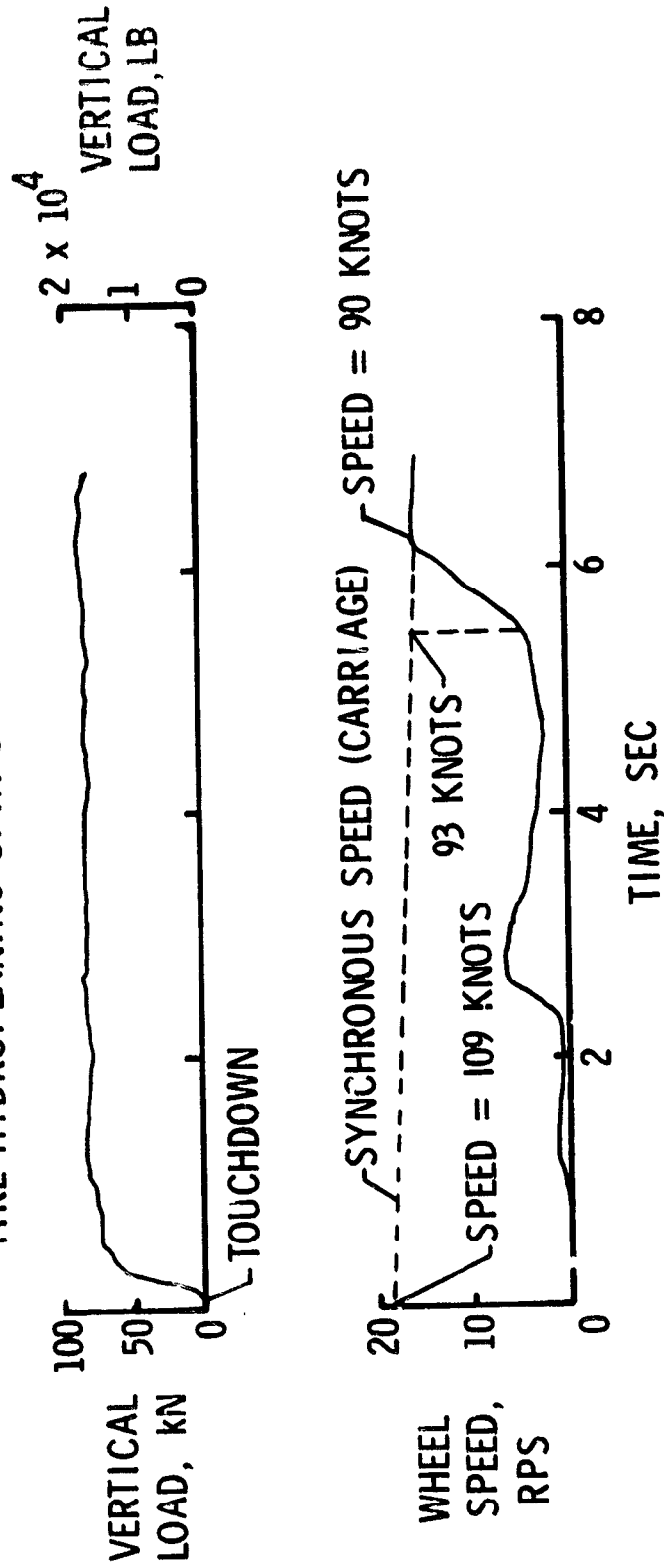
Figure 7.- Delayed wheel spin-up at touchdown on flooded runway test surface at Langley track facility.

HYDROPLANING ACCIDENT - WET RUNWAY 4 ENGINE
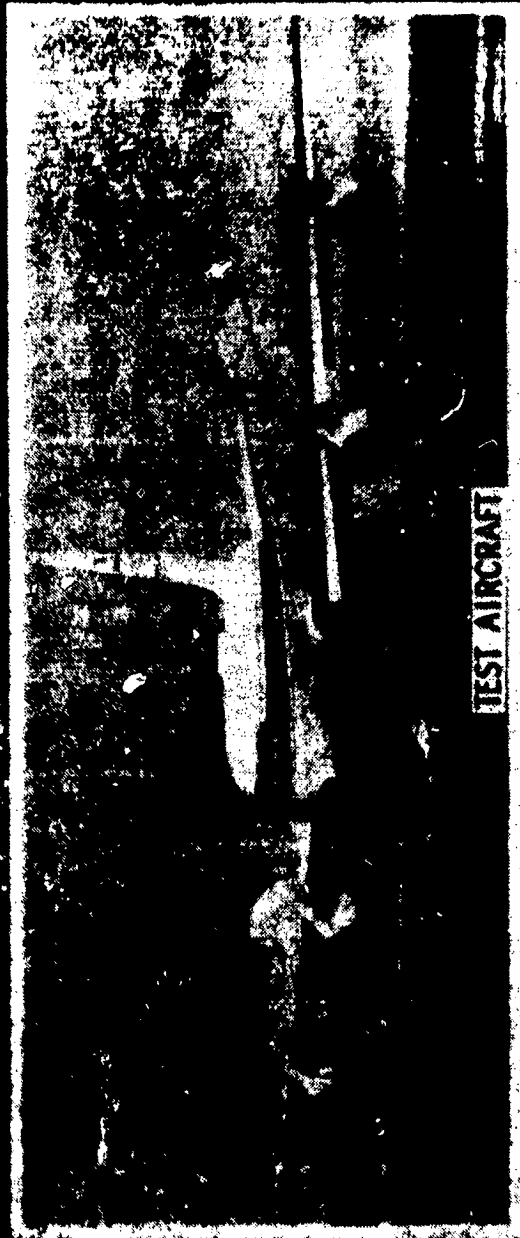JET TRANSPORT

MAIN LANDING GEAR TIRE WITH
REVERTED RUBBER SKID PATCH
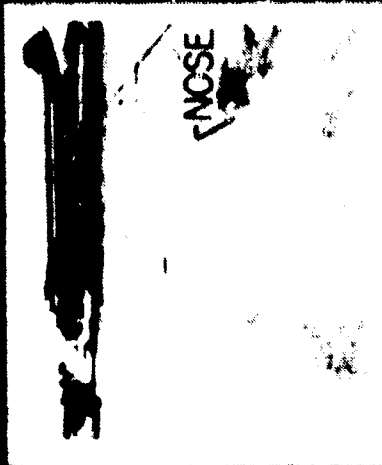
NOSE

LEFT MAIN AND NOSE
TIRE TRACKS

RIGHT MAIN TIRE
TRACKS

Figure 8.- Example of reverted rubber skidding during aircraft wet runway landing.
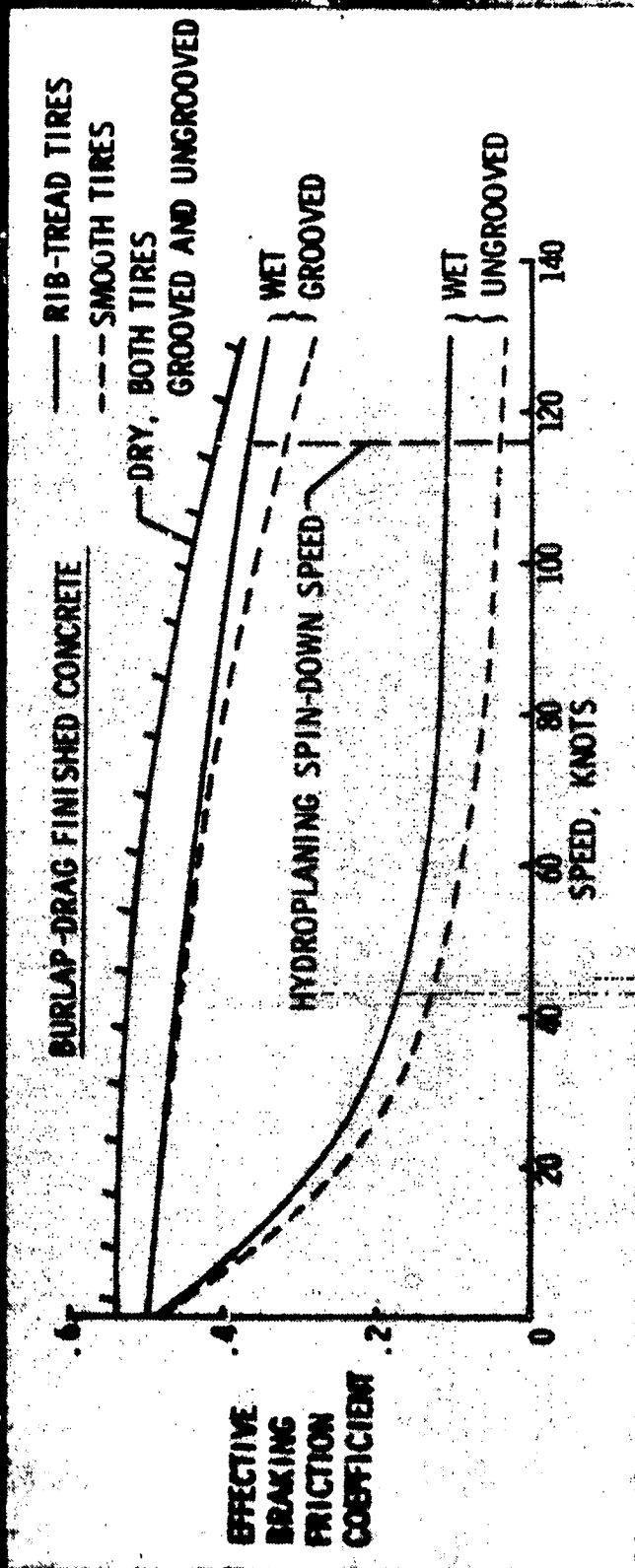
Figure 9.– Effect of tire tread design and pavement surface condition on CV990 aircraft braking friction.
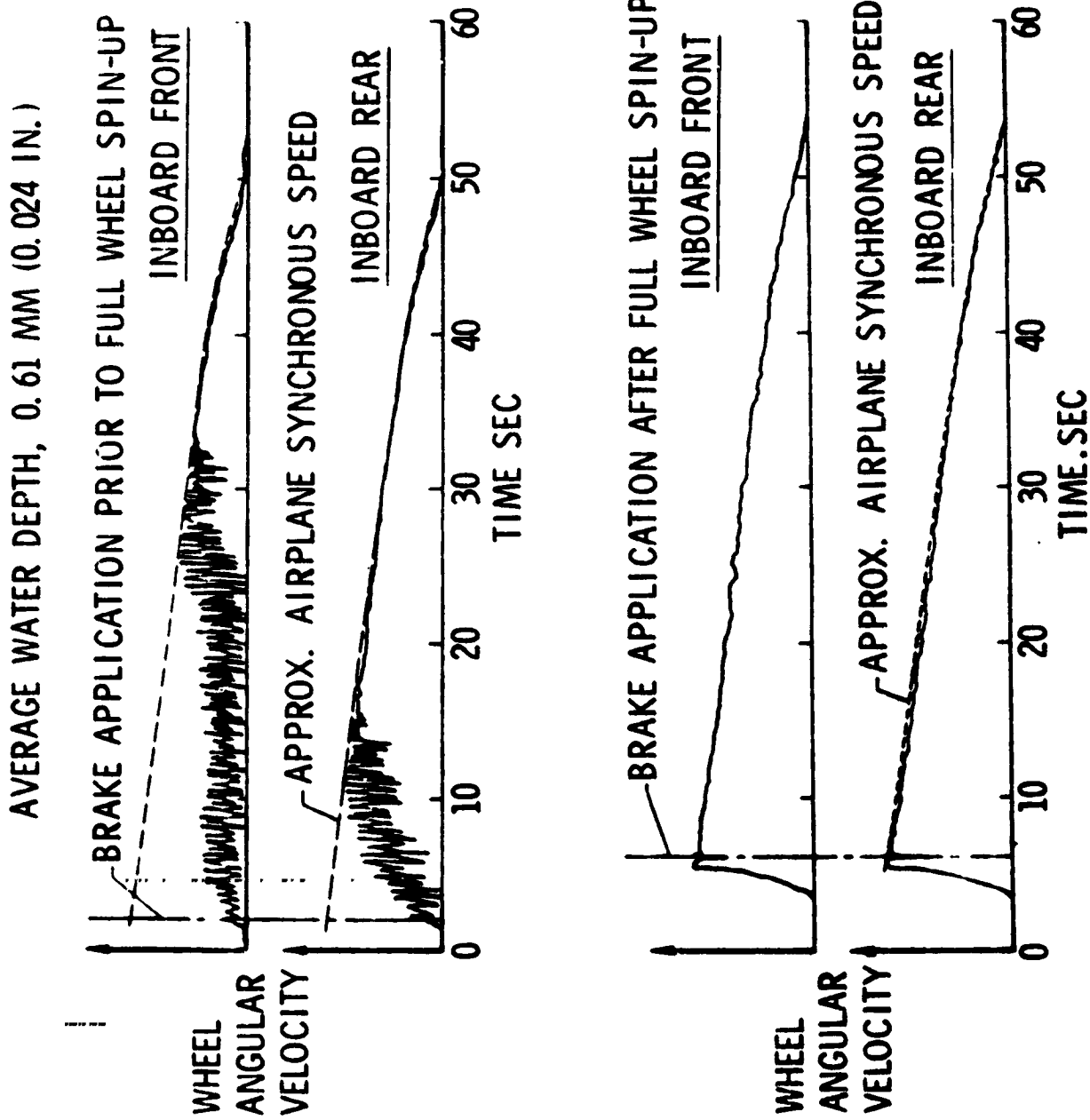
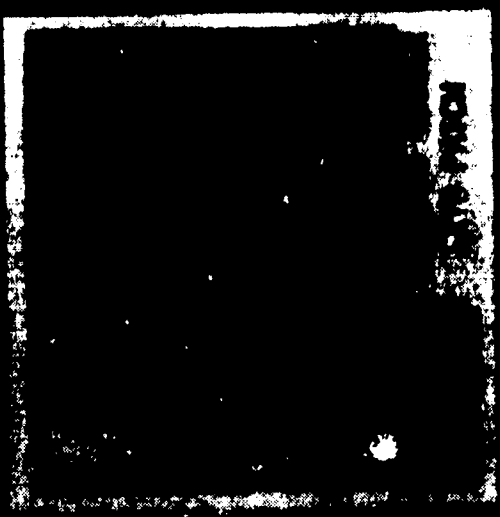Figure 10.– Aircraft braked wheel responses for antiskid brake application prior to and after full wheel spin-up during landings on wet surface.
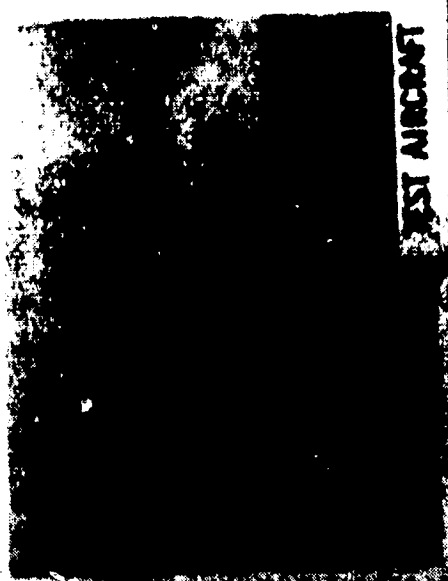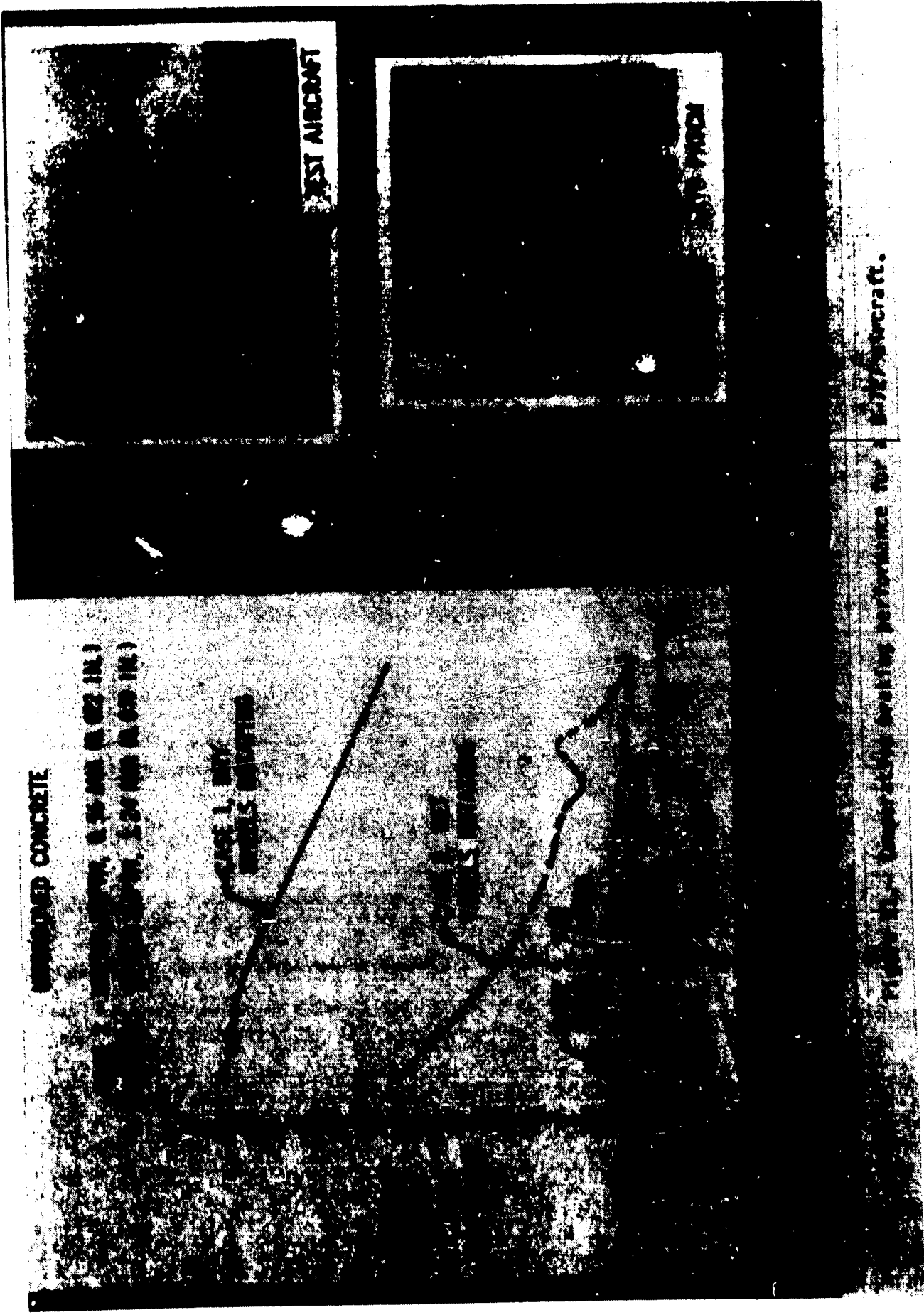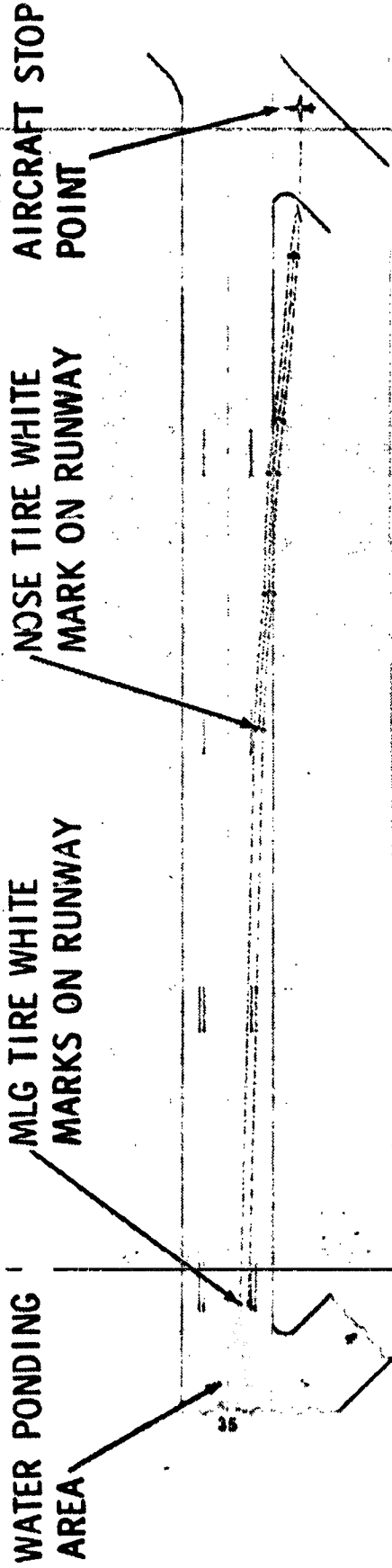
WATER PONDING
AREA

MLG TIRE WHITE
MARKS ON RUNWAY

NOSE TIRE WHITE
MARK ON RUNWAY

AIRCRAFT STOP
POINT

ACCIDENT AIRCRAFT RUNOUT TRACK

MLG TIRE TRACKS

LEFT   RIGHT

RIGHT

LEFT

SKID PATCHES ON MLG TIRES

DAMAGED AIRCRAFT

RUNWAY SURFACE

Figure 12.- Aircraft wet runway landing accident with reverted rubber skidding occurring without wheel
brake application.