AIRCRAFT ACCIDENT PREVENTION

THE PHENOMENON OF AIRCRAFT AQUAPLANING

CIVIL AERONAUTICS BOARD
WASHINGTON, D.C. 20428

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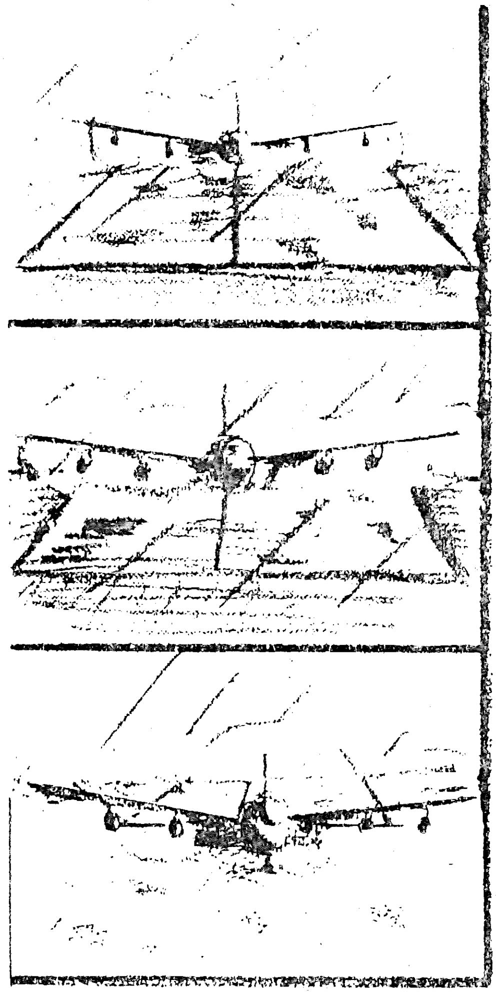

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PURPOSE

The purpose of this paper is to acquaint the reader with the phenomenon of Aircraft Aquaplaning, or Hydroplaning as it is sometimes called, and further, to stimulate sufficient interest that Air Carrier personnel will incorporate wet runway factors in their Operations and/or Flight Manuals.

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THE PHENOMENON OF AIRCRAFT AQUAPLANING

NASA describes the phenomenon of aircraft aquaplaning as follows: "Aquaplaning - a condition in which hydrodynamic lift force developed between the tire footprint and the fluid-covered runway surface equals or exceeds the vertical reaction of the airplane mass acting on the tire, resulting in loss of directional stability and braking effectiveness." A typical characteristic of tire planing is the whitish marks on the runway, after this phenomenon of aircraft aquaplaning has taken place. These marks are the result of a scrubbing or cleaning action provided by large suction forces under the tire when aquaplaning

Present Civil Air Regulations criteria for extablishing minimum runway length is applicable only to dry runways. Since water is incompressible and unable to develop shearing forces, varying coefficients of friction are developed between the tire and runway during adverse weather, depending on the depth of water and the forward speed of the aircraft. NASA test results for wet runways show that the coefficient of friction varies from 0.3 at slow speeds to 0.00 at high speeds in the realm of aquaplaning. as compared to 0.8 for a dry runway. This should be ample proof that additional runway length will be required when landing during adverse weather conditions.

Military aviation considers the problem of operating on wet and slippery runways so important that they have included a wet runway factor in the operating manual for each type of aircraft. Safety in the civil fleet would be greatly improved by doing likewise.

Aquaplaning is the major problem encountered after an aircraft touches down on the runway during adverse weather conditions Listed in Appendix 1 are nine accidents that have occurred since 1959 in which aquaplaning was a contributing factor. Also listed are eighteen incidents that have occurred since 1959 that are directly attributable to aquaplaning.

It is our conviction that these accidents and incidents reflect the fact that the information on aquaplaning compiled during various research programs is not being effectively disseminated to those operational personnel who are in need of this knowledge. It is hoped that air carriers will take appropriate action to assure that the information contained in the aquaplaning references (Appendix 2) is put to use in the development of improved company procedures for operating on wet runways. To be truly effective, pilots must then comply with these company-established procedures.

DISCUSSION

The advent of heavy, turbine-powered, commercial transports has greatly increased the dangers associated with landing and taking off from wet, slippery runways.

There has been a considerable amount of research conducted and results published by NASA, FAA, the aircraft manufacturers, and the air carriers pertaining to the phenomenon of aircraft aquaplaning and associated subjects. Unfortunately, as was stated above, it appears that this information has not been adequately disseminated. An attempt has been made to correct this situation by compiling a comprehensive list of projects and publications that have been printed and attaching them to this paper as Appendix 2. Although no unit price is given with this list there may be a slight fee for some of the publications However, it is believed that this should have no deterrent effect on any one obtaining material that is needed to update Flight Manuals and to acquaint the pilots with the hazards of the phenomenon of aquaplaning.

During the course of a recent air carrier accident investigation in which aquaplaning was found to be a contributing factor, attention was focused on the question of how well the phenomenon of aquaplaning was understood The investigation revealed that the Captain and several other pilots interviewed at later dates were not familiar with the phenomenon. Examination of the flight manuals and training syllabi of several air carriers failed to reveal any reference to aquaplaning or to techniques for combating it.

As stated previously, it was found that military aviation uses a wet runway factor for each aircraft in determining minimum length of runway for landing as well as takeoff.

For example:

> The T-33 manual computes the wet runway length by multiplying the dry, no wind, runway length by <u>1.8</u>. The B-47 manual increases the runway length required to take off under slippery conditions by <u>2.5%</u> of each 1000 feet required under dry conditions. At the same time refusal speed is reduced by 10K, which in effect provided additional runway for stopping purposes. Navy publications state that required runway length may increase from 40% to 100% when wet, over that required when runway is dry.

No factor has been found in any air carrier manual examined, which could be used to compute the additional runway required when landing or taking off under wet, slippery conditions Some of the formulas to compute these factors can be found in Item 2 in Appendix 2.

The military employs runway distance markers in conjunction with their stopping concept. This is considered to be a better method than the timing system used by civil aviation. Even though stopping is a function of both distance and time, distance can be more readily evaluated. Several airline Captains, who have been involved in aquaplaning incidents in the past, suggested changing to the distance marker concept also.

The Civil Air Regulations require that an aircraft be capable of stopping within 60% of the determined minimum runway length for a destination. The remaining 40% buffer is supposed to cover such things as possible pilot error, adverse weather, etc., but this buffer was established before the phenomenon of aquaplaning had reached the critical proportions it has assumed with the advent of heavier, faster aircraft

The determination of minimum runway length is based on crossing the threshold at 50 feet, at reference or boundary speed, and on a dry runway. In order to conform to the computed minimum runway, the pilot must meet the above conditions of speed and altitude over the threshold In adverse weather this is not always possible A Boeing 720B aircraft is used in the following example to indicat what can happen when some of the parameters are varied slightly (See Figure 1)

> A Boeing 720B aircraft at maximum gross landing weight has a minimum CAR runway length of 6500 feet and a reference speed of 134K.
>
> Boeing recommends that the aircraft touch down at a point 1000 feet from the threshold.
>
> The ground distance to stop a Boeing 720B aircraft touching down at reference plus 10K is 2704 feet using brakes, speed brakes and full reverse thrust. Place the aircraft 100 feet over the threshold instead of 50 feet, which is not at all unrealistic during adverse

weather. On a 3° glide slope an additional 950 feet of runway will be required to stop. Now assume the air speed is 10K high on the approach, which is not an unrealistic assumption. An additional 350 feet of runway will be required to bleed this 10K off on the ground. Under these conditions the aircraft would require a total of 5004 feet of dry runway on which to stop. From the minimum runway length of 6500 feet this leaves [illegible] feet for a safety buffer, or a factor of 23% instead of 10% to cope with wet and slippery runway conditions. Since NASA tests revealed that the coefficient of friction on a wet runway may be zero at high velocities and as little as [illegible] at slower speeds compared to 0.8 for a dry runway, it can readily be seen that the 23% buffer mentioned above is completely inadequate.

In the light of the above considerations, it is urged that each air carrier establish a wet runway factor as well as landing techniques for adverse weather, and publish this information in the Flight Manual for each type aircraft. This information should also be taught formally at pilot training sessions. Some of the carriers do verbally discuss landings on wet, slippery runways at pilot training sessions and publish bulletins at different times concerning this problem. However, this is not considered adequate coverage of the subject. The information needs to be available to the pilot in written form for ready reference at those times when conditions conducive to aquaplaning are found to exist upon arrival over the destination airport.

Propeller or thrust reversers are relied upon to provide additional deceleration during landings. When a headwind or no wind condition exists on a runway, reversing is very effective. However, if the landing is made under crosswind conditions, reversing can actually be a detriment. (See Appendix 1, Accidents 3, 5, Incidents 4, 11, 14, 15) An aquaplaning aircraft tends to weathervane in a crosswind and if reversing is applied while the aircraft is in this cocked position to the runway, it will actually assist the crosswind in moving the aircraft off the side of the runway. (See Figure 2) This is actually what occurred in the accident referred to earlier on page 3. When an aircraft becomes cocked to the runway it may become necessary to add forward thrust to alleviate the situation and return the aircraft to the runway centerline. (See Figure 2) This requires additional runway, further diminishing the buffer provided by the CARs when a minimum length runway is used.

Another example that indicates the wet runway problem is not receiving adequate attention was revealed during the comparison of the different operating techniques used by one air carrier in operation of the L-188 aircraft. Their L-188 Manual considers that "20K is the maximum crosswind component allowable for landing on wet runways of normal characteristics." However, it considers "10K as a maximum crosswind component when landing on snow or ice where braking is poor." It is difficult to correlate this fact with the previously mentioned evidence regarding reduction of friction coefficient due to aquaplaning.

One other interesting point that was learned during this study is that as the wheel aquaplanes it comes to a complete stop. If this condition lasts more than three seconds the anti-skid warning system is deactivated. This means that at that point, the aircraft is in a full skid condition. (See Figure 3)

SUMMARY

The advent of heavier, faster aircraft has served to increase markedly the problem of aircraft aquaplaning during the landing and takeoff regimes. Considerable research has been conducted by NASA, FAA, the aircraft manufacturers and some of the air carriers. However, the results of this research have not been reflected in the techniques and procedures published by the airlines in their Training and Flight Manuals.

It is our firm conviction that the air carriers should take the initiative in this matter by establishing a wet runway factor for each different type aircraft they operate by utilizing formulas that have already been obtained by research. Landing techniques to cope with aquaplaning should also be published and all pilots should be indoctrinated concerning this phenomenon.

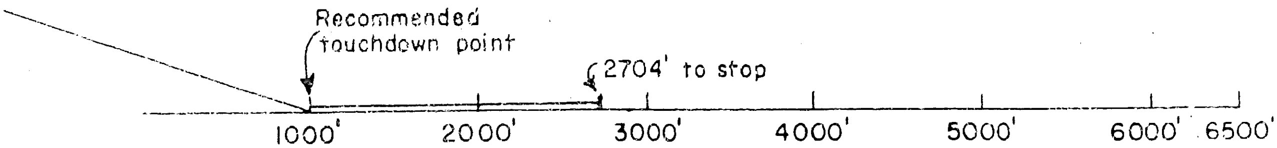
D

FIG. 1

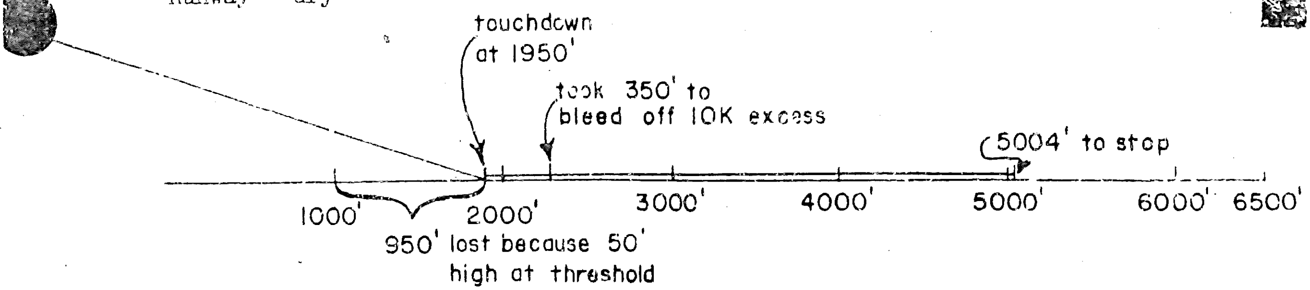
Aircraft - Boeing 720B

Constants - Will use:
brakes, speed brakes,
full reverse to 60K
on each landing

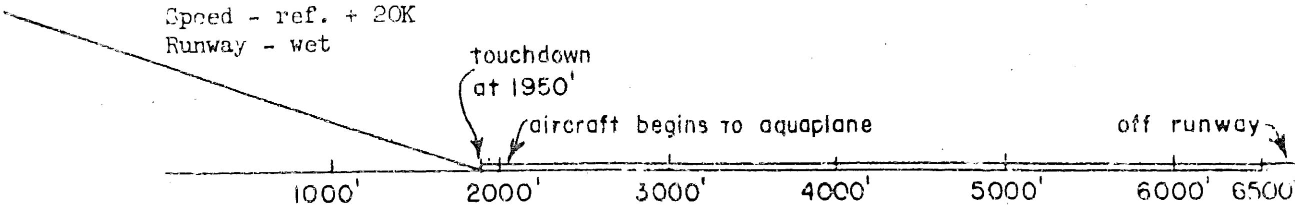
#1 Over threshold:
Alt. - 50'
Speed - ref. + 10K
Runway - dry



#2 Over threshold:
Alt. - 100'
Speed - ref. + 20K
Runway - dry



#3 Over threshold:
Alt. - 100'
Speed - ref. + 20K
Runway - wet



#3. Stopping distance will depend on: Tire condition, type of runway depth of water, amount of head wind, delay in applying reverse thrust, etc. Shortly after aquaplaning begins (3 sec.) anti-skid system is deactivated and aircraft is in full skid condition.

FIG. 2 - During cross-wind landing side thrust from thrust reversers, once airplane is canted to centerline, plus cross-wind can drive airplane off runway. To correct path, return all engines to forward thrust at low power to return to center, use differential braking to straighten roll path then reverse thrust to stop. (Extracted from December 1960 Boeing Airliner)

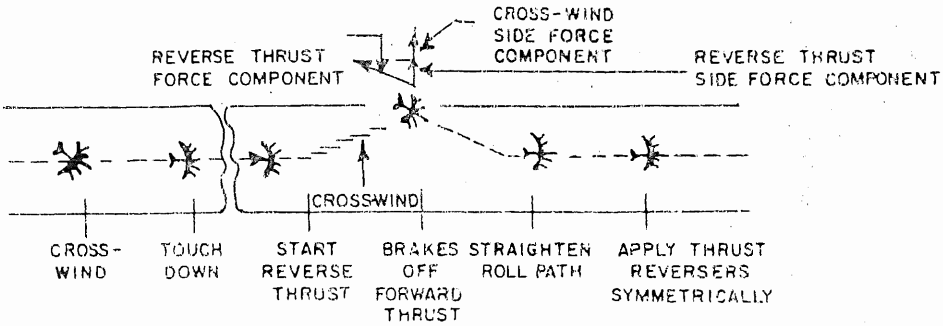
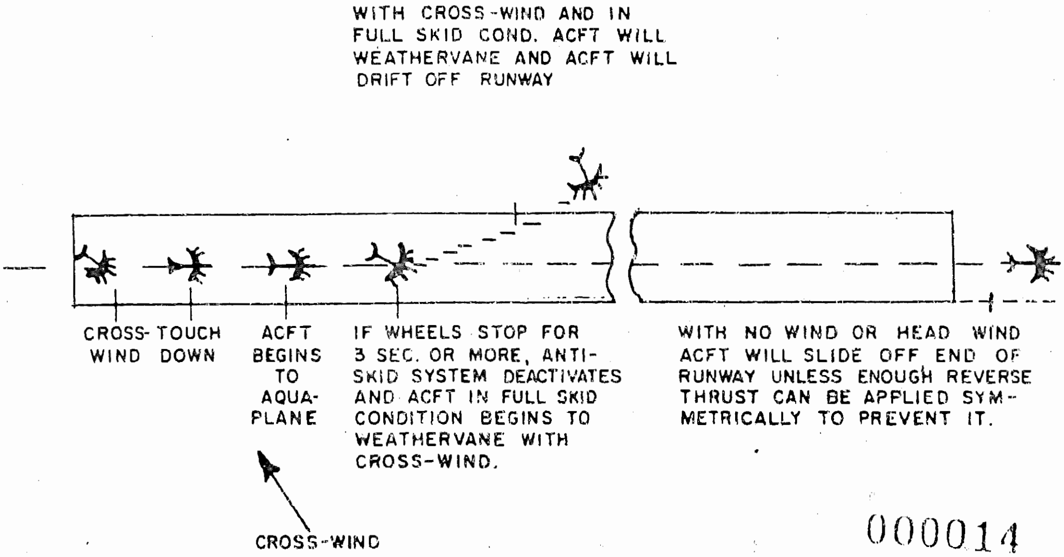


FIG. 3 - Touchdown is made on a wet runway. The aircraft begins to aquaplane almost immediately. The wheels stop turning either from brake action or spin down from the aquaplaning effect. If this condition lasts more than 3 seconds the anti-skid equipment becomes deactivated. The aircraft is now in a full skid.



APPENDIX 1

AQUAPLANING ACCIDENTS

1959 Accidents

(1) 4/9/59 Houston, Texas, Viscount. The aircraft touched down in a normal landing on the centerline of runway 3 during a heavy rain storm. A crab of 5° had been maintained on final approach. The Captain said the aircraft began "water planing" on touchdown. He said that even with 20°-30° of right crab and full right nose-wheel steering he was unable to prevent the aircraft sliding off the left side of the runway.

The weather at the time was 900' scattered, measured 1200' broken, 5000' overcast, visibility 1½ miles in rain, thunderstorm overhead moving southeast. 3.06 inches of rain had fallen since 1800 hours.

(2) 10/10/59 Winston Salem, N. C., C-46. After executing a missed approach to runway 33 because of low visibility caused by heavy rain over the approach end, the pilot elected to land on runway 15 as the wind was given as calm and the approach was clear. Upon touchdown on the wet runway, the brakes had no effect so an intentional groundloop was attempted to keep from running off the embankment at the end of the runway.

The weather was 800 feet scattered, estimated 3000 feet overcast, visibility 3 miles. Light thunderstorm.

(3) 5/12/59 Charleston, W. Va., Lockheed L-1049. Weather - rain falling at time of approach and touchdown with standing water on runway, scattered clouds at 600' and 1500', wind 4 knots east-southeast.

Aircraft landed first third runway 32 (4750' long), flaps fully extended, airspeed 105 knots approach. Brakes functioned properly but no response due to aquaplaning. Ran out of runway, Captain groundlooped but aircraft skidded to left and slid down steep embankment in reverse beyond airport boundary. The aircraft was consumed by fire. There were two fatalities (1 passenger and 1 flight engineer).

1960 Accidents

(4) 5/8/60 Baltimore, Md., Douglas DC-3. Weather - heavy precipitation, 800' ceiling, wind 8 knots northwest.

Aircraft landed 500' from approach end of runway 32 (4440' long) with full flaps. Initial braking action positive; however, with flaps up and tail wheel down just past midway of runway, braking action negative and ineffective. Aircraft proceeded off end of runway, over the seawall and into a creek. Considerable damage to aircraft.

(5) 2/19/60 Utica, N. Y., Convair 440. Weather - ceiling 400', visibility 1½ miles in rain, snow and fog, cross wind of 11 knots, 1 inch of snow covering a wet runway.

Aircraft slid left while weathercocking to right. Attempted correction with right reverse, brakes and nose wheel steering. Struck 4 inch snow bank on left side of runway.

(6) 2/13/60 Washington, D. C., Lockheed 1049C. Takeoff aborted 2500' down the wet slush covered runway at 90 knots. Couldn't stop so ground-looped the aircraft to right at which time side loads failed left gear.

1961 Accidents

(7) 2/6/61 Dallas, Texas, DC-8. Night ILS approach, ceiling 300' visibility 3/4 mile, light snow and sleet, 8 knot tailwind, runway covered with 1 inch to 3 inches of slush.

Attempting to land on runway 13 Touchdown occurred at 161 knots instead of 134 recommended. Flaps were retracted and held on runway by forward yoke, #2 and #3 engine full reverse with "some" reverse on #1 and #4. Slid off edge of runway 4220' from touchdown.

(8) 11/23/61 Morgantown, W. Va., DC-3. The aircraft touched down at 80 knots within 300' of the approach end of the 3578' long, 100' wide runway. When brakes were applied they had no effect so the pilot unlocked the tail wheel in anticipation of an intentional ground loop to the left. The aircraft continued in a gradual right skid and departed the runway 50 feet from the end.

The weather was 3000' scattered, estimated 4500' overcast, visibility 6 miles, moderate steady rain, winds calm.

(9) 7/19/61 Orlando, Fla., DC-[illegible] [illegible] touchdown was made within the first 1200 feet of runway 25 which is 6000 feet long and 150 feet wide. As reversing was applied, the aircraft began veering to the left. Full right rudder and aileron, then nose-wheel steering were used, but to no avail and the aircraft departed the runway on the left side, 2727 feet from the approach end of the runway.

Weather at the time was 800 sky obscured, visibility 1 mile, thunderstorm and heavy rain shower, wind 3 knots east-northeast, thunderstorm overhead.

([illegible]) [illegible]/11/61 New Orleans, La., L-[illegible]. The Captain estimated touchdown at a point 1200-1500 feet from the approach end in a normal manner on the centerline of the 8525-foot runway. The nose was lowered and full reverse applied. At this time the nose appeared to assume a lower-than-normal attitude and the ship began to move slowly to the left. Full right rudder and additional reverse on #3 and #4 engines failed to stop this northward drift and the aircraft departed the left side of the runway approximately 6000 feet from the approach end of runway. The powdery marks associated with aquaplaning existed from point of touchdown (approximately midpoint of runway) to the place the aircraft departed the runway.

The weather was 900' scattered, measured 1100' broken, 4000' overcast, moderate rain showers, wind west-southwest 10 knots.

1962 Accidents

(11) 2/3/62 New York. N. Y., DC-8. Landing on a slush and snow-covered runway with a 10K tailwind, touchdown occurred with excessive speed and aircraft slid off end of runway.

(12) 8/6/62 Knoxville, Tenn., L-188. Landed in heavy rain storm. Runway covered with water. Strong crosswind from left. Landed on right gear, bounced, came down on both. Began aquaplaning as nosegear touched down and full reverse thrust was employed. Slid off right side of runway tearing off right wing and gear.

1959 Incidents

(1) 11/4/59 Indianapolis, Ind., DC-7B. While landing on runway 22 from a back course ILS, heavy rain was encountered just prior to touchdown. Touchdown was made in the center of the runway. 2900 feet from the approach end of the runway the right wheel slid off the runway; at 3400 feet the nose wheel left the runway and at 4200 feet the left wheel departed the runway surface.

Weather was 300 scattered, 600 variable overcast, visibility 5 miles in moderate rain and fog, wind SSE 8 knots, visibility occasionally 1¼ miles in heavy rain.

No brakes used, normal reversing at first, then excessive on 1 and 2 which only tended to weathercock the aircraft more.

(2) 5/23/59 Taipei, Formosa, DC-7B. The aircraft touched down on the centerline of runway 10, approximately 300 feet from approach end at 108K. The Captain said #1 propeller ran away momentarily and veered the aircraft to the right. The aircraft then held that line and hydroplaned off the edge of the wet runway. Corrective action to straighten the path of the aircraft was to no avail. The aircraft landed approximately 5 minutes after a moderate shower.

1960 Incidents

(3) 2/4/60 St. Louis, Mo., B707-131. During approach to runway 24 the pilot was given weather: wind ESE 10-15K, 700' overcast, visibility 1½ light rain and fog. Crossed threshold at 136K then touched down 1000' down the 6000' runway, skipped then touched down again 1000' further down. Spoilers were placed to fullup, full brakes and maximum reverse thrust were applied. Aircraft continued 450' off end of runway into the mud where #2 engine struck the ILS localizer shack.

(4) 3/18/60 Houston, Texas, DC-7. Aircraft made an ILS approach to runway 3. Weather was 300' ceiling, 1 mile visibility, light rain, wind west at 10K, wheel marks indicate that aircraft touched down 2/5 of way down 7600' runway. Shortly after touchdown aircraft commenced to swerve to left and continued the swerve until the left wheel left the runway 5800' from the

approach end. It continued 1689' further where all three wheels became mired in the mud. No malfunction or failure of brakes, propeller reversing, or nose wheel steering.

(5) 4/20/60 Kansas City, Mo., B707. Pilot appeared to be unable to stop his landing roll and aircraft slid off west side of south end of runway 18. No damage to aircraft.

1961 Incidents

(6) 12/11/61 Jackson, Miss., DC-3. Landed 400' from approach end of runway. Brakes applied but very little braking action resulted. With 1500' of runway left an intentional ground-loop attempted to left with no results. Attempted to the right and attained turn of approximately 45° as it slid off end of the [illegible] runway. Thunderstorm passed over field 10 to 15 minutes before the landing had deposited .36" of rain.

(7) 12/12/61 Atlanta, Ga., DC-7B. Landing was made on runway 27 by 1st Officer. Landing was normal. Shortly after touchdown light brake applications were made and they seemed to be operating satisfactorily. As western end of the runway was approached and brakes were applied, 1st Officer indicated he had no brakes. The Captain checked, then opened the emergency air valve after having pumped the hand pump to no avail. Aircraft slid off end of 7860' runway where it stopped in the mud. White marks from point of touchdown to end of runway. Had rained .5" at the airport over previous 2-hour period.

(8) 10/2/61 New York, N. Y., DC-8. Landed on runway 4R out of an ILS. Reverse thrust used on 2 and 3 to [illegible]K. The aircraft began to aquaplane as indicated by the white tire marks about 650' from the approach of runway and slid 309' past the end of the 8000' runway. Pilot stated he touched down at 125K. Light rain at the time and had been raining for a prolonged period of time.

(9) 7/29/61 New York, N. Y., DC-8. Landing on 22L during a rain storm with a 10-15K crosswind. Touched down at 135 to 143K at ILS touchdown point. Applied brakes and 70-80% reverse thrust on 2 and 3 and idle reverse on 1 and 4. Braking was ineffective, so full reverse was applied to all 4 engines. Aircraft slid 243' off end of a 8400' runway.

(10) 8/7/61 Jackson, Michigan, DC-3. Aircraft landed out of a low visibility approach. Brakes were applied but seemed to be weak then faded away completely. Ground loop attempted but to no avail, and aircraft slid off end of runway.

(11) 5/7/61 Kansas City, Mo., DC-6. During a low visibility approach in moderate rain, heavy rain similar to a water spout was encountered upon touchdown just as windshield wipers broke. Could see outside window that aircraft was sliding to right. Engines taken out of reverse pitch. Captain said aircraft was aquaplaning across a thick layer of water and skidding to the left with no response from nose wheel steering, brakes or corrective power. Soft ground slowed the aircraft sufficiently to regain steering control, rolled back onto the runway after passing through the heavy rain, then taxied to the gate.

(12) 4/9/61 Buffalo, N. Y., Viscount 700D. Landing on runway 23. Ceiling 600' obscured, $1\frac{1}{4}$ mile visibility, light snow showers. Snow melting as it landed. Smooth landing at approximately 130K. Brakes applied then hand brake applied locking the wheels. Speed not arrested until aircraft slid into the mud beyond end of runway.

(13) 3/5/61 Akron, Ohio, DC-7. Landing on runway 01 which is 5598' long. Stated crossed field boundary at 110/115K touching down 500-800' from beginning of runway. Applied reversing until slowed to approximately 50K. Said taxi speed was slow and reasonable. As end of runway was approached brakes were again applied and when not effective full reverse again applied but aircraft slid off end of runway into the mud. Weather was 400' overcast, light rain and fog.

(14) 3/8/61 Chicago, Ill., L-188. Landing on 32R. 600' overcast, visibility 2 miles in light drizzle and fog. Slush on runway, wind NNE 14-17K. At touchdown full reversing was applied. Aircraft began sliding to left side of runway. Asymmetrical reverse thrust applied but aircraft continued to slide off left side of runway 1700' from threshold, coming to rest 2500' from threshold with the left wheel stuck in the mud. Nose gear and right main gear remained on pavement.

(15) 3/23/61 Utica, N Y., Convair 240. A circling approach was made to runway 15. Weather was 700' obscuration, visibility $\frac{1}{2}$ mile, light snow showers and fog, temperature 33°, wind east 11 m.p.h., slush on runway and braking action was poor. Touchdown made at 97K and as nose wheel touched down aircraft began to skid right. Right throttle used to correct twice, then aircraft slid through snow bank and off edge of runway. Reversing not used. Delay in getting flaps up as copilot waiting to assist in reversing. Captain said braking action was nil.

(16) 2/8/61 Baltimore, Md., B707. During takeoff by the 1st Officer from right seat on slush-covered ($\frac{1}{4}$" - [illegible]") runway 33, the aircraft weathervaned into the 13K [illegible]. Corrected once by Captain using nose wheel steering. Occurred again so Captain aborted at 80K using full reverse on all engines. Aircraft slid off of the side of the 200' wide, 9450' long runway at the midpoint. It was found that rudder trim tab had been left in the 5 points right position that had been used for landing.

(17) 3/9/61 Boston, Mass., Viscount 745D. During takeoff from runway 9 the aircraft accelerated normally to 70K but then was slow accelerating beyond that point and the takeoff was aborted. Inspection of the runway found the snow to be up to 8" and the distance between the heavy accumulations was 300' to 450'. The Captain noted that, "apparently the slush problem has many more ramifications than any of us realized previously. I personally feel operation in ANY snow or water condition would be benefited by an additional safety factor of a distance marking or acceleration check point on the runway." The carrier at this time limited the operation of their Viscounts to $\frac{1}{2}$" slush or standing water for takeoff or 1" of either for landing.

1962 Incidents

(18) Fall Shannon, Ireland, DC-8. The aircraft landed on runway 24 which is 10,000 feet long. Approach and configuration were normal. Touchdown occurred at 1000-2000 feet from the beginning of the runway. The runway was wet. Weather consisted of drizzle with low ceiling, wind 100° 10 knots with a tailwind component of 3 knots. Braking action was ineffective until the aircraft decelerated below 80 knots. This occurred during the last several hundred feet of the landing roll and the aircraft came to rest with the tail overhanging the runway. Braking system and spoilers checked normal and the foot thumpers and anti-skid device were operational.

APPENDIX 2

AQUAPLANING REFERENCE PUBLICATIONS

1. NASA Report, "Tire-to-Surface Friction - Coefficient Measurements with a C-123 Airplane on Various Runway Surfaces" by Sawyer and Kolnick, dated June 1952.

2. Second Edition of Garbell Aeronautical Series No. 3, 1954 "The Ground Run of Aircraft in Landing and Takeoff in ICAO Units"

3. NATO Report 51, "Tire-Runway Braking Friction Coefficients" by M. N. Gough, R. H Sawyer and J. P. Trant, dated February 1956.

4. NACA Technical Note 4406, "Low Tire Friction and Cornering Forces on a Wet Surface" by Harrin, dated September 1958.

5. NASA Memorandum 2-23-59L, "Tire-to-Surface Friction Especially Under Wet Conditions" by Sawyer, dated March 1959.

6. NASA Report D-405, "Investigation of Tandem-Wheel and Air-Jet Arrangements for Improving Braking Friction on Wet Surfaces" by E N. Harrin, dated June 1960.

7. NASA Report D-552, "Studies of Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water" by W. B. Horne, V. T. Joyner and T. J. W. Leland, dated September 1960.

8. "Approach Speed Control" and "Stopping Under Adverse Conditions" in the February 1961 and December 1960 issues, respectively, of the Boeing Airline publication. Our Fig. #2 extracted from the December publication.

9. "Runway Slush Effects on the Takeoff of a Jet Transport, FAA Project #308-3X" dated May 1962. Appendix II referred to "Tire Aquaplaning Velocity Calculations."

10 "Vehicular Measurements of Effective Runway Friction" FAA Project No. 308-3X Amendment I, dated May 1962

11. FAA - Flight Standards Service Release #470 - "Statistical Presentation of Operational Landing Parameters for Transport Jet Airplanes" dated August 8, 1962.

12. "Runway Slipperiness and Slush" NASA Report, by Walter B. Horne and T. J. W. Leland, dated May 16, 1963. (Presented at Symposium on the Royal Aeronautical Society, London, England)

APPENDIX 3

FORMULAS RELATED TO AQUAPLANING

I. $F = \frac{1}{2} C_s p\ d\ b\ V^2$ Ref. (9)

Where F = Retardation force acting on the airplane tire due to slush

p = Mass density of slush

d = Slush depth on runway

b = Chord length of tire cross section at slush surface

V = Aircraft forward velocity

C = Slush drag coefficient

II. Tire Aquaplaning Velocity Calculations

$F_v = F_{v,s} = \frac{1}{2} C_{L,s}\ p\ A_G\ V_p^2$ Ref. (9)

Where F_v = Vertical load on tire due to airplane mass

$F_{v,s}$ = Hydrodynamic pressure force

$C_{L,s}$ = Hydrodynamic lift coefficient

p = Fluid density

A_G = Gross tire contact area

V_p = Tire aquaplaning velocity

III. $V_p = 9\sqrt{p}$ Ref. (12)

Where V_p = Tire hydroplaning velocity (knots)

p = Tire inflation pressure (lbs./in.)

Assumptions: (1) Average tire ground-bearing pressure may be approximated by tire inflation pressure (p)

(2) All possible runway fluids that can collect in depths large enough to produce tire hydroplaning have densities approaching water

IV. Retardation Forces, Acceleration & Distance Traversed by Aircraft During Takeoff Ref. (7)

(1) $F_{x,g,e} = N_n F_{x,g,n} + N_m F_{x,g,m}$

Where $F_{x,g,e}$ = Total aircraft retardation force due to slush or water

N_n = Number of nose-wheel tires

$F_{x,g,n}$ = Retardation force - single nose-wheel tire

N_m = Number of leading main-wheel tires

$F_{x,g,m}$ = Retardation force - single main-wheel tire

(2) $a_r = \frac{F_{x,g,e}}{W}$

Where a_r = Horizontal deceleration aircraft due to slush water

W = Aircraft total gross weight

(3) $a_n = a - a_r$

Where a_n = Aircraft horizontal acceleration on wet runway

a = Aircraft horizontal acceleration on dry runway

(4) $\Delta s_1 = \frac{(V_{H,1})^2 - (V_{H,0})^2}{a_{n,0} + a_{n,1}}$

Where Δs_1 = Incremental takeoff distance of aircraft

$V_{H,1}$ = Aircraft forward velocity at instant (1)

$V_{H,0}$ = Aircraft forward velocity at start (0)

$a_{n,0}$ = Aircraft horizontal acceleration on wet runway at start (0)

$a_{n,1}$ = Aircraft horizontal acceleration on wet runway instant (1)

(5) $\Delta s_2 = \frac{(V_{H,2})^2 - (V_{H,1})^2}{a_{n,1} + a_{n,2}}$ (same as above for different instant or step)