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SUMMARY REPORT ON AIRCRAFT AND GROUND VEHICLE FRICTION CORRELATION TEST RESULTS OBTAINED UNDER WINTER RUNWAY CONDITIONS DURING JOINT FAA/NASA RUNWAY FRICTION PROGRAM

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Summary Report on Aircraft and Ground Vehicle Friction Correlation Test
Results Obtained Under Winter Runway Conditions During Joint FAA/NASA Runway
Friction Program

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Abstract

Aircraft and ground vehicle friction data collected during Joint FAA/NASA Runway Friction Program under winter runway conditions are discussed and test results summarized. The correlation between the different ground vehicle friction measurements obtained on compacted snow- and ice-covered conditions is defined together with the relationship to aircraft tire friction performance under similar runway conditions.

Introduction

There is an imperative operational need for information on runways which may become slippery due to various forms and types of contaminants. Experience has shown that since the beginning of "all weather" aircraft operations, there have been landing and aborted takeoff incidents and/or accidents each year where aircraft have either run off the end or veered off the shoulder of low friction runways. From January 1981 to June 1987, more than 400 traction-related incident/accidents have occurred according to the Federal Aviation Administration (FAA) and National Transportation Safety Board (NTSB) records. These cases have provided the motivation for various government agencies and aviation industries to conduct extensive tests and research programs to identify the factors which cause the runway friction to be less than acceptable. (refs. 1 to 15).

The current Joint FAA/NASA Aircraft/Ground Vehicle Runway Friction Program is aimed at obtaining a better understanding of aircraft ground handling performance under a variety of adverse weather conditions and to define relationships between aircraft and ground vehicle tire friction measurements. These tests have involved a specially instrumented NASA B-737 aircraft and FAA B-727 aircraft together with seven different ground friction measuring vehicles described in references 16 to 19. Between June 1983 and March 1986, tests were performed on 12 different concrete and asphalt runways, grooved and ungrooved, including porous friction coarse, under dry, truck wet, rain wet, snow-, slush-, and ice-covered surface conditions. A limited assessment of some runway chemical de-icing treatments was also obtained. Over 200 test runs were made with the two transport aircraft and over 1100 runs were made with the different ground

test vehicles. Since the winter runway conditions with snow and ice are the most hazardous to aircraft ground operations and the aviation industry has indicated the greatest interest in the test results obtained under these conditions, this summary report has been prepared to help facilitate the creation of an advisory circular or other useful document for the industry. The principal objective of this report is to indicate the friction correlation obtained between the different ground test vehicles under compacted snow- and ice-covered runway conditions and then show the relationship to the B-737 and B-727 aircraft tire braking friction performance. For the winter runway conditions evaluated, aircraft stopping distance variation with braked energy is also discussed.

Test Site and Procedures

The test site selected for these winter runway tests was Brunswick Naval Air Station located about 40 miles northeast of Portland, Maine. This northern United States location enhanced the chances of obtaining the desired snow and ice test conditions and the parallel runway arrangement shown in the aerial view of Brunswick NAS in figure 1(a) minimized the interruption to normal Navy flight operations. During the winter season, the inboard runway 1R/19L was maintained in a clear, clean condition for Navy aircraft use and the outboard runway 1L/19R was left in a snow/ice-covered condition until melting occurred with higher temperatures in the spring. The runway pavement was dense-graded, moderate-to-high textured, asphalt (ungrooved) with a nominal 1% crown.

When notified by the Navy base operations personnel that there was a snow accumulation on the outboard runway and temperatures were well below

freezing, the test aircraft, ground vehicles, and FAA/NASA test team traveled to Brunswick NAS for testing. The winter runway braking performance of the NASA B-737 aircraft was evaluated in March 1985 and the FAA B-727 aircraft between January and March of 1986. A wide range of snow-covered runway conditions were evaluated during these aircraft tests including snow depths up to 6 inches. Test aircraft gross weights were maintained within a 10 percent range with the B-737 gross weight varying from 75,400 to 81,400 lb and for the B-727, 121,900 to 135,300 lb. Since useful friction data from the ground test vehicles could only be obtained in loose snow depths equal to or less than 2 inches or on compacted snow- or ice-covered runways, the test results and friction correlation between ground vehicles and aircraft discussed in this report only pertain to the latter two runway conditions. These two test surface conditions, compacted snow- and ice-covered, are shown in figures 1(b) and (c). Insufficient aircraft and ground vehicle friction measurements were collected for slush and loose snow conditions to determine a reasonable friction correlation. FAA Advisory Circular 150/5200 on Airport Winter Safety and Operations describes several operational runway snow/ice contamination conditions. Loose snow, slush and standing water can impede aircraft acceleration as well as extend aircraft stopping distances. Although limits vary by aircraft, most jet aircraft are limited to landing with one inch or less of slush or standing water on the runway and to taking off with one-half inch or less of slush or standing water. FAA Advisory Circular 91-6 describing turbine powered aircraft performance with water, slush, snow, or ice on the runway provides additional information on this subject of winter runway operations.

For each series of snow-covered runway runs with the instrumented aircraft and the different ground test vehicles, 2000 ft at each end of the runway was cleared using plows and snow blowers and approximately 50 ft on each side (shoulder) of the runway was also cleared. This snow removal procedure produced a 4000 ft long, 100 ft wide snow-covered test section located in the middle of the runway. The general test sequence for each surface condition was to conduct aircraft tests starting first at low brake application speed (approximately 60 knots) and progressing up to 100 knots. On each of these maximum antiskid controlled wheel braking runs, the pilot came off the the brake pedals at approximately 20 knots ground speed or when the aircraft exited the test section, whichever occurred first. For each aircraft run, the pilot displaced the aircraft path laterally to minimize the effect of the tire operating in snow displaced from earlier runs. Upon completion of the aircraft braking runs covering the nominal landing speed range, test runs were conducted with the ground vehicles at speeds of 20, 40, and 60 mph in both runway headings. During the course of each aircraft and ground vehicle test series for a particular snow-covered surface condition, several environmental measurements were taken and recorded including snow depth and density, ambient and surface temperature, and wind heading and velocity. Temperature sensors were located in the runway surface at both ends with readout gages at base operations (control tower).

To implement safe testing on the more hazardous, low friction, ice-covered surface condition, water was sprayed on a clear pavement at night with ambient temperatures well below freezing. The area covered was 2000 ft long and approximately 50 ft wide near the middle of the overall runway. This procedure left 3000 ft long, clear, uncontaminated, high friction areas at both ends of the runway. Aircraft testing was performed

at daybreak under calm wind conditions. The initial aircraft test run was conducted with maximum wheel braking applied at 60 knots and released when aircraft reached approximately 20 knots. Subsequent runs were conducted up to 100 knots brake application speed. During each aircraft test run, an onboard observer activated a data recorder event marker to indicate start and end of runway test section. Instrument calibrations and check-outs were performed daily on the aircraft and ground vehicle test instruments to help insure accuracy of test results.

Data Analysis

Aircraft test run parameter data, recorded on analog magnetic tape filtered at 100 Hz, were transcribed into a digital format and processed into Engineering Unit (EU) tapes. From these EU tapes, time histories of all instrumented aircraft system parameters required for data analysis were generated. Uniformity in pilot brake application and proper aircraft configuration for given series of test runs was determined from careful review of these time history plots. A maximum sample rate of 40 per second was used in digitizing the aircraft parameter data. For a given runway surface condition, longitudinal acceleration data from non-braking tare runs were analyzed to identify incremental components attributable to aerodynamic drag, tire rolling resistance, engine idle thrust, and accelerometer zero shift due to runway contaminant displacement drag. These tare run values of aircraft longitudinal acceleration were then used to correct the measured values recorded during maximum braking test runs. The aircraft effective braking friction coefficients for a given run were derived using an average percentage of the aircraft gross weight supported on the main gear braking

wheels which varied as a function of the nominal center of gravity position. A least squares curve was fitted to the effective friction coefficient, μ_{EFF} , data variation with ground speed, V_G , and a statistical measure (labeled sigma for standard deviation) of the dispersion of the measured μ_{EFF} values about the least squares curve fit was calculated. To determine aircraft stopping distance values as a function of braked energy (aircraft gross weight multiplied by square of brake application speed), an average uncorrected longitudinal accelerometer variation from maximum brake application speed down to zero was used in making the calculation. An average aircraft gross weight for a given runway condition test run series was used in deriving the braked energy values.

The Tapley meter and Bowmonk brakemeter devices were read manually and the data recorded on log sheets. Values of runway condition reading (RCR) were determined by multiplying the Tapley meter reading (percentage of G) by 100 and dividing by 3. The mu-meter, Saab friction tester, runway friction tester, and BV-11 skiddometers had time history records for each test run showing variation in both friction coefficient and ground speed. In analyzing the ground vehicle friction data, friction data obtained on snow- and ice-covered surfaces reported in references 3, 7, 12-14, and 20 were also considered.

Test Results and Discussion

The friction measurements obtained with the various ground test devices indicated that forward speed had little effect on the magnitude of the

friction values recorded for compacted snow-covered and ice-covered conditions. Furthermore, the friction readings obtained were similar on both of these surface conditions for each test vehicle. The Tapley and Bowmonk meters were installed in the Navy's runway condition reading vehicle (pickup truck) and the manually recorded values were in close agreement for each test run. Reference 20 describes the RCR test procedure used at U.S. military bases for monitoring runway friction conditions. Both the Tapley meter and Bowmonk brakemeter manufacturers caution users that these devices should only be used for snow- and ice-covered surface conditions. Table I provides a listing of the range of friction readings for four braking action levels derived from the tests conducted at Brunswick NAS as well as other similar winter runway tests (see references 3, 7, 12-14, and 20) conducted at other locations. The vehicle test tire conditions, range of ambient temperatures, and test speeds are indicated in the notes accompanying Table I. Qualitative verbal braking action terms namely, excellent, good, marginal, and poor, were used to identify four distinct levels or ranges in friction readings for each device. The correlation determined between each of the ground vehicle friction measurements is given in Table II.

In general, the excellent friction readings were close to some wet surface values, e.g. 0.5 and above, whereas, the poor friction readings were normally below 0.25 and found on solid glare ice-covered surface. The data suggests that ambient temperature does influence the friction readings on solid ice-covered surfaces with lower temperatures producing higher friction values. Unfortunately, the ambient temperatures for the ice-covered surface tests only varied from 5 to 31^oF and additional tests with a greater temperature range are required to better define its effect on friction performance. The data contained in table I is plotted in the chart given in

figure 2 to illustrate the friction relationship between the different ground vehicle devices. The BV-11 skiddometer and Saab friction tester measured similar friction values as expected since the test tire and braking slip operation were identical. The format for this chart was derived from a chart contained in reference 20 used by European countries. The dashed line represents a sample derivation of other vehicle friction measurements comparable or equivalent to an RCR equal to 15. The range of friction values at each of the four levels is nearly the same for the mu-meter, Tapley meter, runway friction tester, and the Bowmonk meter. Slightly higher values of friction for each level were obtained with the Saab friction tester and the BV-11 skiddometer mainly because of using a higher test tire inflation pressure (100 vs. 30 psi or less) combined with a grooved tread pattern on the tire instead of a smooth (blank) tread. These findings are also applicable to aircraft tires since average tire footprint bearing pressure is directly proportional to inflation pressure.

The range of aircraft effective braking friction coefficient values with ground speed for compacted snow- and ice-covered runway conditions is shown in figure 3. The data symbols and line codes distinguish between the different test runs and aircraft. The best fit linear curve for the compacted snow-covered surface friction data (solid line) is nearly four times greater than that measured on the solid ice-covered surface (dashed line). The linear equations and standard deviation (σ) values are given for both runway conditions with no significant difference found between the two test aircraft. With increasing speed, the level of aircraft braking performance decreased on the ice-covered surface but slightly increased on

the compacted snow-covered runway. These slight variations in μ_{EFF} with speed, however, are not considered significant.

Since both test aircraft indicated a significant difference between the compacted snow-covered and the ice-covered surface conditions, two ranges or means of aircraft braking friction data were selected to define the relationship with the ground vehicle friction measurements. The resulting aircraft and ground vehicle friction correlation chart is shown in figure 4 where the compacted snow-covered and ice-covered surface condition is delineated for the two aircraft. For the compacted snow-covered surface condition, an aircraft effective braking friction coefficient value of 0.21 was selected for the excellent braking action level and 0.12 was used for the poor braking action level. An effective braking friction coefficient range from 0.055 to 0.01 was selected for comparable aircraft braking action levels on the ice-covered surface condition. The dashed line depicts comparable values for other ground vehicles and the two aircraft/surface conditions for an RCR equal to 15. The relationships shown in figure 4 between the various ground vehicle and aircraft friction measurements were derived from the range of values collected from a variety of tests conducted under compacted snow- and ice-covered conditions (see ref. 3, 7, 12-14, and 20). Not all of the winter runway test conditions were evaluated with either or both aircraft. Consequently, a distinct regression equation and correlation coefficient values between the two test aircraft and six ground vehicle friction values cannot be determined.

The data in figure 5 give an indication of how the snow- and ice-covered runway surface conditions influence aircraft stopping distance. These curves for the two test aircraft were derived from time history

records of aircraft longitudinal deceleration during maximum braking test runs. The difference in stopping distance variation with braked energy for the two test aircraft is due to the difference in aircraft gross weight values.

From an aircraft operator's viewpoint, these values of friction for a snow- or ice-covered runway must be considered in respect to the actual runway geometry and several environmental conditions such as pressure/altitude, winds, and ambient temperature at the time of a particular aircraft operation. It is also recognized that aircraft operations can occur on runways which have a nonuniform mixture of compacted snow-covered area and exposed solid ice-covered surfaces. In such circumstances, additional ground vehicle friction measurements need to be taken to adequately determine average friction numbers for each portion (surface condition change) of the runway. How well this established relationship between aircraft and ground vehicle friction values remains for other aircraft types is somewhat questionable although the available data tends to suggest a similar correlation (ref. 12 and 14). The use of actual friction numbers in place of qualitative braking action terms is strongly recommended because with experience, these runway friction values measured by a ground vehicle will provide the pilot a more precise and accurate gage on the safety margins available for landing on a given runway. Proper and timely use of snow removal equipment and runway chemical treatments to minimize and/or remove snow/ice contaminants is still recognized as a necessity to return as soon as possible runway friction levels back up to near dry surface performance.

Conclusions

Extensive aircraft and ground vehicle winter runway friction tests have been conducted at Brunswick NAS, Maine as part of the Joint FAA/NASA Runway Friction Program. The test results and friction correlation discussed in this summary report indicate the following:

- (1) Friction values measured with the different ground vehicles were independent of both the forward speed and the type of surface condition (snow- or ice-covered).
- (2) The Tapley meter and Bowmonk brakemeter installed in the same vehicle produced similar readings for each test run.
- (3) The high pressure, grooved tread, test tire used on the Saab friction tester and BV-11 skiddometer developed the highest friction readings compared to the values measured with the other, low pressure, smooth tread, test tires used on the mu-meter and runway friction tester.
- (4) The range of friction values measured by the different ground vehicles for compacted snow- and ice-covered runways could reasonably be divided into four distinct levels of braking action classified as "excellent", "good", "marginal", and "poor".

- (5) The ground vehicle friction measurement correlation was defined and a relationship to aircraft effective braking friction coefficient values was identified.
- (6) Aircraft effective braking friction coefficient variation with ground speed indicated a significant difference between compacted snow-covered and solid ice-covered surfaces.
- (7) Aircraft braking performance tended to decrease slightly with increasing speed on the ice-covered runway, but on the compacted snow-covered surface, braking performance increased slightly. This speed effect is considered insignificant and well within the data scatter.
- (8) With proper maintenance, equipment check-out, and instrument calibration performed on a regular schedule, each ground friction measuring device performed satisfactory and produced consistent, repeatable, and accurate friction data.
- (9) Ambient temperature variation inversely effected the friction measurements on compacted snow- and ice-covered surfaces with lower temperatures giving higher friction readings.
- (10) Proper and timely use by airport operators of snow/ice removal equipment and chemical treatments are essential to restore as soon as possible runway friction levels back up to near dry surface performance.

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Table I.- Ground vehicle friction reading correlation data for four levels of braking action.

Runway Surface Conditions: Compacted Snow and Ice

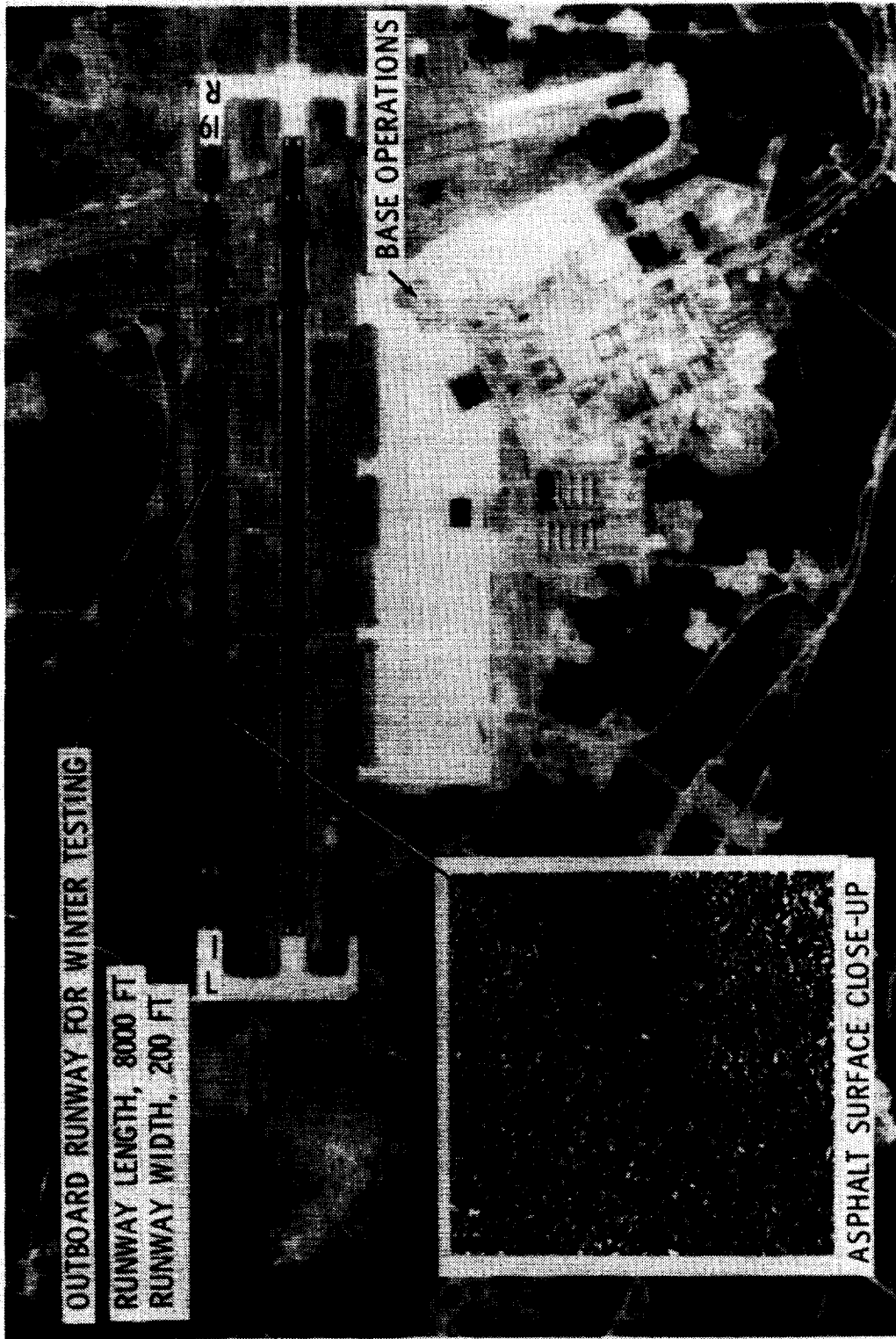
VERBAL BRAKING ACTION	GROUND VEHICLE FRICTION READINGS						
	MU-METER	TAPLEY METER	RUNWAY CONDITION READINGS (RCR)	BOWMONK METER	SAAB FRICTION TESTER	RUNWAY FRICTION TESTER	BV-II SKIDDOMETER
EXCELLENT	0.50 and above	0.48 and above	16 and above	0.46 and above	0.58 and above	0.50 and above	0.58 and above
GOOD	0.49 to 0.36	0.46 to 0.35	15 to 12	0.44 to 0.34	0.56 to 0.42	0.48 to 0.35	0.56 to 0.42
MARGINAL	0.35 to 0.26	0.33 to 0.25	11 to 9	0.32 to 0.24	0.39 to 0.29	0.33 to 0.24	0.39 to 0.29
POOR	0.25 and below	0.24 and below	8 and below	0.23 and below	0.27 and below	0.23 and below	0.27 and below

NOTES:

- (1) Mu-meter equipped with smooth RL-2 tires inflated to 10 lb/in.²
- (2) Runway friction tester equipped with smooth RL-2 tire inflated to 30 lb/in.²
- (3) Saab friction tester and BV-11 skiddometer equipped with grooved aero tire inflated to 100 lb/in.²
- (4) Ambient air temperature range, -15 to +5° C (5 to 41° F)
- (5) Test speed range, 20 to 60 mph except for Tapley meter, RCR, and Bowmonk meter readings which were obtained at speeds from 20 to 40 mph.

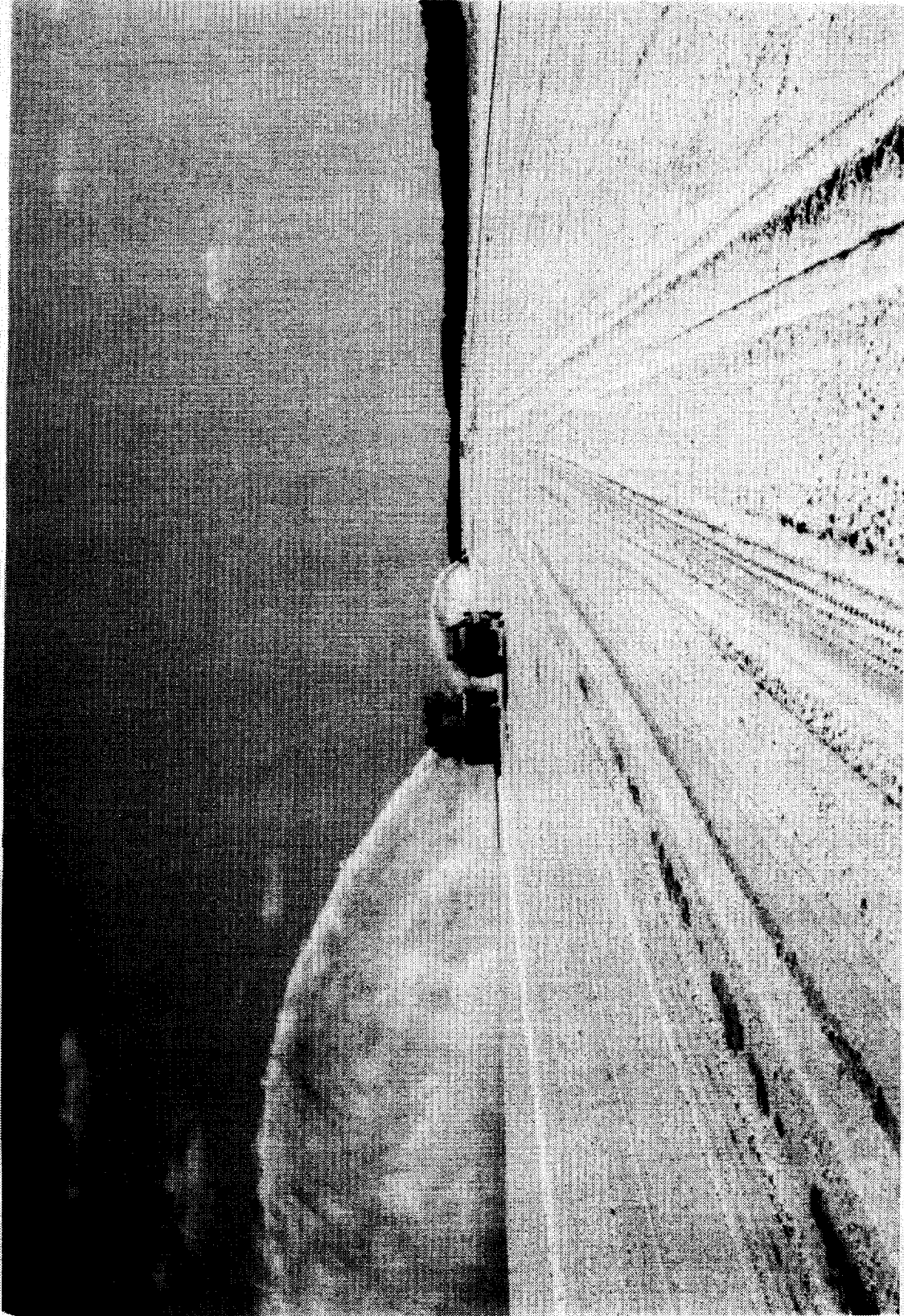
TABLE II. Correlation between ground friction measuring devices.

Regression equation	Sigma (Standard deviation)	Correlation Coefficient	Number of points
MuM = -0.08 + 1.20 TAP	0.00016	.998	22
BOW = -0.01 + 0.96 TAP	0.0032	.999	21
BV/SFT = -0.05 + 1.30 TAP	0.0011	.997	21
RFT = -0.05 + 1.13 TAP	0.0012	.994	10
RCR = 100/3 TAP	0	1.00	N/A
BOW = 0.05 + 0.80 MuM	0.007	.998	22
BV/SFT = 0.04 + 1.10 MuM	0.019	.993	22
RFT = 0.03 + 0.92 MuM	0.018	.986	10
RCR = 2.33 + 27.55 MuM	0.233	.998	22
BV/SFT = -0.03 + 1.37 BOW	0.010	.998	21
RFT = -0.04 + 1.18 BOW	0.012	.994	10
RCR = 0.33 + 34.83 BOW	0.11	.999	21
RFT = -0.002 + 0.84 BV/SFT	0.012	.994	10
RCR = 1.20 + 25.29 BV/SFT	0.28	.998	21
RCR = 1.50 + 29.13 RFT	0.34	.994	10



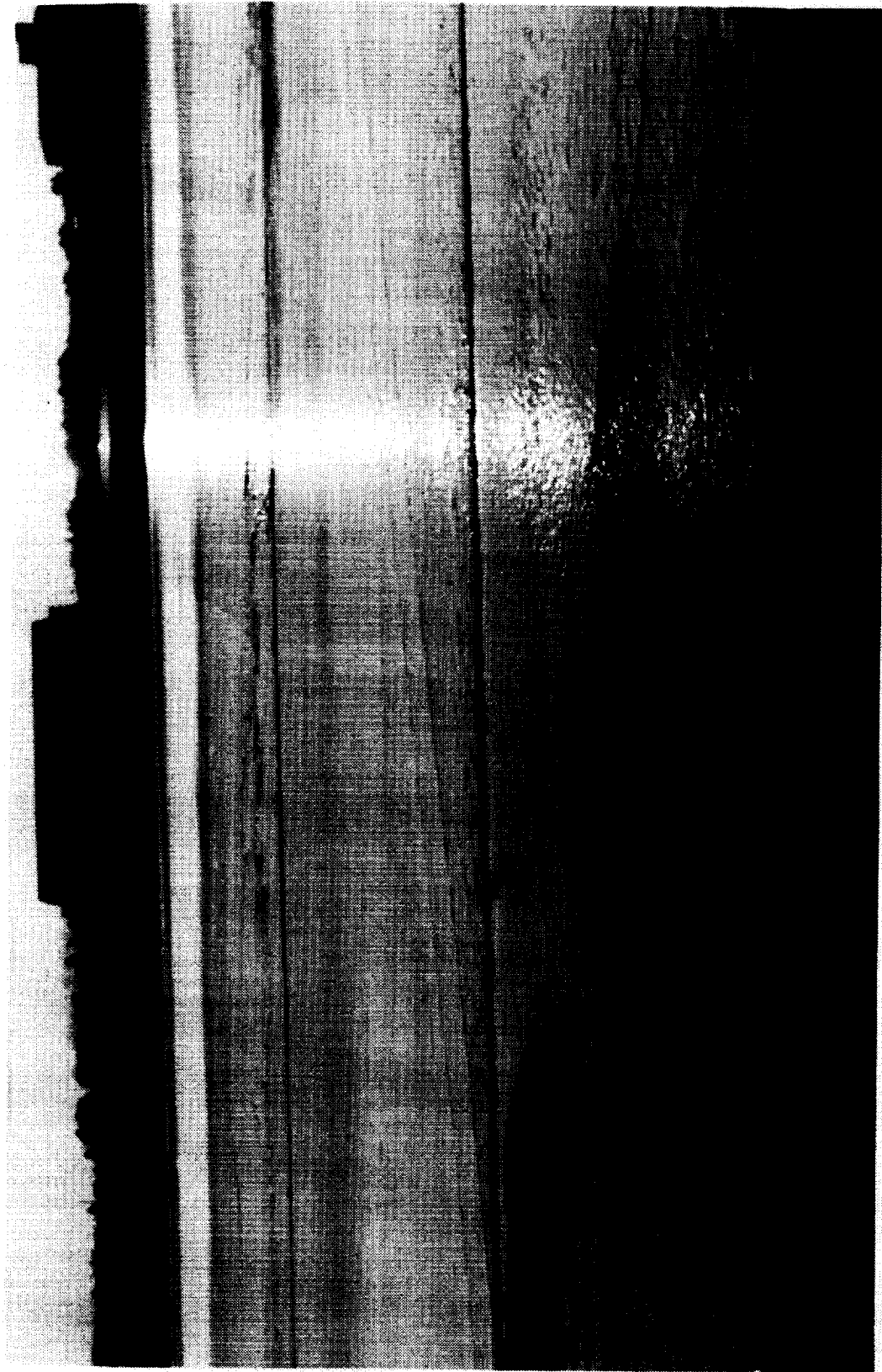
(a) Aerial view showing runway layout.

Figure 1.- Winter runway test site and conditions at Brunswick Naval Air Station, Maine.



(b) Compacted snow-covered runway test condition.

Figure 1.- Continued.



(c) Ice-covered runway test condition.

Figure 1. - Concluded.

Compacted snow- or ice-covered surface condition

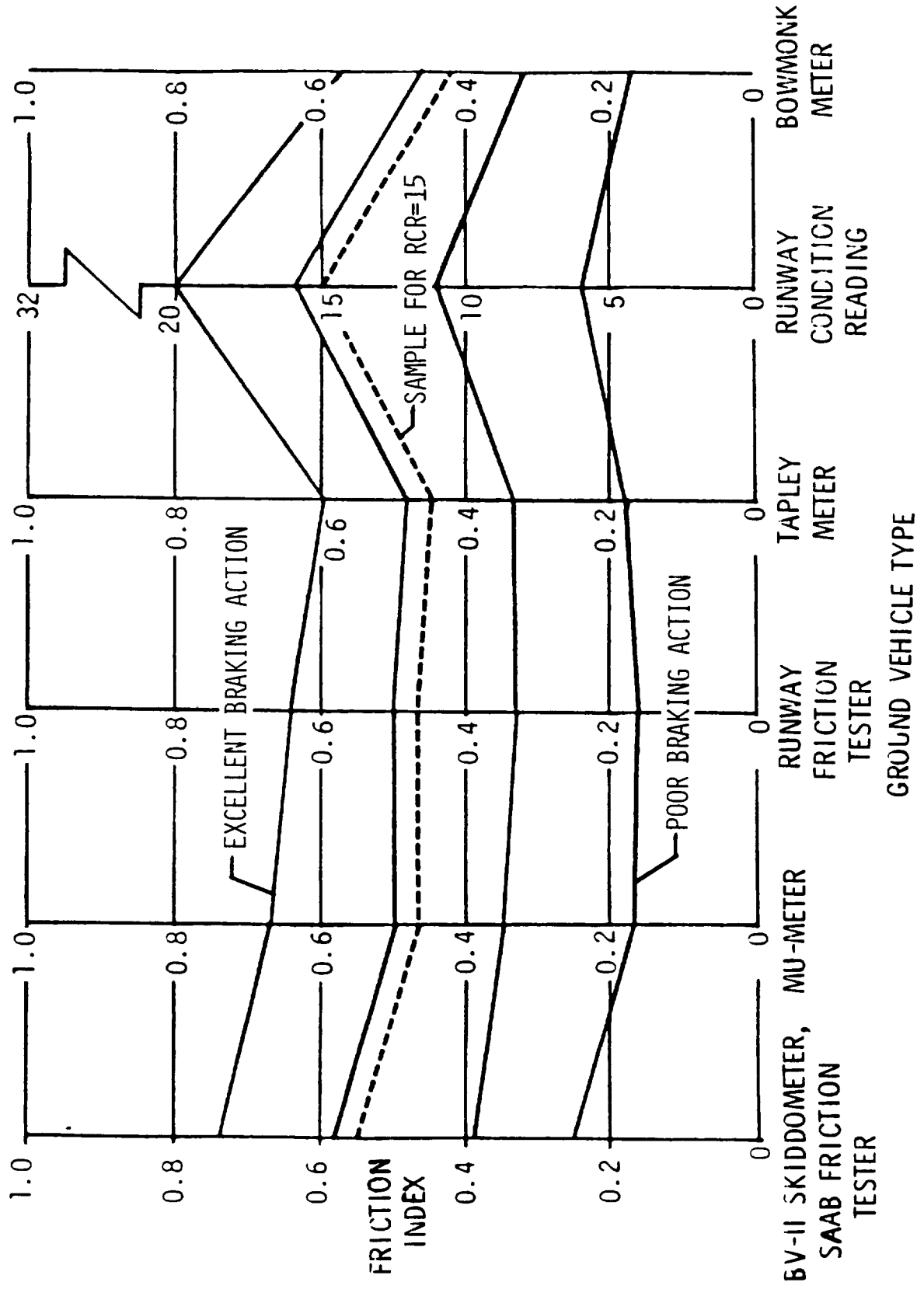


Figure 2.- Ground vehicle friction correlation chart.

BRUNSWICK NAS, ME.; WINTER RUNWAY CONDITIONS

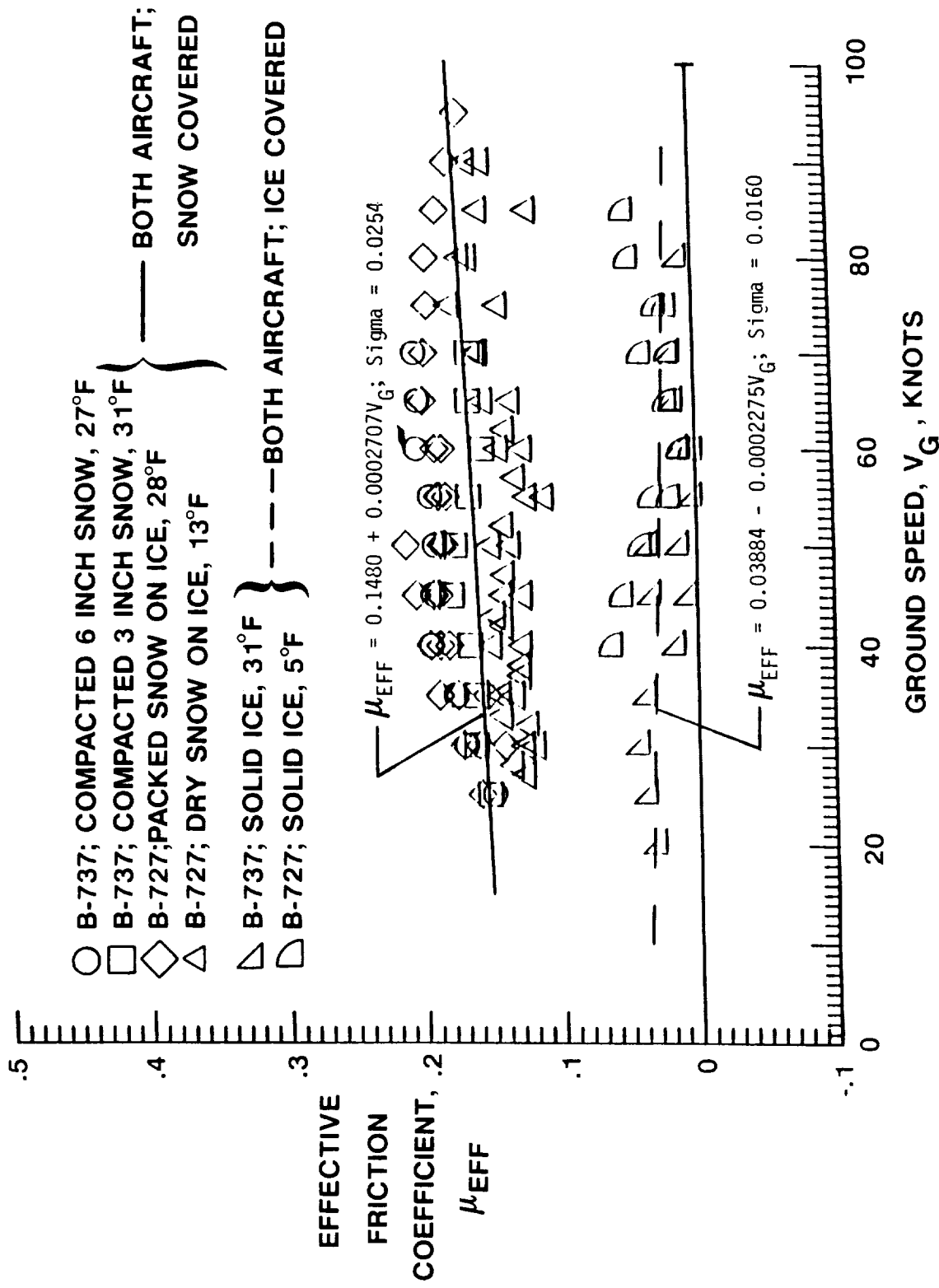


Figure 3.- Comparison of test aircraft tire effective friction coefficient variation with ground speed for compacted snow- and ice-covered runway surface conditions.

COMPACTED SNOW- OR ICE-COVERED CONDITIONS

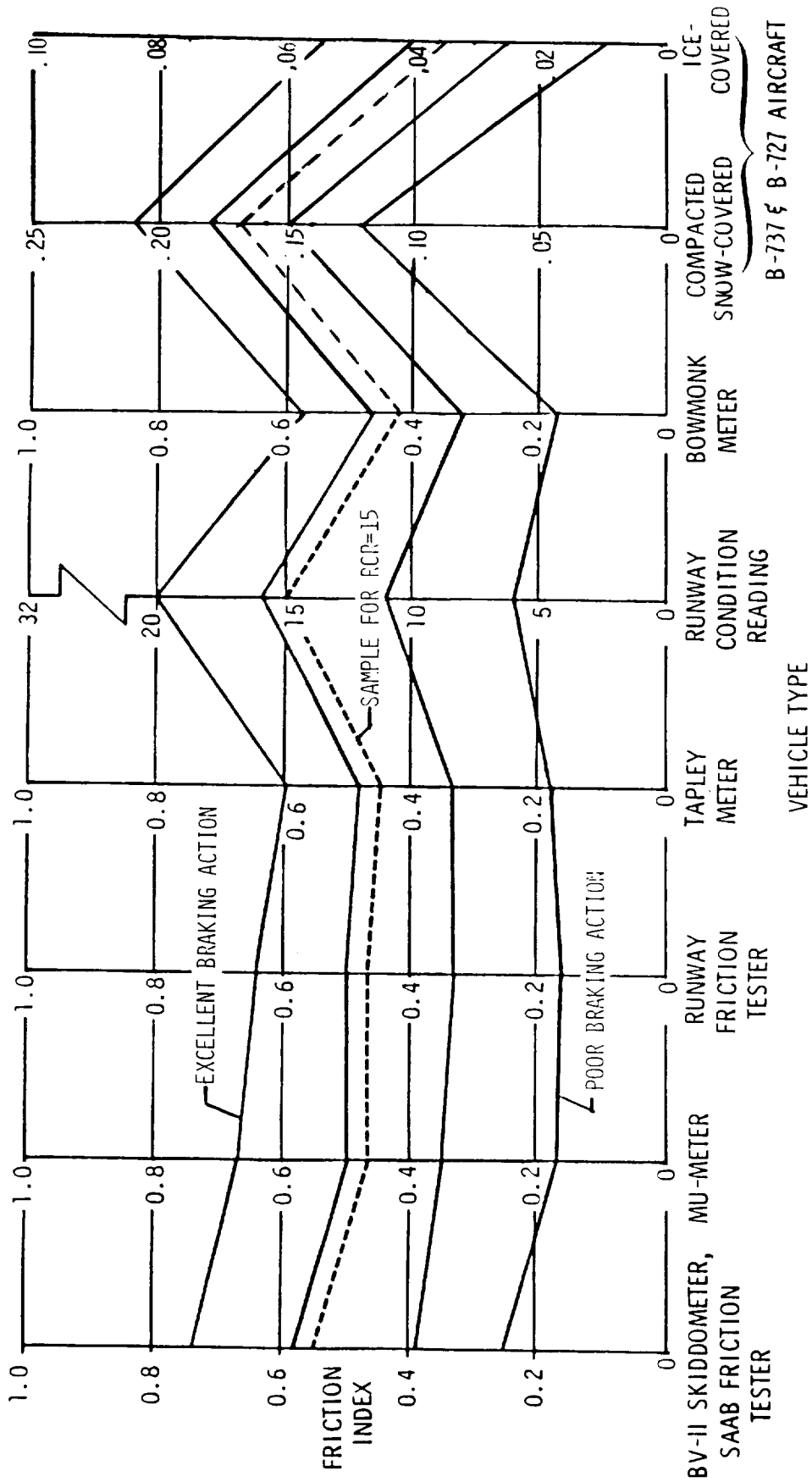


Figure 4.- Aircraft and ground vehicle friction correlation chart.

BRUNSWICK NAS, ME.; WINTER RUNWAY CONDITIONS

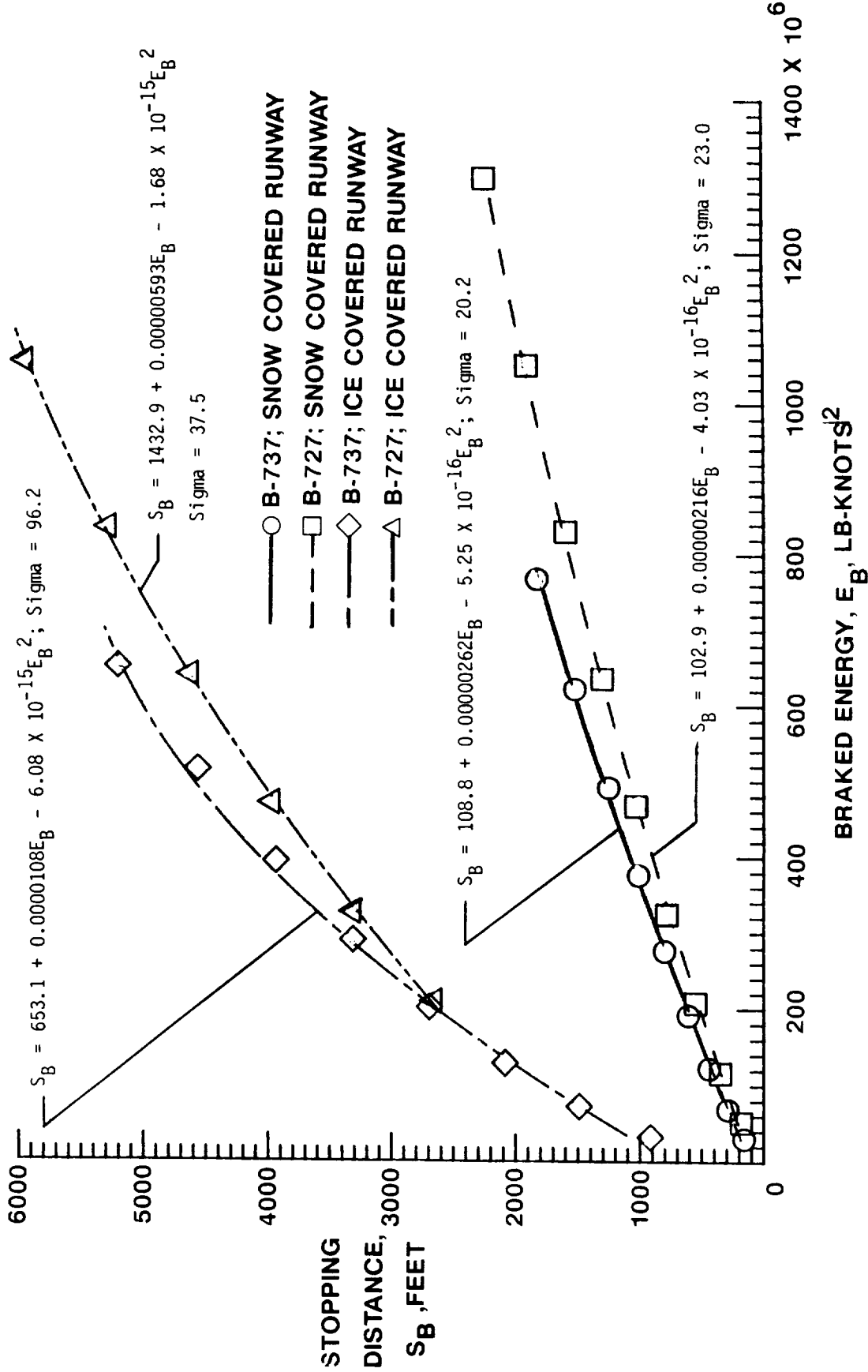


Figure 5.- Variation in aircraft stopping distance with braked energy for compacted snow- and ice-covered runway surfaces.



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