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MEASUREMENT OF RUNWAY FRICTION CHARACTERISTICS ON WET, ICY OR SNOW COVERED RUNWAYS

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PROGRESS REPORT

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1 APRIL 1971

REPORT NO.
FS-160-65-68-1

DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

1. <u>PURPOSE</u>. The purpose of this report is to present current information on three methods of measuring runway friction characteristics and indicate possible usage of the data obtained.

2. <u>REFERENCES</u>.

a. "Pavement Grooving and Traction Studies," NASA SP-5073, Langley Research Center, Langley Station, Hampton, Virginia, 19 November 1968.

b. "A Comparison of Wet and Dry Stopping Distances on Several Runway Surfaces Using an Aircraft and Diagonal-Braked Automobile." An interim report on Project Combat Traction, ASD-TR-69-117, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson AFB, Ohio, April 1970.

c. "Report on the Civil Development Program of the James Brake Decelerometer as a Potential Means for Identifying the Runway Surface Traction to the Airplane Stopping Capabilities," Federal Aviation Administration, Flight Standards Service, unpublished report August 1969.

d. "Measurement and Notification of Runway Braking Action In Ice, Snow and Slush," NOTAM No. 849/1969, United Kingdom Board of Trade, Civil Aviation Department, Aeronautical Information Service, Tolcarne Drive, Pinner, Middlesex, December 1969.

e. Information Circular, "Use of James Brake Decelerometer," Canadian Department of Transport, Air Service Civil Aviation Branch, 0/6/70 23rd February.

f. U. S. Air Force Technical Order 33-1-23, December 15, 1965.

g. A Comparison of Aircraft and Ground Vehicle Stopping Performance on Dry, Wet, Flooded, Slush-, Snow-, and Ice-Covered Runways. Final Report on Project Combat Traction, a Joint USAF-NASA Program. NASA TN D-6098, November 1970.

3. **BACKGROUND**. In the 1950 decade, with the advent of the turbojet transports, increased attention began to focus on the effects of wet runways on aircraft stopping distances. The FAA and NASA began work early in the 1960 decade to define the phenomena that cause reduced braking effect on wet runways. To date the FAA has issued Advisory Circular 91-6, Water, Slush and Snow on the Runway, January 1965; Advisory Circular 121-12, Wet or Slippery Runways, August 1967; and FAR 121.195(d). Although FAR 121.195(b) already required that the measured dry runway landing distance must not exceed 60% of the available runway length, FAR 121.195(d), effective January 15, 1966, specified an additional 15% increase in required runway length for forecast wet or slippery runway conditions. The preamble to amendment 121-9 pointed out, however, that these factors are not expected to cover all possible adverse conditions, and that hazardous runway conditions must be controlled in accordance with FAR 121.551 and 121.553. A significant amount of runway surface friction data has been accumulated, some of which show promise of correlation with aircraft stopping distances on wet, icy or snow-covered runways. It is timely, therefore, for the Federal Aviation Administration to make available pertinent data for information to the aviation industry.

4. **HISTORY**.

a. General. During the years 1967-1968 a joint effort by the FAA, NASA, the United Kingdom, several State highway departments, and others was undertaken to assess the correlation existing among braking friction data obtained by 21 special test vehicles, by the F-4D jet fighter and CV-990 jet transport, and by several methods of predicting aircraft stopping distances on wet runways. Tests were conducted on nine different runway surfaces under wet, puddled and flooded pavement conditions. Results of these tests, reported in Reference a, showed that the current methods used for predicting aircraft stopping distances on wet runways was inadequate. During the years 1968-1969 the FAA conducted a series of tests with the CV-880 jet transport and a James Brake Decelerometer to determine correlation under dry, wet, and simulated icy runway conditions. Results, reported in Reference c, showed poor correlation on damp and wet runways. From all of the test data accumulated to June 1, 1970 three friction measurement devices emerge as having potential for use in conjunction with air carrier operations. These devices are:

(1) The Diagonal-braked Vehicle (DBV)

(2) The James Brake Decelerometer (JBD)

(3) The Mu Meter

b. Diagonal-Braked Vehicle.

(1) Since 1968 NASA has pursued the evaluation of the diagonal-braked vehicle and has also pursued methods of measuring the effective depth of water on runway surfaces. During 1969-1970, a rather extensive series of tests, Project Combat Traction, was conducted jointly by the USAF and NASA with a C-141 aircraft at 44 airbases in the United States and abroad in which the diagonal-braked car was used to determine correlation in terms of the wet/dry stopping distance ratio measurement index. The statistical analysis of the data, as reported in Reference g shows that the line of perfect agreement through point 1, 1 of a plot of aircraft stopping distance ratio, wet/dry versus diagonal-braked test vehicle stopping distance ratio, wet/dry with least mean square error had a slope of 0.993. The root mean square error in the aircraft stopping distance ratio was only ±0.19. NASA concluded that, "A diagonal-braked vehicle can be used to predict aircraft stopping distance and crosswind limitations for wet, ice-, and snow-covered runways and can be used to measure runway slipperiness."

(2) Wet/dry stopping distance ratio correlation data obtained with the diagonal-braked car now exists for the C-141, CV-990 and F-4D jet-powered aircraft. The USAF has recently obtained data which correlated with the C-5A aircraft. In addition, at the request of the National Transportation Safety Board, NASA has recently utilized the diagonal-braked car and the available data from previous tests to analyze two overrun accidents, one at St. Thomas, Virgin Islands, and the other at Houston, Texas. It should be emphasized at this point that wet/dry stopping distance ratios are necessary for each individual runway since the variables in surface texture between runways are far too numerous to permit a generalized solution for all runways. More tests are required with other airplanes at various weights and flap settings to extend and validate the correlation limits.

c. James Brake Decelerometer (JBD). The JBD has seen extensive use by the USAF for a number of years. USAF Technical Order 33-1-23, dated December 15, 1965 sets forth the requirements for use of the JBD in the Runway Condition Reading (RCR) system of identifying runway surface characteristics to the pilot. An extensive evaluation of the JBD was conducted by the FAA in 1968 in two parts: (1) tests of the JBD and a CV-880 commercial jet transport; and (2) development of calibrated jet transport landing distance ratios as a function of JBD indices. Results of this program showed that the JBD would not produce accurate data for wet runways. Since the FAA evaluation it has been shown by the Canadian Department of Transport and Alaska Airlines that the JBD can be used on hard-packed snow or dry ice-covered runways. Reference e spells out the manner in which the JBD can be used in Canada, and limits its use to ice and snow-covered runway surfaces.

d. Mu Meter. Since its inception the Mu Meter has been subjected to extensive testing worldwide and some units are owned by airport operators. The Mu Meter is sensitive to small changes in surface friction, and for this reason is an ideal vehicle to use in evaluating changes in the runway surface friction characteristics as a function of wear or contaminants. This device is currently used operationally in a qualitative manner in the U. K. in accordance with the criteria established in Reference d which recommends its use for slush, ice or snow covered runway surfaces.

5. PERFORMANCE CHARACTERISTICS.

a. Definitions. There are three primary causes of deterioration of braking effect on wet runways. These are defined as Dynamic Hydroplaning, Viscous Skidding, and Reverted Rubber Skidding.

(1) Dynamic Hydroplaning. The result of the hydrodynamic lift forces developed when a tire moves across a fluid covered surface. (This circular does not cover dynamic hydroplaning which is generally associated with water depths greater than 0.1 inch.)

(2) Viscous Skidding. The result of the reduction in friction coefficient due to the lubrication properties of a thin fluid film between the tire and the runway.

(3) Reverted Rubber Skidding. The result of steam generated between the tire and runway during an initial prolonged skid on a wet runway, causing tire rubber to melt and revert to its uncured state.

(4) Damp, Wet and Flooded Runways. - For purpose of definition NASA has established the following water depth criteria for damp, wet and flooded runways:

Damp	0 to 0.01 inches of water
Wet	0.01 to 0.1 inches of water
Flooded	More than 0.1 inches of water

b. Stopping Distance.

(1) Wet Runways. Wet runways always result in longer stopping distance than do dry runways if the braking system is not torque limited. Both the DBV and the Mu Meter have potential for operational use since both can measure coefficient of friction versus velocity. Such data can be utilized mathematically to estimate the airplane wet runway stopping distance. However, such an operational application would be cumbersome. For this reason the developers of friction measurement devices are

seeking a slipperiness index which will be simple, but provide reasonably accurate results. To date, although some results look promising, quantitative measures have not been completely proven.

In the case of the DBV the index of measurement is the wet/dry stopping distance ratio. It was found by comparing the wet and dry surface Mu versus velocity curves on a number of ground measurement vehicles, that the wet/dry stopping distance ratio produced the best and most consistent correlation between the ground vehicles and the airplanes against which they were compared on a specific surface. Although reasonable correlation has been shown with the CV-990, F-4D, C-141 and C-5A airplanes as reported in References a and g, more testing on the DBV is necessary to more rigorously establish correlation with a wider family of airplanes at various weights and flap settings. However, sufficient data is available such that a qualitative measure of wet runways can be made using this index as follows:

DBV Table of Braking Action

Estimated Braking Action *	Wet/Dry Stopping Distance Ratio
Good	1.4 and below
Medium	1.4 - 1.9
Poor	1.9 and above

* Defined in Appendix 2.

In the case of the Mu Meter the index of measurement is the coefficient of friction, Mu. This Mu value can be determined at various velocities to generate a Mu versus Velocity Curve, or, as is done in the current method, a "representative" Mu is determined at one speed, 40 mph, and is used in a qualitative manner. To date the U.K., in its NOTAM 849/1969, has accepted the Mu Meter for use qualitatively on icy, snow-covered, or slush-covered runways, but not on wet runways. The qualitative usage is shown in the following table:

Mu Meter Table of Braking Action

Estimated Braking Action *	Measured or Calculated Coefficient of Friction
Good	0.40 and above
Medium	0.35 - 0.30
Poor	0.25 and below

* Defined in Appendix 2.

Further tests are currently in progress in the U.K. and are planned in the U.S. to more thoroughly assess the correlations on the Mu Meter with airplane stopping distance on a wet runway surface.

(2) Icy Runways. Results from Project Combat Traction indicate that the DBV can be used to assess the slipperiness of homogeneous ice or snow covered surfaces. More tests are desirable to establish an acceptable level of confidence. The JBD has been tested by Alaska Airlines on hard packed snow and icy runways. Use of this device qualitatively in Canada is authorized by Reference e. The Mu Meter, as indicated above, is approved for qualitative use on ice, snow and slush in the U.K. in accordance with Reference d.

c. Crosswind Effects. It is recognized that wet runway conditions can significantly change the crosswind limitations due to the reduced friction between the aircraft tires and the wet surface. Insufficient data are available at this time to provide acceptable criteria for establishing a crosswind limitation for wet runways. When sufficient data become available future progress reports will identify means for determining the limiting crosswind for wet runways.

6. RESEARCH PROGRAM. As a result of a government/industry meeting in February 1971 a list of tasks has been established and programmed to ensure that a coordinated effort is being applied to solve the problems of correlating measured runway friction characteristics with airplane stopping distances and airplane controllability in crosswinds. Results of these efforts will be included in future progress reports of this type.

7. APPENDICES. Each of the devices for measuring runway surface characteristics is described in more detail and procedures for their use are delineated in the three appendices.

APPENDIX 1. DIAGONAL-BRAKED VEHICLE (DBV) TEST METHOD FOR MEASURING STOPPING DISTANCE ON PAVED SURFACES

1. SCOPE.

a. The DBV, a NASA developed vehicle, provides a high velocity technique for the measurement of pavement skid resistance or slipperiness under dry, wet, flooded, slush, snow, ice-covered surface conditions.

b. The DBV may be used to assess the relative slipperiness of airport runways and taxiways either with controlled artificial wetting or natural wetting of the pavement surface.

c. Data from the DBV may be used to predict aircraft stopping and directional control performance at time of takeoff and landing when the runway surface is under a natural cover from rain, snow, slush, or ice.

d. The DBV measures stopping distance on a paved surface using a four-wheel automotive vehicle equipped with a diagonal-braking system and specified full-scale automobile tires.

e. The DBV provides one diagonal wheel pair of the vehicle to be braked to a full skid condition to provide a decelerating force to the vehicle. The other diagonal wheel pair of the vehicle is unbraked and free rolling to provide steering and lateral stability to the test vehicle.

f. Use of the DBV enables brakes to be engaged on the test vehicle at high speed (60 mph), and furnishes adequate directional control for the driver to bring the vehicle to a safe stop in the runway or taxiway test area.

g. The stopping distance measured from brake application to a stop represents a summation of the decelerating forces acting on the vehicle; that is, braking friction from the diagonal-braked wheels, rolling resistance from the diagonal-unbraked wheels, and aerodynamic drag acting on the vehicle. This stopping distance does not necessarily correlate with other methods of skid resistance measurements.

h. Use of the DBV requires making dry stops as well as stops under artifically wet or natural conditions due to rain, slush, ice or snow, at similar brake engagement speeds. The ratio of wet/dry stopping distances obtained represents the skid resistance or slipperiness of the pavement for a given situation.

2. SUMMARY OF METHOD.

a. The test apparatus consists of an automotive type vehicle with four wheels containing transducers, instrumentation, and a modified diagonal-braking system for the four wheels. The two diagonal-braked wheels of the test vehicle are to be equipped with ASTM Standard Test Tires E249 (smooth tread), or equivalent, for these tests. The two diagonal-unbraked wheels of the test vehicle are to be equipped with new standard production tires having a good skid resistant tread design. These tires provide the vehicle with steering and lateral stability during testing and should be replaced when the tread is approximately 20 percent worn.

b. The pavement area on the runway or taxiway to be tested should be delineated by means of runway distance markers or by traffic cones. The test vehicle is accelerated to slightly above the desired test speed in advance of the pavement test section. The transmission is placed in neutral and the vehicle allowed to coast until the desired brake engagement speed is reached at the beginning of the test section. The brakes are then firmly applied to cause a quick lock-up of the diagonal-braked wheels. The resulting distance required to stop is recorded with the aid of suitable instrumentation, and the vehicle velocity at the moment of brake application should be noted.

c. The skid resistance or relative slipperiness of the paved surface is determined by the magnitude of the wet/dry stopping distance ratio obtained.

3. APPARATUS.

a. Vehicle. The vehicle should be a four-wheel automobile equipped with heavy-duty suspension system.

(1) Engine. The engine should have sufficient displacement, i.e., 350 cubic inches or greater, and horsepower to provide rapid acceleration to the required brake engagement speed, keeping to a minimum the distance required to reach such speed.

(2) Steering System. The vehicle should be equipped with power steering. The scrub radius of the tires-steering linkage should not exceed 1.5 inches to minimize unbalanced steering wheel torque during diagonal braking.

(3) Braking System. The vehicle should be equipped with heavy-duty brakes and a conventional power braking system to ensure rapid, even brake application during testing. This braking system is modified by appropriate manually controlled valves in the brake lines to enable operation in the diagonal wheel braking mode during testing. A safety light should be

connected in the diagonal-braking mode so the test driver will know that the vehicle is in the normal-four-wheel braking mode for road use, or the diagonal braking mode for test use.

(4) Rear Axle. Conventional differential axle drive systems ONLY should be used for the diagonal-braked vehicle. Positraction type differentials or limited-slip-differential systems are NOT SUITABLE since they will prevent operation in the diagonal-braked mode.

(5) Tires. The two diagonal-braked tires should be the standard tire for pavement tests, ASTM specification E249 (smooth tread modification), or equivalent. Currently, this tire is made only in the 7:75 X 14 size. The two diagonal-unbraked tires can be standard production tires possessing a good skid resistant tread design. These tires should be replaced with new tires when 20 percent worn.

b. Instrumentation.

(1) Vehicle Speedometer. Transducers such as "fifth wheel" or transmission-coupled tachometers and speed-indicating meters should provide velocity resolution and accuracy of ±1.5 percent of the indicated speed or ±0.5 mph, whichever is greater. Output speed indication should be directly viewed by the operator.

(2) Stopping Distance Recorder. Transducers such as "fifth wheel" or transmission-coupled odometers should actuate a high speed distance counter capable of accepting a count rate equivalent to the number of counts produced at test speed. One count per 0.001 mile (5.28 feet) is deemed the maximum acceptable count.

(3) Pressure Sensitive Switch. A pressure sensitive switch, such as a brake light switch, requiring 70-79 psi to close should be installed in the diagonal-braking system to actuate the stopping distance counter under the testing condition.

(4) Longitudinal Accelerometer Recording. A 0-1g longitudinal accelerometer, recording type, provides valuable information necessary to identify variations of the surface friction within a runway test section.

(5) Recorder. A permanent record of actual test results is obtained by a multichannel brush recorder which is used to measure those data items required.

4. CALIBRATION.

a. Speed. The test vehicle's speed indicator should be calibrated at the test speed by determining the time for traversing, at constant speed, a reasonably level and straight, accurately measured pavement at least one mile in length. The test vehicle should be loaded to its normal operating weight for this calibration, and the tire pressure properly adjusted if transmission-coupled tachometer is employed. A minimum of two speed determinations should be made at the test speed.

b. Distance. The distance transducer and counter should be calibrated by traversing, at the approximate test speed, a reasonable level and straight, accurately measured pavement at least half a mile in length. The calibration should be initiated from a complete stop at the beginning of the test course and terminated by stopping at the end of the test course. A minimum of two distance calibrations should be performed.

5. TEST PROCEDURE.

a. Vehicle Preparation. New tires should be conditioned by running them at their rated inflation pressure on the test vehicle several miles at speeds up to 60 mph before they are used for test purposes. The tire and front wheel assemblies and tires on rims for the rear wheels should be dynamically balanced after conditioning. Prior to each series of tests the tires should be warmed up by driving several miles at normal traffic speeds. The tires should be inspected after a test, especially on dry surfaces for excessive flat spotting, damage, or other tire defects that may compromise vehicle safety or affect test results. Tires which have been damaged or worn excessively should be rejected and replaced. The tire inflation pressure should be the rated inflation pressure for the auto/tire combination used for the test at ambient temperature (cold). This was 24 ±0.5 psi for the NASA vehicle. The test vehicle should always be driven in the four-wheel braking road mode until immediately before a test run. Prior to accelerating the vehicle up to the desired test speed (60 mph), the operator should switch to the diagonal test mode. The operator should immediately switch to the four-wheel braking mode when each stopping distance test is completed.

b. Runway Test Section. The runway may be divided into sections which cover the touchdown areas at either end of the runway and the middle of the runway. Most runway touchdown areas are contaminated by rubber deposited by the aircraft tire on the runway during the landing touchdown spin-up process. These runway areas are usually more slippery when wet than the middle of the runway which normally is free of this contamination. The vehicle stopping tests should be made in the landing gear tracks approximately 10-15 feet to the right or left of the runway centerline.

c. Runway Traffic Control. The airport tower operator should direct the test vehicle to the runway. The runway should be closed to traffic during test operations on the runway. The test vehicle should maintain direct radio communications with the tower at all times so that the runway may be cleared quickly in case of an aircraft landing emergency.

d. Pavement Wetting. An approximately 10-foot wide test lane on the runway or taxiway should be wetted prior to vehicle testing using a water truck with spray bar or other means of distributing water evenly and rapidly. The rate of water application should be 200-300 gallons per minute with the water truck traveling at a speed of 2-3 miles per hour. A sufficiently long segment of the test lane should be wetted to permit the test vehicle to skid to a stop from 60 mph on the wet surface. As a minimum, two passes should be made over the test section with the water truck to ensure a water depth of 0.01 inch or greater as measured by the NASA water depth gauge, Figure A-1, or equivalent.

e. Procedure. After pavement wetting, as outlined in 5.d, or for testing under dry or natural pavement conditions of rain, slush, snow or ice, the procedure for vehicle testing in Paragraphs 2b and 5a should be followed. A minimum of three runs on each wet section should be made to ensure reliable data. One run on the dry section is normally adequate. All wet runs should be conducted prior to the dry runs since tire wear is most severe in the dry condition.

6. TESTING.

a. Test Speed. The standard test speed has been established at 60 mph by NASA after evaluation of various speeds. The 60 mph speed produces the best correlation with airplane stopping distances for all the aircraft tested to date; therefore, tests should be initiated within 2 mph of the desired test speed. The stopping distance obtained within this speed range, but not at 60 mph, may be corrected to 60 mph by the equation:

$$S_{corrected} = \frac{3,600}{(V_{actual})^2} \times S_{actual}$$

where: $S_{corrected}$ = Stopping Distance corrected to 60 mph base ~ feet

V_{actual} = Velocity at which brakes are locked ~ mph

S_{actual} = Stopping Distance for V_{actual} ~ feet

Tests that are manifestly faulty, or conducted at an improper speed should be discarded and the tests repeated.

b. Use of Data. Figure A-2 provides the method for use in determining the average wet/dry stopping distance ratio for the complete runway, or any portion thereof.

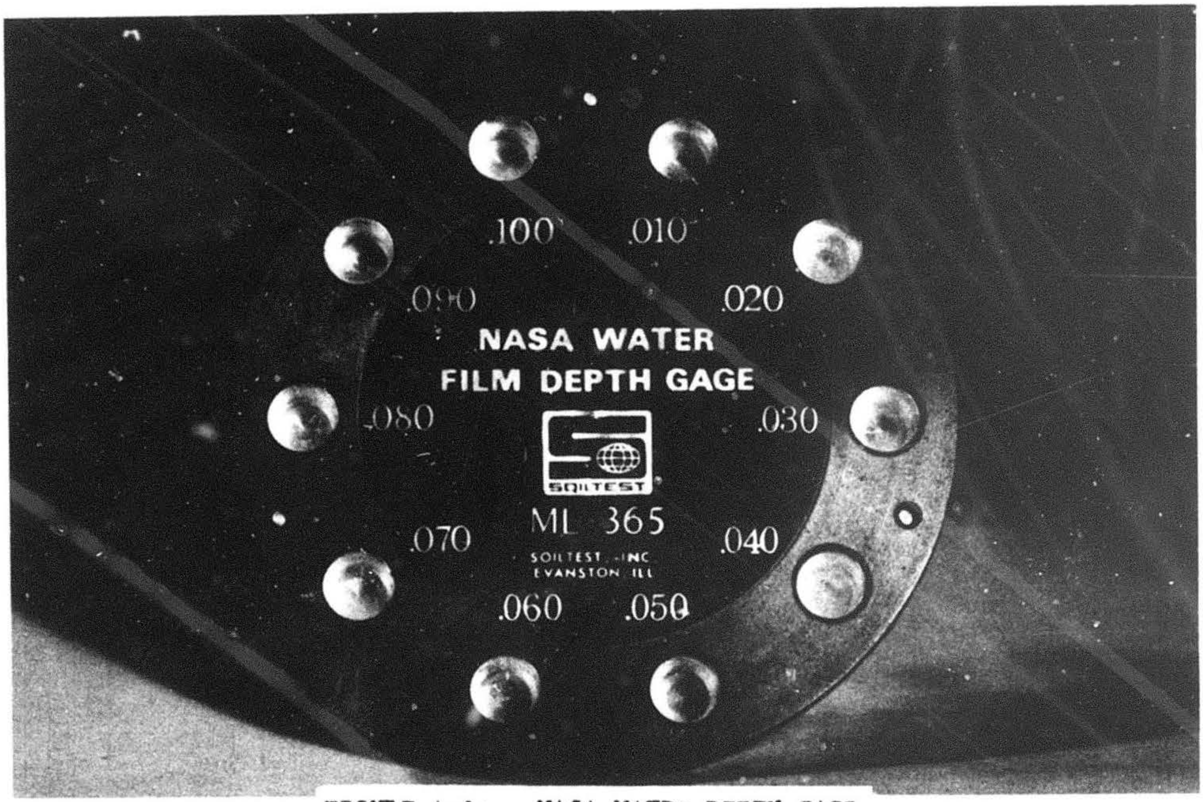


FIGURE A-1a - NASA WATER DEPTH GAGE
(Front View)

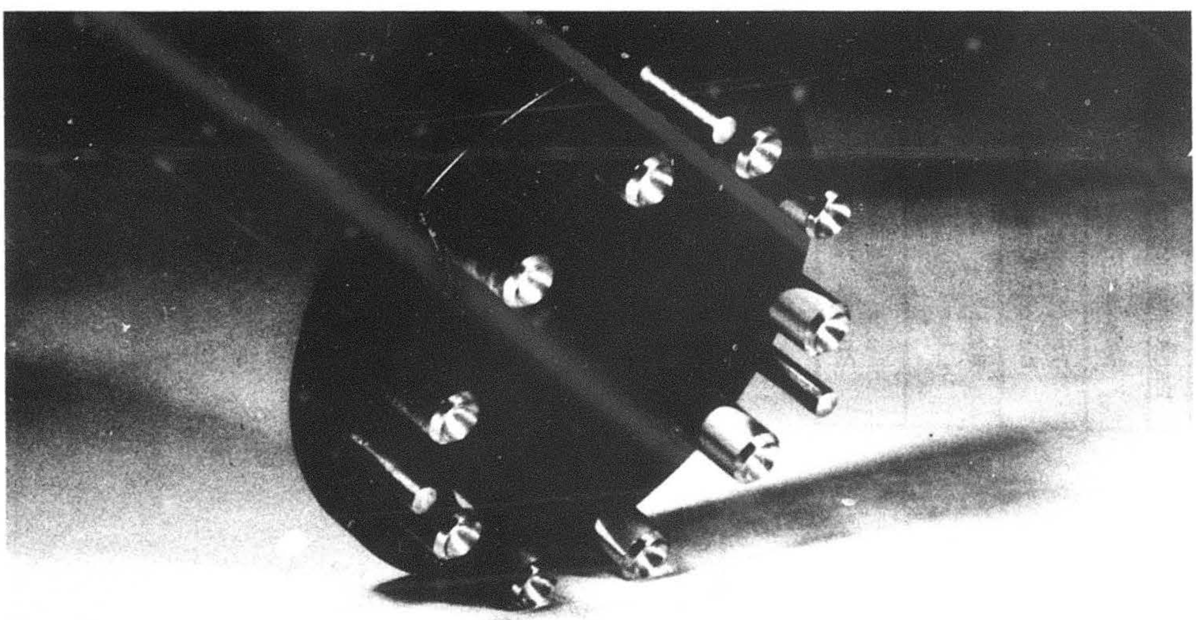
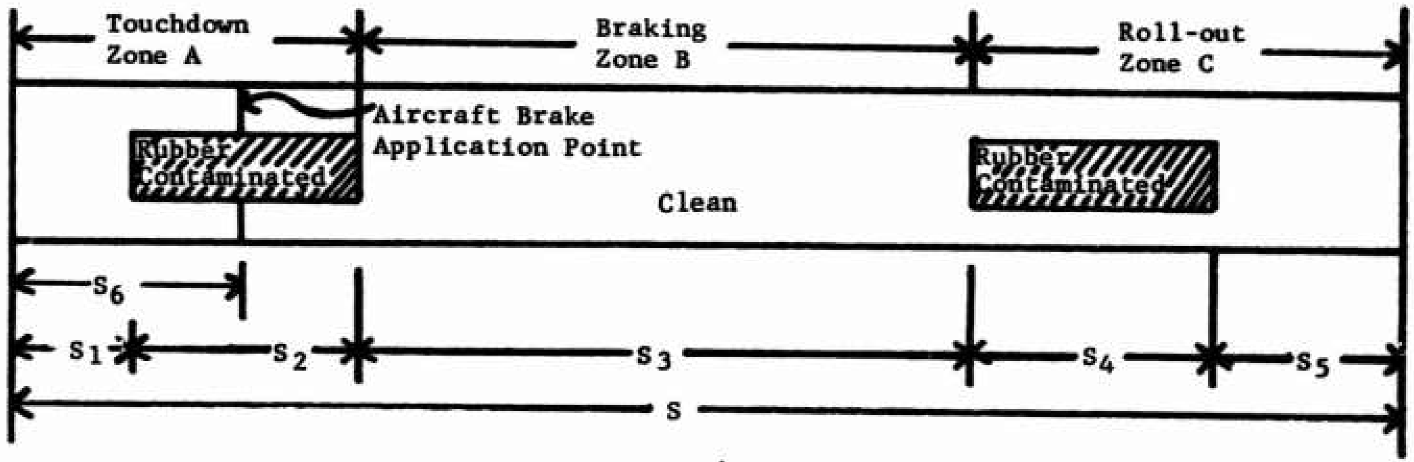


FIGURE A-1b - NASA WATER DEPTH GAGE
(Rear 3/4 View)

NASA DIAGONAL-BRAKED CAR RUNWAY SLIPPERINESS MEASUREMENTS	
Runway Location	Stopping Distance Ratio Wet/Dry
Touchdown Zone A, Rubber Contaminated	$\overline{X}_A$
Braking Zone B, Clean	$\overline{X}_B$
Roll-out Zone C, Rubber Contaminated	$\overline{X}_C$



Average Wet/Dry Stopping Distance Ratio During Landing Roll = $\overline{X}$

$$X = \frac{(S_1 + S_2 - S_6)\,\overline{X}_A + (S_3 + S_5)\,\overline{X}_B + S_4\,\overline{X}_C}{S - S_6}$$

FIGURE A-2. METHOD FOR CALCULATING THE AVERAGE DIAGONAL-BRAKED CAR WET/DRY STOPPING DISTANCE RATIO, $\overline{X}$, FOR A GIVEN LANDING CONDITION

APPENDIX 2. MU METER METHOD FOR EVALUATING RUNWAY SURFACE CHARACTERISTICS

1. SCOPE.

a. The Mu Meter is a continuous-recording friction-measuring trailer.

b. The Mu Meter measures the side force friction coefficient generated between the test surface and the pneumatic tires on two wheels which are set at a fixed toe-out, 15° included angle to the line of drag.

c. Friction values are recorded on a paper graph and on digital readout counters.

d. The paper trace gives an immediate, continuous representation of the changing values of friction for the whole distance travelled. Digital counters give the total distance traveled and total friction values. From these recorded totals, average friction can be calculated quickly. Hydroplaning conditions can be identified.

e. The Mu Meter can be used to check on the surface conditions of a runway after resurfacing, or for suspected deterioration after a long period of use with heavy traffic. If a plot of friction coefficient, μ, versus speed is desired, it is necessary to tow the Mu Meter over a wide speed range, i.e., from slow speeds to over 100 mph.

f. The Mu Meter is qualitatively used in the United Kingdom as follows: (Reference d)

MU METER TABLE OF BRAKING ACTION

MOTNE Code	Estimated Braking Action *	Measured or Calculated Coefficient of Friction
5	Good	0.40 and above
3	Medium	0.35 - 0.30
1	Poor	0.25 and below

*GOOD - Indicates that aircraft can expect to land comfortably within the scheduled "wet" distance without undue directional control problems.

MEDIUM - Aircraft are likely to use all the "wet" scheduled distance including the safety factor part of the distance, and may run even further. Directional control might be impaired.

POOR - Aircraft can expect to run for at least the full "very wet" or aquaplaning distance where this too is scheduled. Directional control will also be poor.

If runway average friction values are below 0.30 (a reading usually obtained over a wet runway covered with rubber deposits), the airport operator should check these areas and if rubber deposits are excessive, these deposits should be cleaned off the surface. The Mu Meter could be used to check these areas periodically to determine when the pavement should be cleaned to remove the contaminants. Advisory Circular 150/5380-3 provides information relative to cleaning of these contaminants from the runway surface.

g. "Braking action assessments are only intended as a guide to pilots and should always be used with discretion. For example, it is unwise to attempt to calculate precise corrections to landing or accelerate/stop distance required. The assessments should, in any case, be related to all other pertinent factors, e.g. the type and amount of precipitant to be encountered, crosswind component, aircraft handling characteristics and limitations." This statement is quoted from Reference d.

2. SUMMARY OF METHOD.

a. The test apparatus consists of an automobile towing the Mu Meter trailer, a relatively light (540 pounds) three-wheeled trailer, which continuously measures and records friction coefficient. Friction coefficient measurements are represented in a continuous recording mode as a stylus trace on a moving roll paper chart. An integrated total figure for friction is represented in numerical form on a digital counter. Another figure representing the distance traversed in units of 20 feet is also represented. The main components of the Mu Meter are (1) dual frames, (2) two friction measuring wheels, (3) one rear wheel, (4) ballast, and (5) recorder system.

b. Since the Mu Meter is a continuously recording device any segment of, or total length of a runway or taxiway may be evaluated by simply towing the Mu Meter over the surface at a speed of 40 mph. Speeds greater than 40 mph may be used in accordance with Paragraph 1.e.

3. APPARATUS.

a. Frame. The frame is triangular form constructed of box section members, with a lower Y-shaped section carrying the two measuring wheel assemblies, the rear wheel assembly, and the load sensing cell. An upper triangular section carries the recorder and ballast. Tubular cross members stiffen the upper frame, and its rise is stabilized during movement of the trailer by two hydraulically damped spring shock absorbers. A towing hitch eye is attached to the joined end of the lower frame fork. Also at this end of the frame is a horizontal pivot on which the separately sprung upper frame swings up and down, and a vertical pivot on which the left-hand frame members swing laterally during testing when the measuring wheels are toed-out. Running transversely between and attached to the two side members of the lower frame is the load sensing cell. See Figure A-3.

b. Measuring Wheels and Rear Wheel. Wheels are the split rim type. Measuring wheel tires are pneumatic, 6-ply, size 4.00 X 16 with smooth tread and the rear wheel is of the same size, but with a patterned tread. Tire pressure for the measuring wheels is 10 ± 1/2 psi and for the rear wheel, 30 ± 1/2 psi. Use a pressure gage calibrated to low pressure (below 8 psi) to measure these pressures accurately. The two outer wheels are the measuring wheels. The rear wheel drives the moving chart through a flexible cable.

c. Wheel Mountings and Suspension. The left-hand wheel is fixed in a 7 1/2 degree toe-out position; the left frame member is pivoted and swings laterally during testing. The right wheel is adjustable to the 7 1/2 degree toe-out position for testing or to a position parallel to the left axle for highway towing. Two hydraulically damped shock absorbers on which the upper frame rides also suspend these wheels. The rear wheel is mounted at the end of a long arm trailing between the two main frame side members. Suspension for this wheel is a low-rate compression spring mounted vertically between the trailing arm and the upper frame. This wheel is raised and latched clear of the ground for highway towing.

d. Mudguards. Two heavy mudguards enclose the measuring wheels, serving the dual purpose of both mudguard and ballast. The rear wheel is fitted with a mudguard which also serves as a writing surface for the operator during evaluation of test results and installation and removal of chart paper.

e. Load Cell. The load cell is a cylinder-and-piston mechanism acting on a fluid which actuates a bourdon tube in the recorder which, in turn, moves the recording pen.

f. Recorder. The recorder consists of: (See Figure A-4.)

(1) A movable chart drum, driven by the rear wheel through a flexible shaft.

(2) A friction recording stylus operated by linkages connected to the bourdon tube.

(3) An integrator digital counter which displays total friction values, and is driven by the flexible drive from the rear wheel. This device also receives pulses from the bourdon tube.

The value displayed represents a summation of friction values based on samples taken once every 20 feet of operating distance.

(4) A distance digital counter yields a numerical value for the total number of 20 foot units of distance covered.

(5) An event marker stylus moved by linkages driven by pneumatic pressure transmitted to the recorder from the towing vehicle.

g. Towing Vehicle. The towing vehicle may be any one of the following:

(1) Pickup truck

(2) Jeep-style vehicles

(3) Private cars

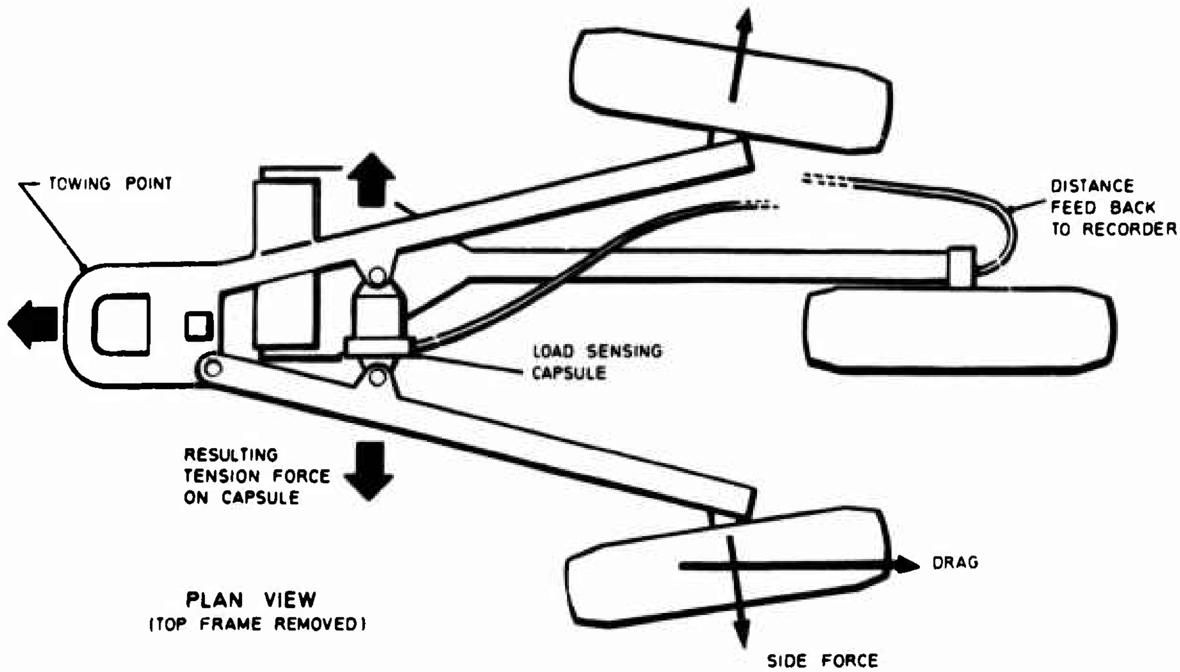
(4) Station wagons

The vehicle should weigh at least 1200 pounds, and should maintain good directional stability on slippery surfaces, particularly in strong crosswinds. Power should be sufficient to accelerate the car and Mu Meter to a speed of 40 mph in about 200 yards, even on inclines up to three percent. Sufficient power should then be available to maintain the 40 mph speed within ±3 mph in a smooth, jerk-free manner. The braking system should be adequate to stop the towing vehicle and trailer in a reasonable distance for the specific surface conditions without any tendency to slew or skid. The suspension system should be firm, well damped and free of major oscillations during acceleration, braking or traversing undulating surfaces. The wheel track should be not less than four feet. A suitable towing hitch which will accept the towing eye of the Mu Meter should be used. The bottom face of the towing eye should be not more than 17 3/16 inches from the ground when attached to the towing hitch.

4. TEST PROCEDURE.

a. Vehicle Operation. The Mu Meter is attached to the towing hitch of the towing vehicle. The right-hand wheel of the Mu Meter is moved to the tow-out position to form an included angle of 15° with the left-hand wheel. The trailer is then towed over the surface to be measured at a speed of 40 mph. The friction produced by the towed-out wheels is sensed by the hydraulic load cell and the resulting pressure is transmitted through a flexible pipe to the bourdon tube and indicating mechanism in the recorder. The recording stylus makes a trace on the moving, pressure-sensitive graph paper which is moving at a rate of one inch of graph for every 450 feet of test surface covered. A remotely operated event recorder may be used to mark the graph at the start, finish and any other points of interest.

b. Runway Traffic Control. The same procedure should be followed as stated in Appendix 1, Paragraph 5c.



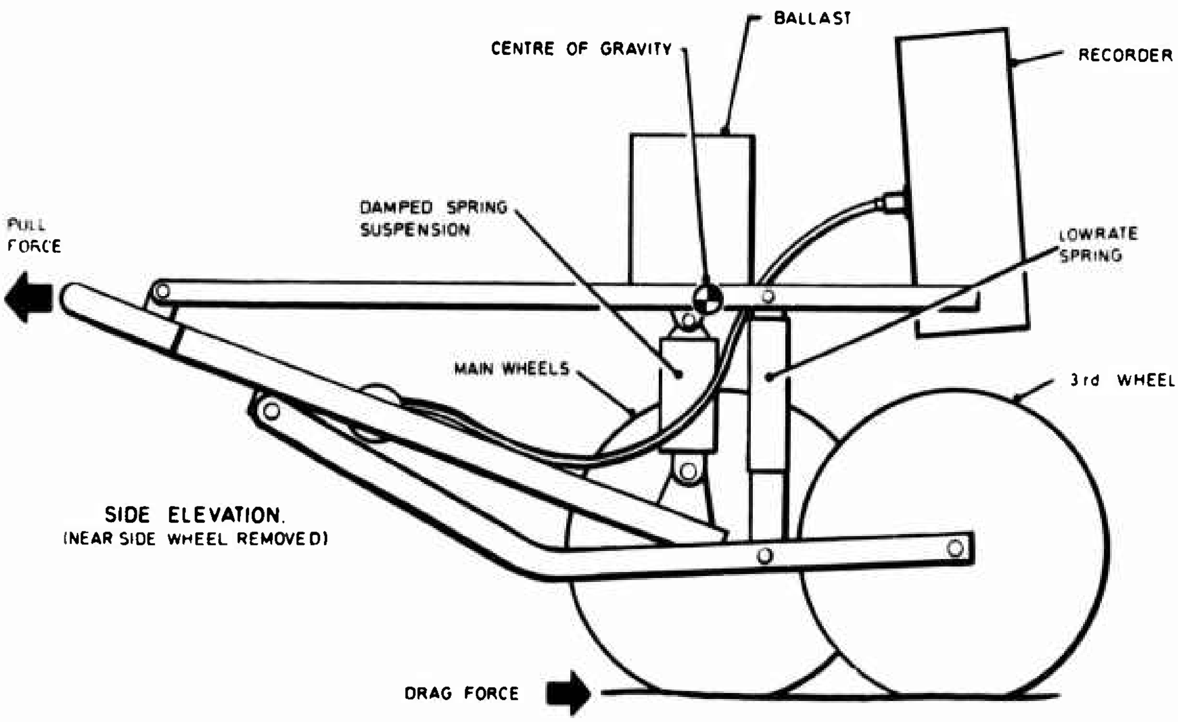


FIGURE A-3. DIAGRAMMATIC LAYOUT OF MU METER

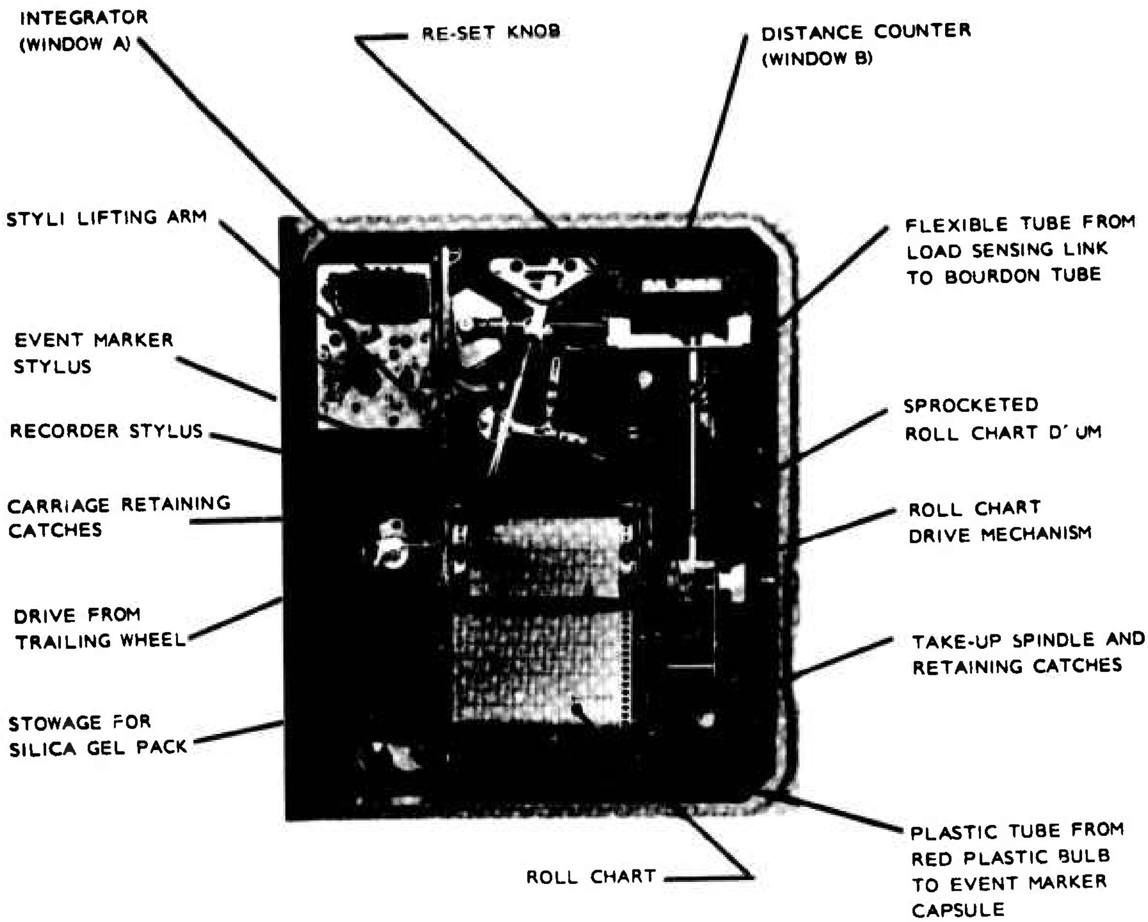


FIGURE A-4. MU METER RECORDER

APPENDIX 3. THE JAMES BRAKE DECELEROMETER FOR EVALUATING RUNWAY SURFACE CHARACTERISTICS

1. SCOPE.

a. The James Brake Decelerometer (JBD) provides an instantaneous deceleration reading and must be reset between each reading.

b. The JBD is read and the reading is manually recorded.

c. The JBD can be mounted in any firmly suspended vehicle.

d. Reference d states that the JBD is limited to use on ice and dry snow, as it is likely to produce misleading high readings in slush, wet snow or water (for example, it will not detect that there is a possibility of "slush planing"). Braking action therefore will not be assessed in the latter conditions. Reference e further states, "The equipment is not suitable for use if there is water or slush on the runway and will therefore not be used under these circumstances."

2. SUMMARY OF METHOD.

a. The JBD is mounted, level, on the floor of any firmly suspended automotive vehicle.

b. The automobile is accelerated to a speed of 30 mph and at the point on the surface to be measured the brakes are smoothly and firmly applied until all four wheels are locked and the vehicle skids.

c. The slipperiness of the runway is determined in the form of a friction coefficient, Mu, from the JBD reading.

3. APPARATUS.

a. Vehicle. The vehicle can be any firmly suspended automobile, station wagon, pickup truck or van.

(1) Suspension. The suspension of the vehicle shall be such that when the brakes are applied there shall be no severe pitching tendency.

(2) Braking System. The braking system shall provide uniform pressure to each of the vehicle's four wheels and the brake shoes shall be adjusted so as to provide a nearly simultaneous lockup of all four wheels when the brakes are firmly applied.

(3) Safety Equipment. The vehicle should be provided with seat belts and suitable shoulder harnesses for the driver and observer.

b. JBD Mount. Steel base plates should be provided to afford a rigid attachment fixture for the JBD installation. The base plate should provide for a level JBD mounting.

c. JBD. The James Brake Decelerometer design is predicated on recording a maximum change in acceleration through a damped pendulum displacement resulting from the action of component forces. The dial on the JBD has a scale of 0 to 32.2 feet per second to indicate the acceleration rate as generated by the pendulum's travel.

4. DRIVER TRAINING.

a. Drivers of vehicles using the JBD should be carefully trained in accordance with Air Force Technical Order 33-1-23. This training is important since the operation technique is the key to success in use of the JBD.

5. TEST PROCEDURE.

a. The runway to be measured is usually divided into three equal parts.

b. JBD readings are obtained at fixed intervals, i.e., 500 feet or 1000 feet, approximately 30 feet each side of the runway centerline over the entire length of the runway. The readings will be averaged for each one third of the runway tested to establish the value for that third.

c. Runway traffic control during the JBD tests should be the same as stated in Appendix 1, Paragraph 5c.

d. The JBD reading is obtained by accelerating the vehicle to 30 mph and then firmly and smoothly applying brake pressure until all four wheels lock up and a steady skid is established. The JBD reading is recorded, the instrument reset to zero, and the next reading made as the vehicle progresses down the runway. Detailed procedures may be found in USAF Technical Order 33-1-23.

6. USE OF THE DATA.

a. The JBD readings are in terms of the James Brake Index (JBI) and range from 0 to 32.

b. Qualitative use of the data, as used in References d (Tapley Meter) and e (JBD) are:

(1) Reference d.

MOTNE Code	Estimated Braking Action	Measured or Calculated Coefficient of Friction
5	Good *	0.4 and above
4	Medium/Good	0.39 - 0.36
3	Medium *	0.35 - 0.30
2	Medium/Poor	0.29 - 0.26
1	Poor *	0.25 and below

(2) Reference e.

Estimated Braking Action	James Brake Index (JBI)
Excellent	25 - 32
Good	22 - 24
Fair	18 - 21
Poor	10 - 17
Nil to very poor	0 - 9

* Defined in Appendix 2.

c. Alaska Airlines has used the JBD to establish Runway Condition Reading (RCR) values as a function of stopping distance for the Boeing 727 on ice or hard-packed snow-covered runways. These data were established by flight test and correlation with JBD data obtained at the same time.

d. JBI readings are converted to coefficient of friction, Mu, by:

$$Mu = \frac{JBI}{32.2}$$

remainder is scattered and rebound as O2 molecules. The chemical composition of the products evaporating from the surface is held to be identical to that of an equilibrium mixture at the temperature of the solid so that evaporation rates are related through equilibrium constants. This quasi-equilibrium analysis also provides an ap- [illegible] as ions. Also described is a simplified method for determining enthalpies and free energies of formation of volatile species that form in gas-solid chemical reactions at high temperatures and low pressures. The principle feature of this procedure is a Langmuir source for attaining molecular flow conditions and mass spectrometric measurements of the rates of species evaporating from the probes surface as ions. G.G.

11 FACILITIES, RESEARCH AND SUPPORT

Includes airports; lunar and planetary bases including associated vehicles; ground support systems; related logistics; simulators; test facilities (e.g., rocket engine test stands, shock tubes, and wind tunnels); test ranges; and tracking stations.

N71-26803# Federal Aviation Administration, Washington, D.C.
MEASUREMENT OF RUNWAY FRICTION CHARACTERISTICS ON WET, ICY OR SNOW COVERED RUNWAYS Progress Report
1 Apr. 1971 19 p refs
(FS-160-65-68-1) Avail: NTIS

Three methods of measuring runway friction characteristics are described and possible usage of the data obtained is indicated. The information presented reflects the current state-of-the-art for measurement and classification of the relative slipperiness of runway surfaces. The three methods described include: (1) the diagonal-braked vehicle test method for measuring stopping distances on paved surfaces, (2) the Mu Meter method for evaluating runway surface characteristics, and (3) the James Brake Decelerometer method for determining runway slipperiness in the form of a friction coefficient. D.L.G.

N71-26880# Army Test and Evaluation Command, Aberdeen Proving Ground, Md.
SHELTER: TENTS (AVIATION) Final Report
9 Mar. 1971 19 p refs
(AD-721153, MTP-7-3-056) Avail: NTIS CSCL 1/5

Procedures are prescribed for evaluating the functional suitability of tents developed for aviation use. Author (GRA)

[illegible]043# Sandia Corp., Albuquerque, N.Mex.
AERODYNAMIC FORCES AND DYNAMIC STABILITY OF A HIGH SPEED, MAGNETICALLY SUSPENDED ROCKET SLED
H. M. Dodd, Jr. and D. L. Preston Jan. 1971 54 p refs
(SC-DR-70-867) Avail: NTIS

The aerodynamic forces and dynamic stability were investigated of a magnetically suspended rocket sled moving at velocities of Mach 4 to Mach 10 close to a stationary wall. An analytical model is developed and experimental verification is obtained from conventional rocket sled tests. Results show that a previous technique yielded aerodynamic lift forces which were an order of magnitude too low. As a consequence, an example dynamic model which previously was found to be stable became unstable in both longitudinal and lateral modes. Author

N71-26984# General Electric Co., St Petersburg, Fla. Neutron Devices Dept.
A HIGH SENSITIVITY ULTRASONIC TEST SYSTEM FOR WELDS
P. A. Fessler and W. E. Michaud 11 Nov 1970 20 p
(Contract AT-(20-2)-656)
(GEPP-83) Avail: NTIS

The scanning and recording equipment [illegible] of electron beam welds. The equipment inspects an [illegible] weld in stainless steel parts and is capable of indicating defects not detectable with conventional X-ray radiographic equipment. Nearly a year's production testing has proven that flaws which are as small as 0.015 inch in diameter and located as deep as one [illegible] of an inch below the surface of the part can be detected [illegible]. Misaligned welds, short welds and cracks are readily shown. The inspection takes about one minute. The ultrasonic information is electronically displayed and stored on the cathode ray [illegible] a storage display unit. Polaroid photographs of the display [illegible] permanent records of each weld inspected. Author

N71-27034# Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt, Goettingen (West Germany). Abteilung Raumfahrt-Aerodynamik
THE SECOND TEST SECTION OF THE AVA HYPERSONIC LOW DENSITY WIND TUNNEL: DESCRIPTION AND OPERATIONAL BEHAVIOR [DIE ZWEITE MESSSTRECKE DES HYPERSONISCHEN VAKUUMWINDKANALS DER AVA-BAUBESCHREIBUNG UND BETRIEBSVERHALTEN]
G. Hefer Sep. 1970 73 p refs In GERMAN; ENGLISH summary
(DLR-FB-70-42; AVA-FB-70-23) Avail: NTIS ZLDI Munich 23.10 DM

The second test section of the hypersonic low density wind tunnel has been put into operation. This facility, operating with air and having a test section diameter of 40 cm allows Mach numbers between 10 and 22. The stagnation temperature can be varied from 400 to 1200 K, the stagnation pressure from 0.2 to 20 atmospheres, yielding a test section mean free path between 0.01 and 1 mm. The test facility is described and the operational behavior, investigated by extensive calibration measurements, is dealt with. Author (ESRO)

N71-27035# Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt, Goettingen (West Germany). Abteilung Raumfahrt-Aerodynamik
INVESTIGATION OF A LIQUID NITROGEN COOLED NOZZLE OF THE HYPERSONIC LOW DENSITY WIND TUNNEL [ERPROBUNG EINER MIT STICKSTOFF GEKUEHLTEN DUESE DES HYPERSONISCHEN VAKUUMWINDKANALS]
G. Hefer and K. Kienappel Sep. 1970 36 p refs In GERMAN, ENGLISH summary
(DLR-FB-70-41; AVA-FB-7024) Avail NTIS, ZLDI Munich. 11.10 DM

In order to extend the test range of the first test section of the hypersonic low density wind tunnel to lower Reynolds numbers this facility has been equipped with a liquid nitrogen cooled nozzle. Extensive pitot pressure surveys have been made to investigate the influence of liquid nitrogen cooling on the test section flow field. It is shown that with this new nozzle much lower test section Reynolds numbers can be achieved. Author (ESRO)

N71-27036* Electro-Optical Systems, Inc., Pasadena, Calif.
MATERIAL HANDLING DEVICE Patent
Douglas G Ritchie, inventor (to NASA) Issued 13 Apr 1971 6 p Filed 6 Oct 1969 Cl 74-18.2, Int. Cl. F16j15/52
Continuation-in-part of US Patent Appl. SN-700120, filed 24 Jan 1968 Sponsored by NASA Prepared for JPL
(NASA-Case-XNP-09770-3; US-Patent-3,574,286; US-Patent-Appl-SN-863987) Avail US Patent Office CSCL 13C

A device for use on unmanned spacecraft is described which separates and screens particles for viewing soil samples in a