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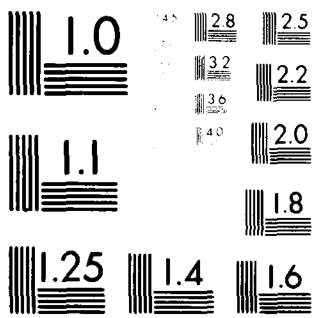

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Special Report 80-32

August 1980

LEVEL II

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CHARACTERISTICS OF ICE IN WHITEFISH BAY AND ST. MARYS RIVER DURING JANUARY, FEBRUARY AND MARCH 1979

George P. Vance

Prepared for
RESEARCH AND DEVELOPMENT CENTER
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This report presents data on the full-scale trials of the U.S. Coast Guard Icebreaker Katmai Bay, which was tested in plate ice that varied in thickness from 10 to 33 in. (25.4 to 83.82 cm) and had a snow cover of 1 to 6 in. (2.54 to 15.24 cm). In January the average temperature was -5 C, and the ice flexural strength was 13,363 lb/ft^2 (640 kPa). In March the average temperature was -2 C and the ice flexural strength was 11,643 lb/ft^2 (560 kPa). The specific weight (density) of the ice was 0.894 g/cm^3. The specific weight of the snow was in the area of 0.32 g/cm^3. The coefficient of friction between

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20. Abstract (cont.)

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the ice/snow and steel plate (coated and uncoated) varied from a low of 0.02 in the dynamic case of ice on the Inerta 160 coating to 0.47 for the static case of snow on a rusty steel plate.

Preface

This report was prepared by Dr. George P. Vance, Research Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The research was accomplished in conjunction with the full-scale trial of the new Coast Guard Great Lakes icebreaker, Katmai Bay (WTGB-201), under Coast Guard MIPR No. Z70099-9-91769-9B.

The manuscript of this report was technically reviewed by Guenther Frankenstein and Stephen DenHartog of CRREL.

Special appreciation and acknowledgement is extended to James Sirois and Stephen DenHartog of CRREL and Ernest Presher and Craig Mayer of the Coast Guard R&D Center for their invaluable assistance in collecting the data presented in this report.

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CHARACTERISTICS OF ICE IN WHITEFISH BAY AND ST. MARYS RIVER DURING JANUARY, FEBRUARY AND MARCH 1979

by

George P. Vance

Introduction

Presented in this report are the environmental data collected as part of the full-scale trials of the new U.S. Coast Guard Great Lakes Icebreaker Katmai Bay (WTGB-101). These data were collected in an effort to document the performance of the new icebreaker under various ice conditions. The tests were carried out between 20 January and 15 March 1979 in Whitefish Bay and the St. Marys River in northern Michigan.

The Katmai Bay is an ice-breaking tug that is 140 ft (42.6 m) long, with a 37.54 ft (11.4 m) beam and a draft of 12 ft (3.6 m). The vessel is powered by a 92,500-hp diesel engine and is outfitted with an air bubbler lubricating system.

The vessel was tested in various thicknesses of sheet ice with snow cover and in various thicknesses and concentrations of brash ice (Table 1). Thickness and temperature profiles were obtained and the mechanical properties of the ice were inferred from these profiles. Limited salinity and density profiles were also obtained to verify these particular properties of the ice cover. Friction tests were conducted to determine the coefficient of friction between the ice and a steel plate (coated and uncoated) under various conditions.

Ice Thickness Profiles

The plate ice thickness was determined by drilling through the ice with a 1.5-in. ice auger and lowering a thickness tape measure into the hole and pulling up on the tape until the T-bar held rigidly to the bottom of the ice sheet. The snow thickness was measured by inserting a steel rule into the snow cover.

At several sites during the early stages of the test program, an impulse radar was utilized to determine the continuous profile of the ice sheet and the brash thickness. In all cases, the radar readings were within ± 2 in. of the physical measurements.

In addition to the limited radar measurements, the brash ice thickness was determined by poking through three or four places in the brash and dropping the thickness tape through the hole and carefully withdrawing the tape until the T-bar held rigidly. The procedure was repeated several times at each hole.

Table 1. Daily summaries of tests conducted and weather conditions.

Tuesday, 30 January 1979

Conducted continuous icebreaking tests in 12-15 in. of plate ice with 2-3 in. of snow cover without the bubbler system. Measured surface roughness of vessel hull. Conducted brash ice tests in shipping channel with no measurement of brash thickness. Obtained salinity, temperature and density data. Weather was overcast with an average temperature of 20°F and a 5 to 8-knot wind from 350° true north (T) (Hourly weather summaries are contained in Internal Report 628).

Wednesday, 31 January 1979

Conducted continuous icebreaking tests in 13-20 in. of plate ice with and without the bubbler system. Obtained thickness and temperature profiles. Conducted tests in brash ice in the shipping channel. Utilized the impulse radar to determine thickness profiles in plate ice. Weather was overcast with an average temperature of 14°F and a 15-knot wind from 350° T. Draft of the vessel taken in the ice was 10 ft 6 in. forward and 12 ft 6 in. aft.

Thursday, 1 February 1979

Conducted brash ice tests in the shipping channel with and without the bubbler system. The impulse radar was utilized to obtain brash thickness in the channel. Attempted ramming tests in pressure ridges; however, the ridges were not consolidated enough or strong enough to stop the vessel. Weather was partly cloudy with average temperatures of 12°F and a 12- to 14-knot wind blowing from 330°T.

Friday, 2 February, to Sunday, 4 February 1979

Conducted no tests, ship was in operational status.

Monday, 5 February 1979

Held demonstrations for Coast Guard representatives. Drafts read at the dock were 10 ft 6 in. forward and 12 ft 2 in. aft, and at the Poe Locks the drafts were 11 ft 10 in. forward and 12 ft 7 in. aft.

Tuesday, 6 February 1979

Left dock on operational mission in White Fish Bay. Conducted test in brash ice in ship channel; however, no thickness of brash was obtained. Conducted ad-hoc ramming tests in heavy ice enroute to USS Munson. Weather was overcast with an average temperature of 10°F with some snow and a wind of 16 knots from 130°T.

Table 1 (con't)

Wednesday, 7 February 1979

Continued operational tasks; no tests conducted.

Thursday, 8 February 1979

Conducted brash ice tests in St. Marys River in area of Stribbley Point with and without bubbler system. Brash was documented to be 2-4 ft thick. Weather was clear with average temperature of 7°F with a wind of 10-14 knots from 040°T.

Friday, 9 February 1979

Conducted comparison tests with 110-ft icebreaking tug in 14 in. of ice with 5 in. of snow cover. The Katmai Bay progressed at about 6 knots and gained approximately 2.3 miles in 10 minutes on the 110-ft icebreaking tug. Conducted continuous tests in approximately 10 in. of ice with 2 in. of snow cover. Ice was under heavy pressure from the prevailing wind. Hull roughness measurements were made. The weather was clear with an average temperature of -10°F and a wind of 8-14 knots from 130°T.

Saturday, 10 February 1979

Conducted brash tests in St. Marys River in approximately 4 ft of brash ice with and without bubbler system. Conducted continuous tests in 27 in. of plate ice with 12 in. of snow cover in anchorage area. Plate ice had incipient cracks due to vessel traffic and thermal effluent. Conducted friction tests on ice and steel plates coated or not coated with Inerta 160. Weather was clear and bright with average temperature of 0°F and a wind of 6 knots from 270°T.

Monday, 12 February 1979

Conducted friction tests on ice. Weather clear and bright similar to Saturday, 10 February. Testing for Phase I completed.

Tuesday, 13 March 1979

Conducted tests in brash ice in St. Marys River with and without bubbler system. Very good documentation of brash thickness. Weather was clear with average temperature rather high at 40°F and an 8-knot wind from 130°T.

Wednesday, 14 March 1979

Started to conduct turning tests in brash when a steering casualty was experienced requiring two days of repair work.

Table 1 (Con't)

Thursday, 15 March 1979

Conducted friction tests on uncoated steel plate at the dock. The weather was clear and sunny with average temperature of 17°F and a wind of 8 knots from 290°T.

Friday, 16 March 1979

Conducted friction tests at dock side with steel plate coated with Inerta 160. Weather was clear and bright with average temperature of 40°F with a 4-knot wind from 195°T.

Saturday, 17 March 1979

Conducted ramming tests in Whitefish Bay in plate ice 22-30 in. thick with 3-4 in. of snow cover. Roughness data on the ship's hull was obtained for the final phase of the tests. The weather was clear with an average temperature of 42°F and a wind of 8-12-knots from 150°T.

Thickness profiles are presented in Appendix Figures A1-A12. The thickness between data points may not be exactly as depicted in the profiles but will lie between the maximum and minimum shown for the particular run. The specific data for each run will be found in Internal Report 628.

Snow cover thickness varied greatly due to the wind effect on the snow cover.

The brash ice thickness was a function of the frequency of ship passage, location and time. The variations in brash ice thickness were much greater than those of the plate ice.

Temperature Profiles

Temperature profiles (Fig. A13-A17) were taken in all the plate ice in which the vessel was tested. Profiles were also taken in the plate ice adjacent to the channels in which the brash ice tests were conducted.

The temperature profiles were obtained by drilling into the ice with a 1.5-in. drill and inserting a thermistor (which read out directly on a bridge calibrated in degrees Celsius) in the hole until it made contact with the ice surface. Extreme care was taken to ensure that all snow and loose ice chips were removed from the hole when the temperature measurements were taken.

Ice temperatures during the early phase of the tests, i.e. January and February 1979, were much lower (-5° to -10°C) than those measured during the March test (i.e. 0° to -3°C). In fact, some of the ice temperatures during March were so close to 0°C that it was difficult to observe any reading on the thermistor bridge.

Mechanical Properties

The mechanical properties of freshwater plate ice will vary with temperature and growth history as well as testing procedures. In addition, in-situ determination of such properties requires an extensive amount of time; therefore, only temperature profiles were taken at various data sites. The mechanical properties of the ice can then be inferred from these profiles.

The enclosed graphs (Fig. A18-A21) summarize the results of the efforts of many researchers (Butyagin 1972, Frankenstein 1961, Gow et al. 1978, Hawkes and Mellor 1972, and Lavrov 1969) over many years. The standard deviation indicates the diversity of test results due to different test conditions and techniques. In addition, the results are not as linear as indicated in these summary curves, particularly as the melting point is approached.

There are two curves (Fig. A20 and A21) presented for the elastic modulus E of freshwater ice. The higher values of E are obtained using acoustic techniques and represent the ideal or linear portion of the stress-strain curve. The lower curve labeled E_{str} is referred to as a strain modulus and is determined by field and laboratory work in beam bending and sheet deflection. It represents the portion of the stress strain curve that incorporates elastic and plastic deformation.

The values presented in this section were obtained from the references given in the Selected Bibliography.

Density and Salinity Measurements

Snow density measurements were made using the CRREL snow density kit.

Ice density was determined by withdrawing an ice core approximately 2 in. in diameter and carefully measuring the length and diameter of a section of the core and carefully weighing the sample. The weight per unit volume was determined.

Due to the excessive effort involved in making such measurements, their relative inaccuracy, and the limited effect of density on the overall program, only one set of density measurements was made.

Salinity was determined by melting sections of a 3-in. ice core and measuring the residual salinity with a Beckman field salinometer. As expected, the salinity was essentially zero.

Snow density (specific weight) varied between 0.32 and 0.36 g/cm^3 and the ice density (specific weight) was found to be 0.898.

Table 2. Friction coefficients

Dynamic	February 1979	March 1979
Inerta-ice with screw jack	0.020	0.015
Inerta-ice with winch	0.045	0.030
Inerta-water with screw jack	0.060	-
Inerta-snow with screw jack	0.145	0.115
Inerta-snow with winch	-	0.085
Steel plate-ice with screw jack	0.050	0.150
Steel plate-ice with winch	0.071	0.100
Steel plate-water with screw jack	0.100	-
Steel plate-snow with screw jack	0.165	0.165
Steel plate-snow with winch	-	0.170
Static		
Inerta-ice with screw jack	0.037	0.085
Inerta-ice with winch	0.080	0.185
Inerta-water with screw jack	0.135	-
Inerta-snow with screw jack	0.200	0.240
Inerta-snow with winch	-	0.250
Steel plate-ice with screw jack	0.080	0.215
Steel plate-ice with winch	0.201	0.310
Steel plate-water with screw jack	0.120	-
Steel plate-snow with screw jack	0.480	0.250
Steel plate-snow with winch	-	0.410

Friction Measurements

One of the most difficult parameters to measure precisely is the coefficient of friction between the ice and snow and the ship hull. Due to the extreme difficulty of measuring the coefficient of friction on the hull itself, the friction was measured between the ice and snow and a metal plating similar to that of the ship. Friction tests were conducted on several different occasions and the results, using different instrumentation and different locations, are fairly consistent (Table 2).

An attempt was made to vary the conditions of the test in as many ways as possible. These variations included two speeds (0.31 and 0.132 knots), two different surfaces (Inerta 160* coating and uncoated steel), several intensities of loadings, and several environmental conditions (i.e. ice and plate, snow and plate, water and plate).

Difficulty was encountered due to the lack of control of the ambient environment. When the sun was bright, the plates absorbed solar radiation, and as the loading increased, a meltwater lubricating layer formed between the ice and plate. During the tests where the sun was not as bright, i.e. cloudy days or late afternoon tests, the water layer would freeze in a nonhomogeneous fashion. These difficulties led to some inconsistencies in the results; however, a distinct and logical trend can be determined from the Figures A38-A42. The only significant inconsistency was in the relative low results of Inerta 160 and snow when utilizing the higher speed winch.

The two towing speeds utilized were 0.31 knots (0.52 ft/sec) and 0.132 knots (0.225 ft/sec), and the trend indicates an increase in friction coefficient with speed except for the Inerta-snow-winch combination.

The friction tests were conducted by loading a 1-ft^3 ice block with 25-lb lead weights such that the normal load could be varied from the weight of the ice block and towing cage to approximately 500 lb. The towing speed was varied by either pulling the block and weights with a small winch or a screw jack. The winch, being a more elastic system, experienced stick-slip phenomena, which made it slightly more difficult to determine a mean value. The jack provided a smoother pulling force but its speed (0.225 ft/sec) was less than half that of the winch (0.52 ft/sec).

The normal force was determined by weighing the ice block, towing harness and weights. The tangential force was obtained with a load cell positioned between the towing harness and the winch cable or jack screw. The tangential force was recorded on a Hewlett-Packard recorder. Typical recorder records are shown in Figures A22 and A23. A summary of all friction tests records is contained in Internal Report 628.

The roughness of the plates utilized is delineated in Figures A24-A26. The roughness was determined using a Surtronic 3 surface profilometer, with three readings at each point being averaged.

Conclusions

This report presents the ice conditions and characteristics encountered during the full-scale trials of the Katmai Bay. It can be seen from the data presented that the ice thickness of the plate ice in Whitefish Bay was very consistent throughout any particular series of tests. The brash ice thickness, on the other hand, had wide variations from one end of the test area to the other and the coagulation

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* Inerta 160 is a non-solvented epoxy compound distributed by International Paints and used for low friction hull coating.

of the brash also varied from test to test. Thus, it can be expected that the brash ice test results have a wider range of uncertainty.

The temperature profiles for the tests indicate the ice was at its coldest in January and February and therefore at its strongest. In March the temperature of the ice began to rise and approached the melting point, leading to weaker ice. This increase in temperature resulted in an estimated 20-25% decrease in ice strength based on data provided in the literature.

The E_{str}/σ_f ratio varied between 6250 and 7250, increasing as the temperature increased. The density of the ice and snow and salinity of the ice was in the range expected.

One of the more extensive areas of the tests was the determination of the friction coefficient between the ice and ship. The series of tests conducted indicates that the coefficient of dynamic friction between ice and Inerta 160 varies from 0.015 to 0.020, and between snow and Inerta 160 from 0.115 to 0.145. The dynamic friction coefficient between ice and steel was about 0.05 and between steel and snow was approximately 0.165. There was a trend indicating an increase in the friction coefficient with an increase in speed. In general, a decrease in the coefficient of friction tended to coincide with an increase in the density of loading until about 500 psf, where it asymptotically approached the values shown in Table 2.

The static coefficient of friction was some two to five times higher than the dynamic coefficient, varying from 0.037 to 0.48.

It is difficult to state a specific coefficient of friction to apply to the vessel. The exact ice condition and lubrication factors varied greatly during the test; however, one could suggest the following values for the dynamic friction coefficient based on observations and the tests conducted:

Smooth hull (Inerta 160) well-lubricated	0.05
Smooth hull (Inerta 160) not well-lubricated (snow)	0.10
Rough hull (old steel) well-lubricated	0.125 to 0.150
Rough hull (old steel) not well-lubricated (snow)	0.175 to 0.200

Recommendations

Although the ice properties were well-documented, several improvements could be made in test procedures and test techniques. It would be more expeditious if ice thickness could be determined in real time, using a remote sensing device such as the impulse radar under development at CRREL. The few times that the radar was used during the tests provided continuous ice thickness measurements that were verified by actual measurements. However, use of the radar in its present configuration is too time-consuming. An instrument and/or technique should be developed to determine the thickness and coagulation of the brash ice in a more reliable and expeditious manner.

A device and/or instrumentation should be developed to determine the coefficient of friction between the vessel itself and the ice environment. As this may be difficult or impossible to do, an alternative would be to develop a technique of correlating roughness (which is relatively easy to measure on the vessel) and the coefficient of friction.

It would be very useful to conduct friction tests under controlled laboratory conditions that are similar to those conducted in the field in order to explain or eliminate the inconsistencies evidenced in the friction data collected on-site. It is recommended that these tests be carried out in the near future in order to validate the field test results presented here.

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APPENDIX A: ICE THICKNESS PROFILES, TEMPERATURE PROFILES, PLOTS OF FRESHWATER ICE PROPERTIES, AND FRICTION TEST RESULTS

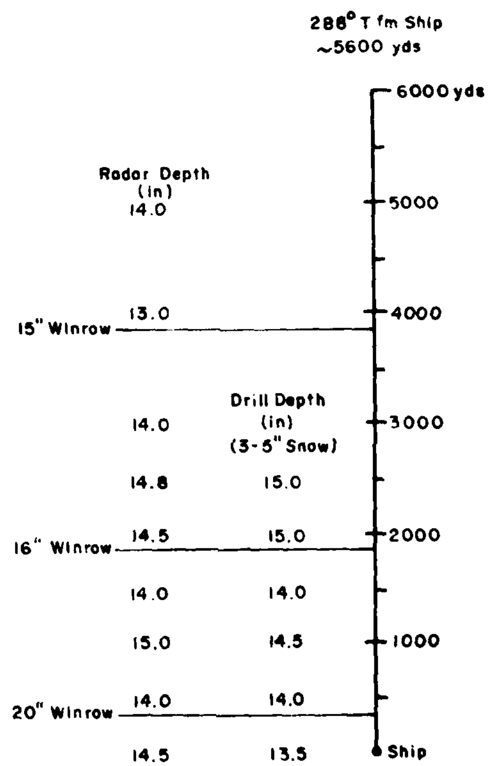


Figure A1. Run 1 radar comparison, 31 January 79.

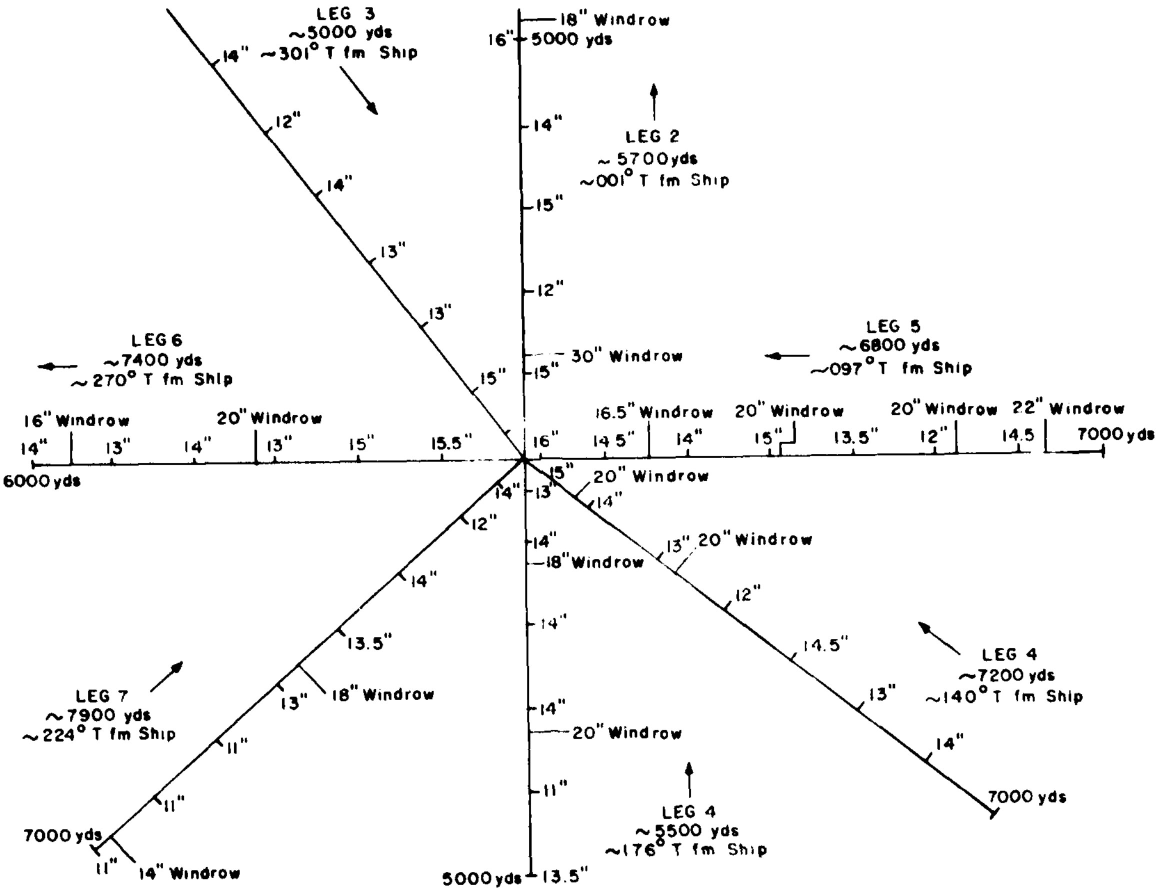


Figure A2. Radar sector survey, 31 January 1979.

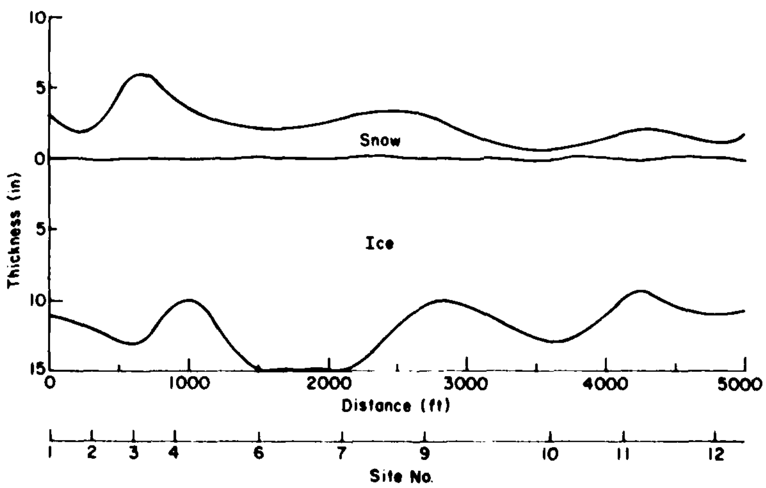


Figure A3. Snow thickness profiles, 30 January 1979.

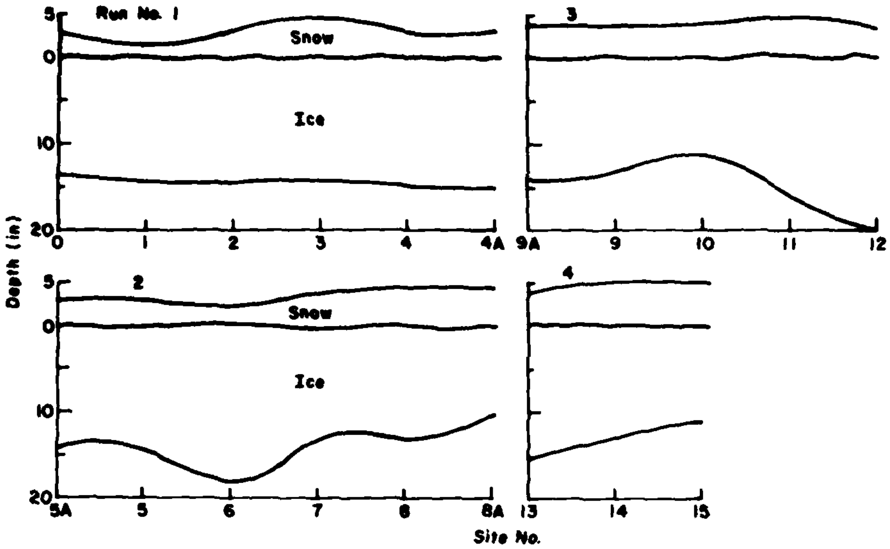


Figure A4. Ice and snow thickness, runs 1-4, 31 January 1979.

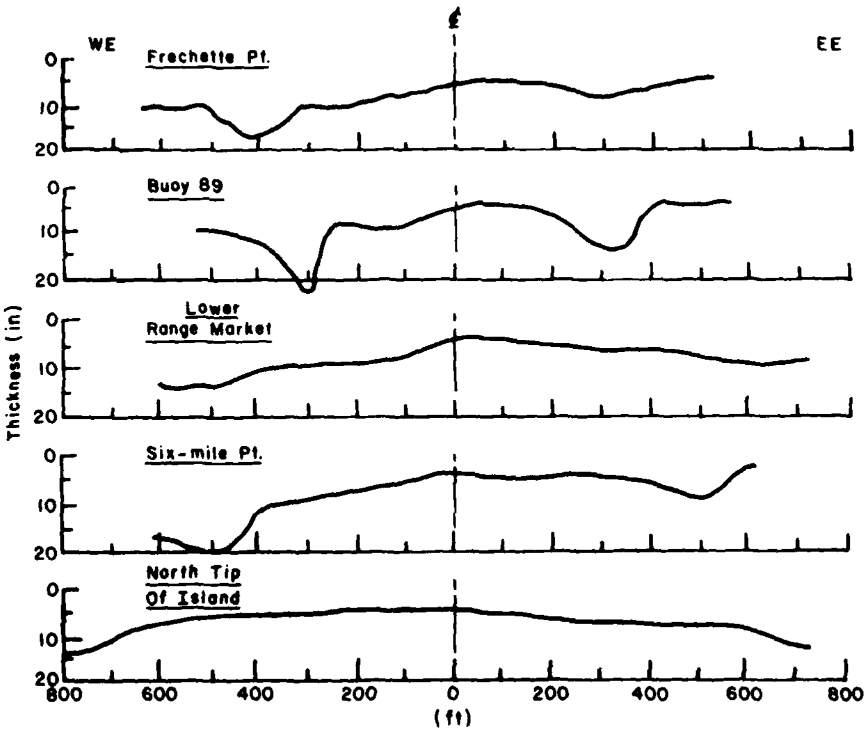


Figure A5. Brash ice in St. Marys River, 31 January 1979.

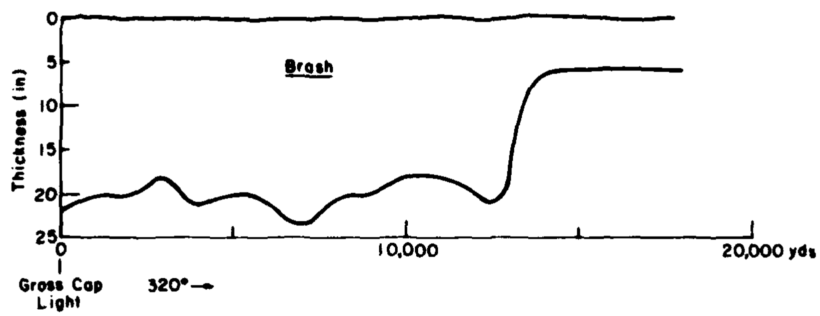


Figure A6. Brash ice thickness, 1 February 1979.

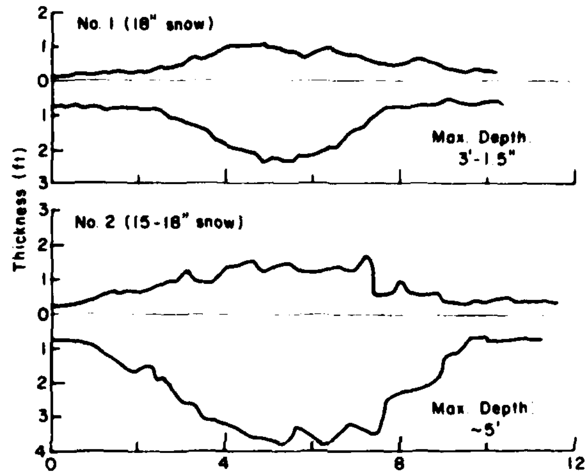


Figure A7. Pressure ridges in Whitefish Bay, 1 February 1979.

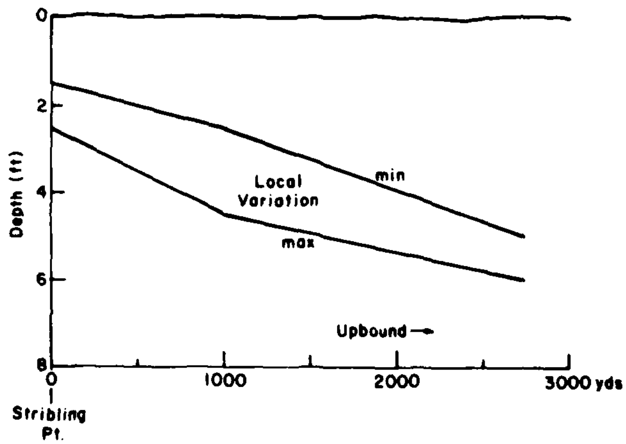


Figure A8. Brash ice thickness, 8 February 1979.

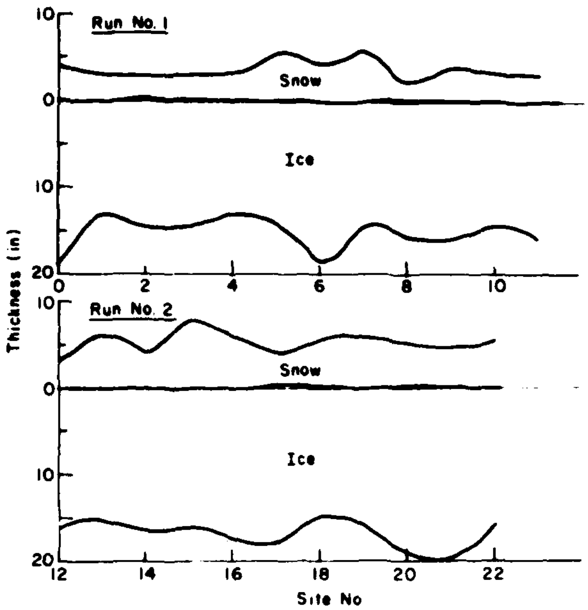


Figure A9. Ice and snow thickness, 9 February 1979.

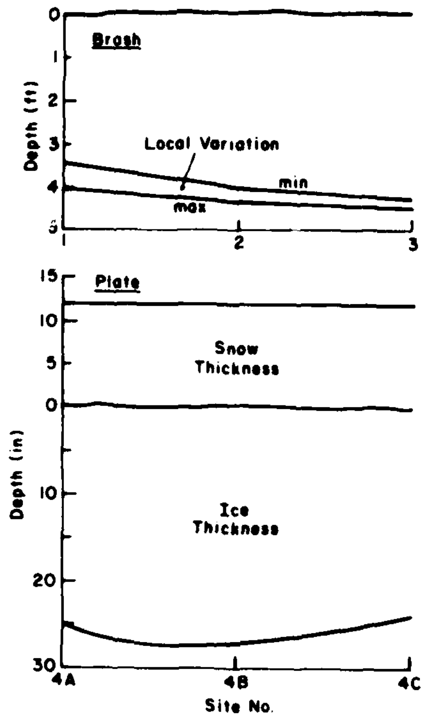


Figure A10. Brash and plate ice thickness, St. Marys River, 10 February 1979.

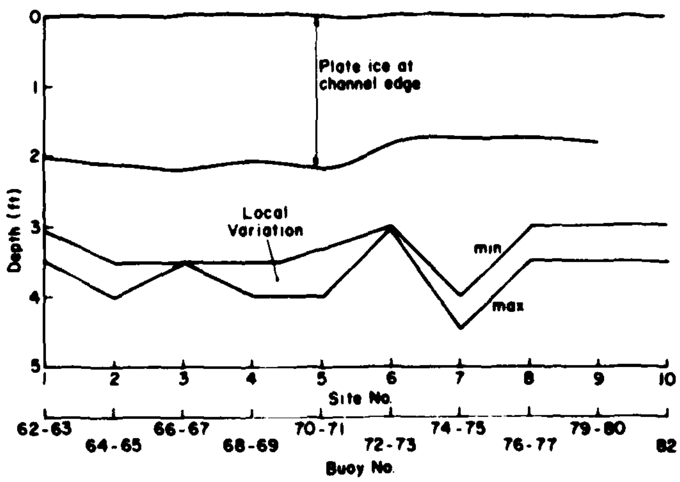


Figure A11. Brash ice thickness, 8 February 1979.

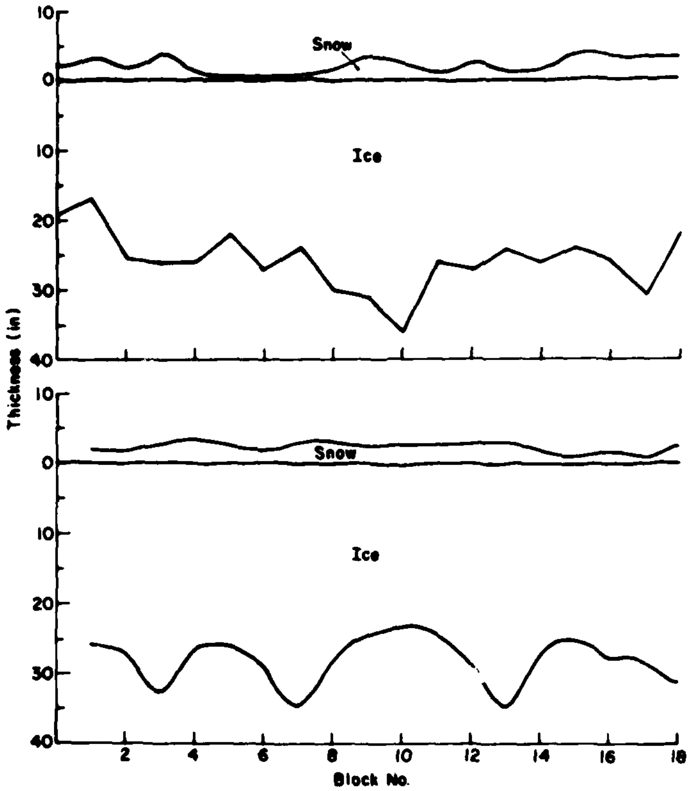


Figure A12. Ice and snow thickness for two runs, 9 February 1979.

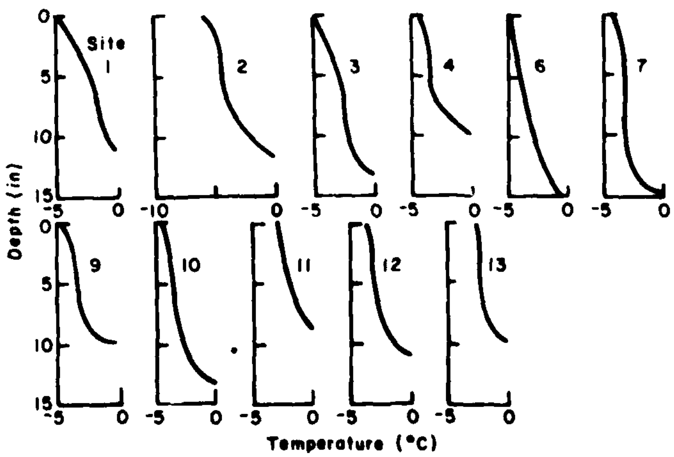


Figure A13. Temperature profiles for Whitefish Bay, 30 January 1979.

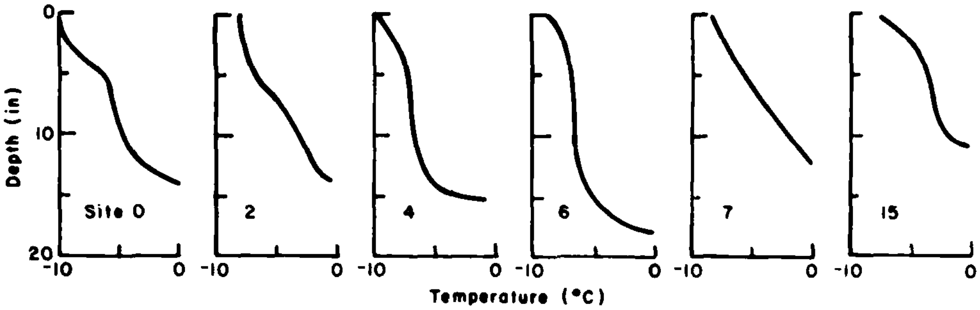


Figure A14. Temperature profiles for Whitefish Bay, 31 January 1979.

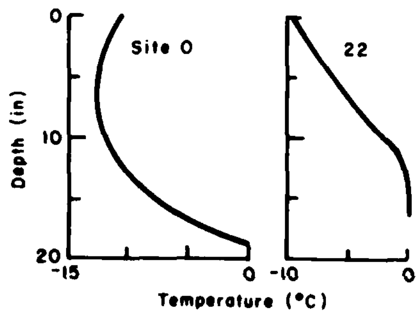


Figure A15. Temperature profiles for Whitefish Bay, 9 February 1979.

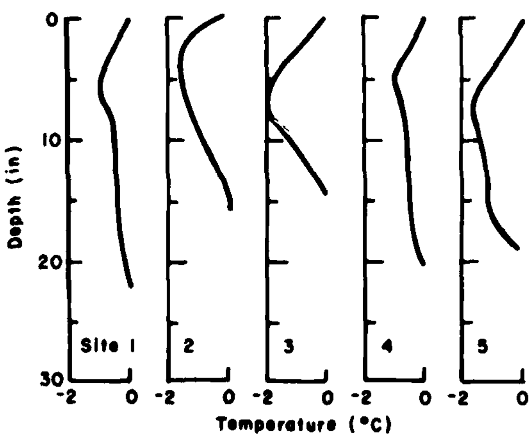


Figure A16. Temperature profiles for plate ice at edge of channel in St. Marys River, 13 March 1979.

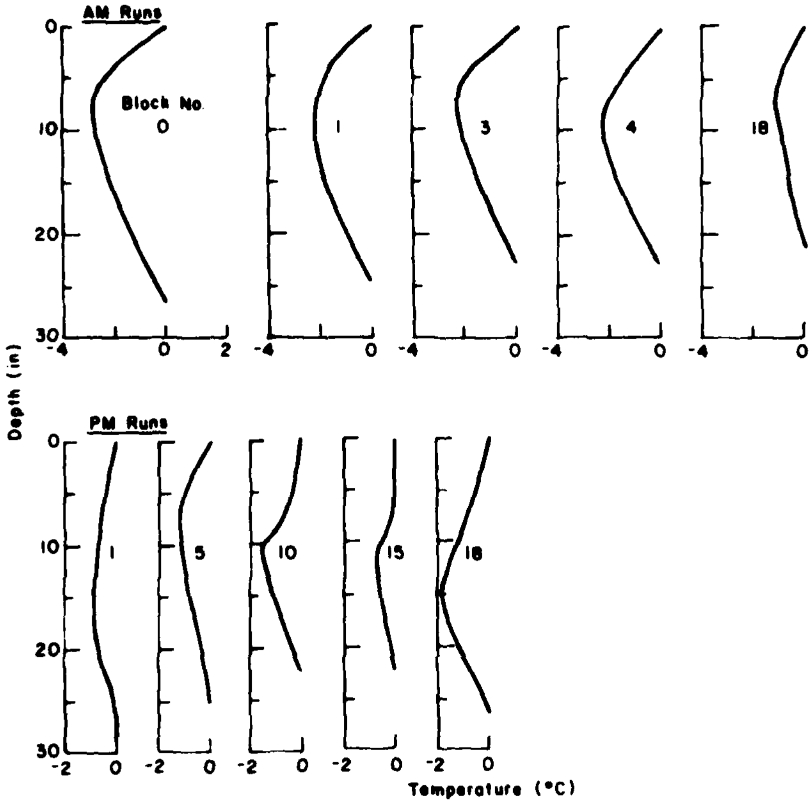


Figure A17. Temperature profiles for AM and PM runs in Whitefish Bay, 17 March 1979.

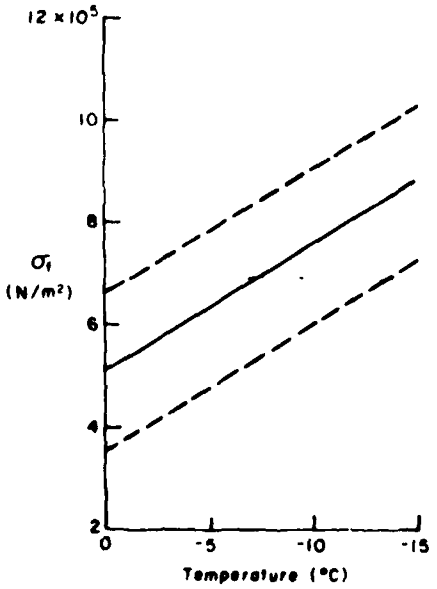


Figure A18. Freshwater ice flexural strength vs temperature.

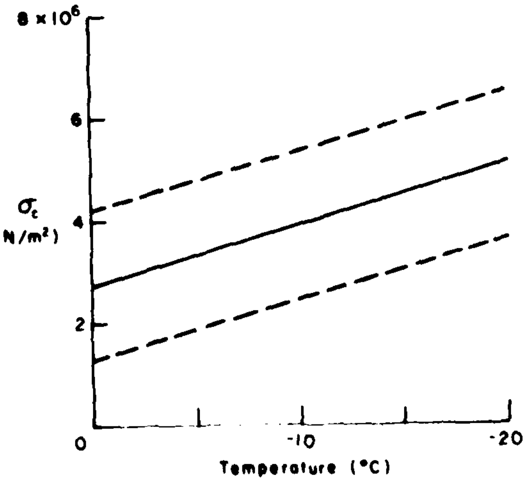


Figure A19. Freshwater ice compressive strength vs temperature.

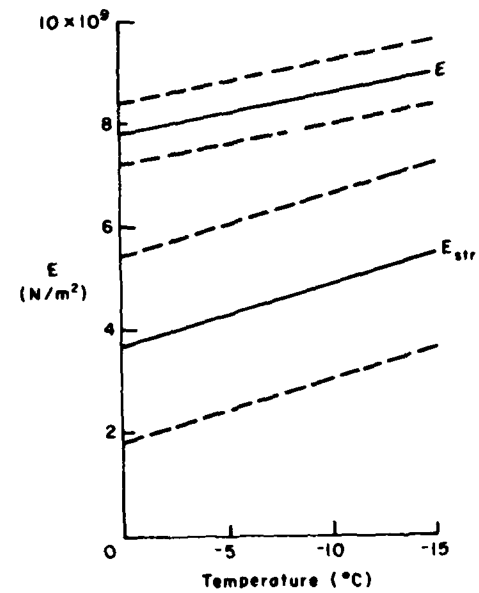


Figure A20. Freshwater ice dynamic and strain modulus of elasticity vs temperature.

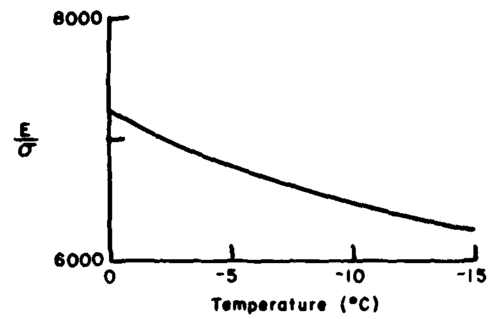


Figure A21. E/σ vs temperature.

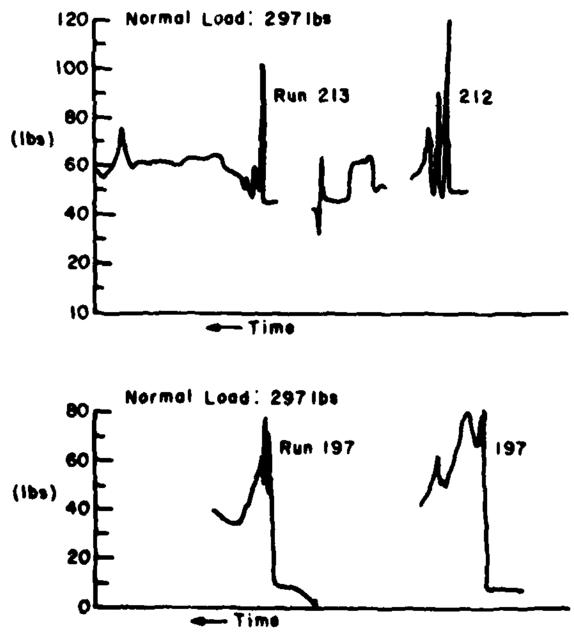


Figure A22. Typical records of ice-steel friction force for four runs.

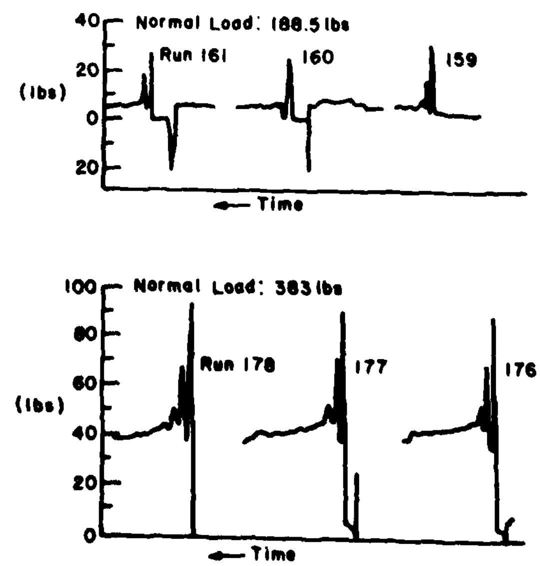
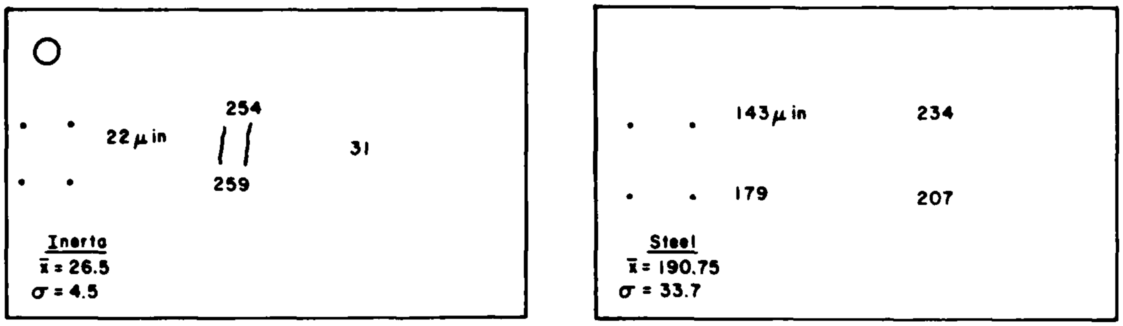


Figure A23. Typical records of Inerta-snow friction force for six runs.



a. Inerta-coated plate, 10 February 1979.

b. Uncoated steel plate, 12 February 1979.

Figure A24. Roughness measurements.

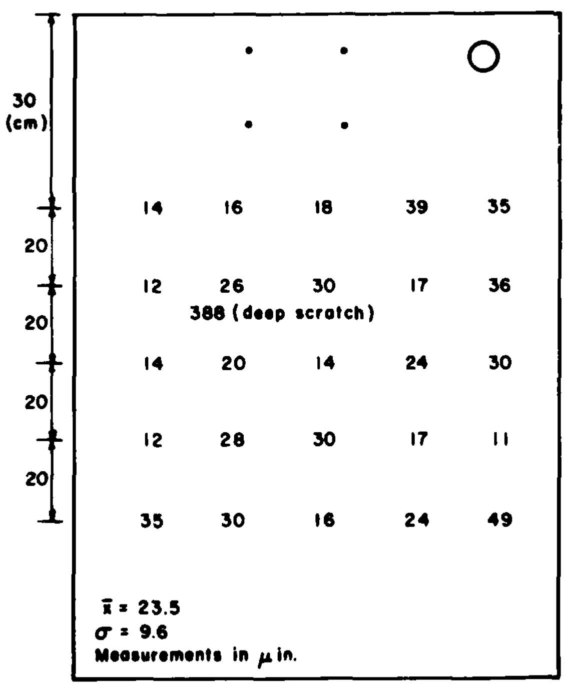


Figure A25. Roughness measurements on Inerta plate, 16 March 1979.

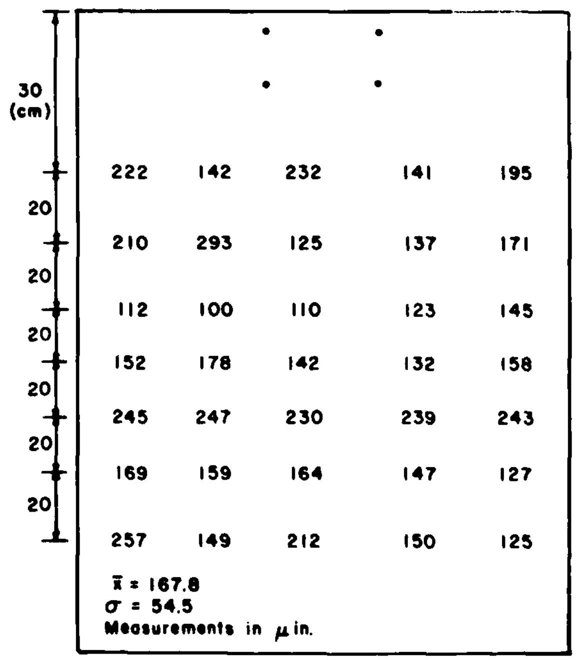


Figure A26. Roughness measurements on steel plate, 15 March 1979.

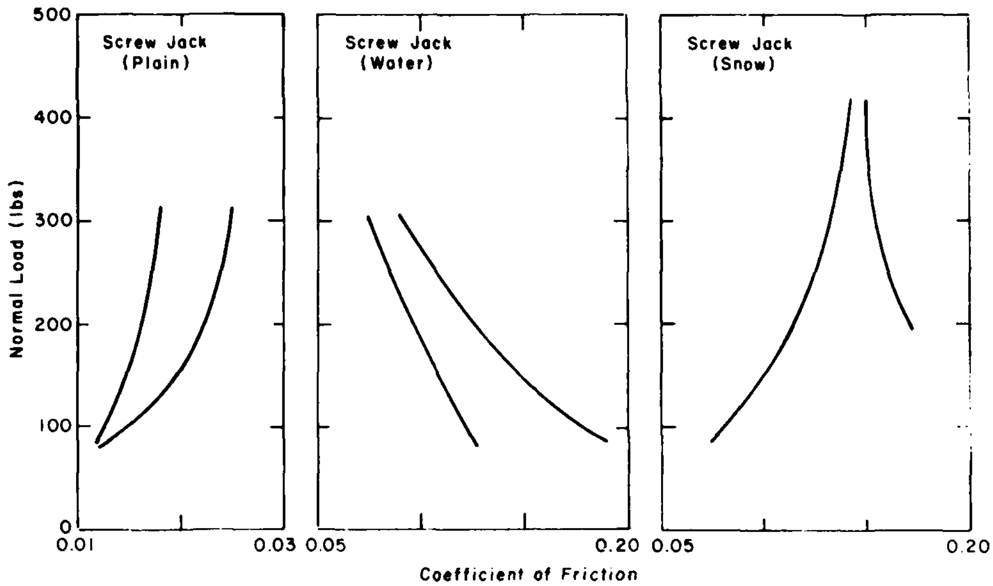


Figure A27. Dynamic coefficient of friction vs normal load for Inerta 160, 12 February 1979.

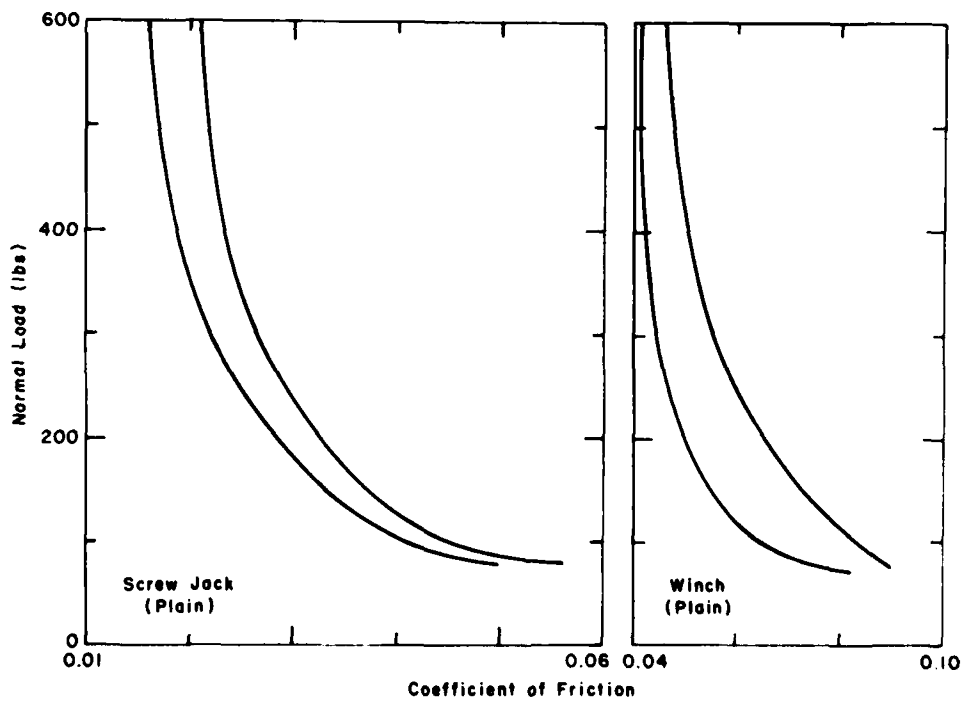


Figure A28. Dynamic coefficient of friction vs normal load for Inerta 160, 10 February 1979.

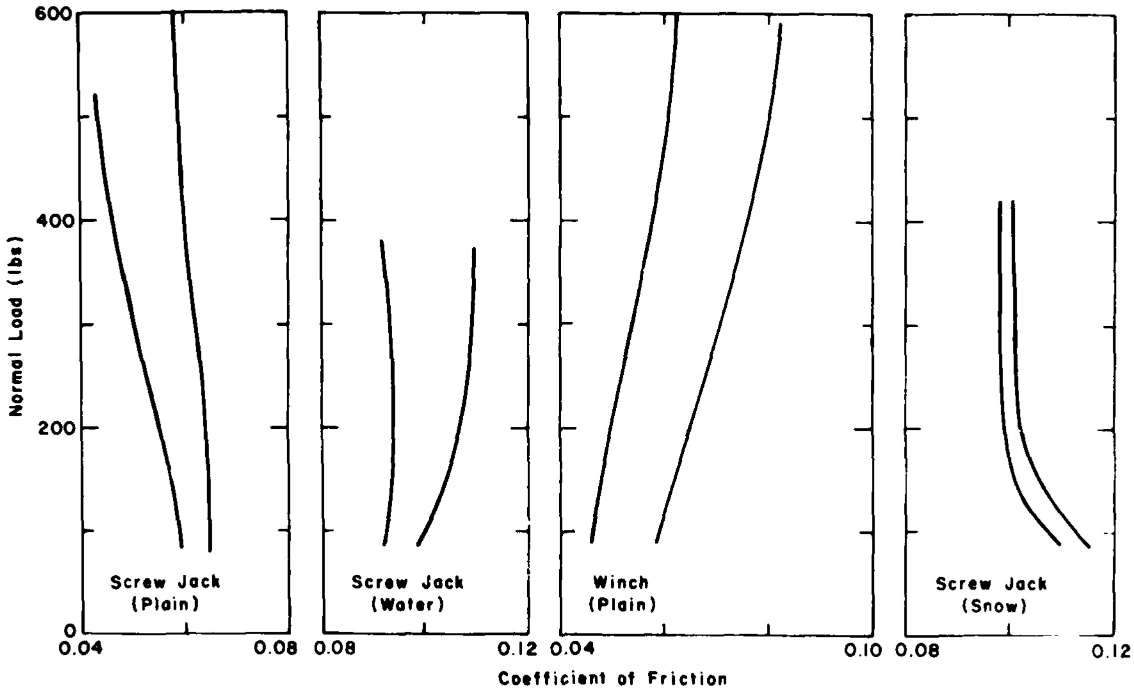


Figure A29. Dynamic coefficient of friction vs normal load for uncoated steel plate, 12 February 1979.

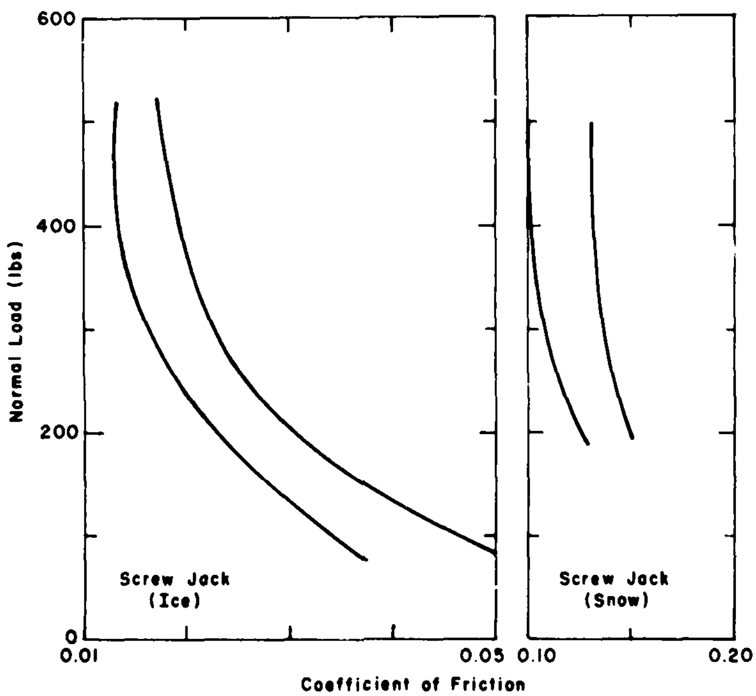


Figure A30. Dynamic coefficient of friction vs normal load for uncoated steel plate measured with screw jack, 15 March 1979.

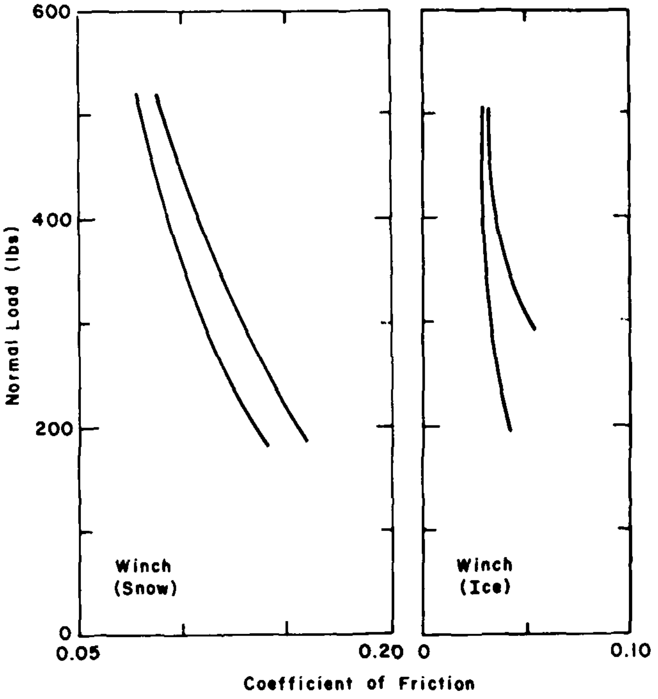


Figure A31. Dynamic coefficient of friction vs normal load with winch for Inerta 160, 15 March 1979.

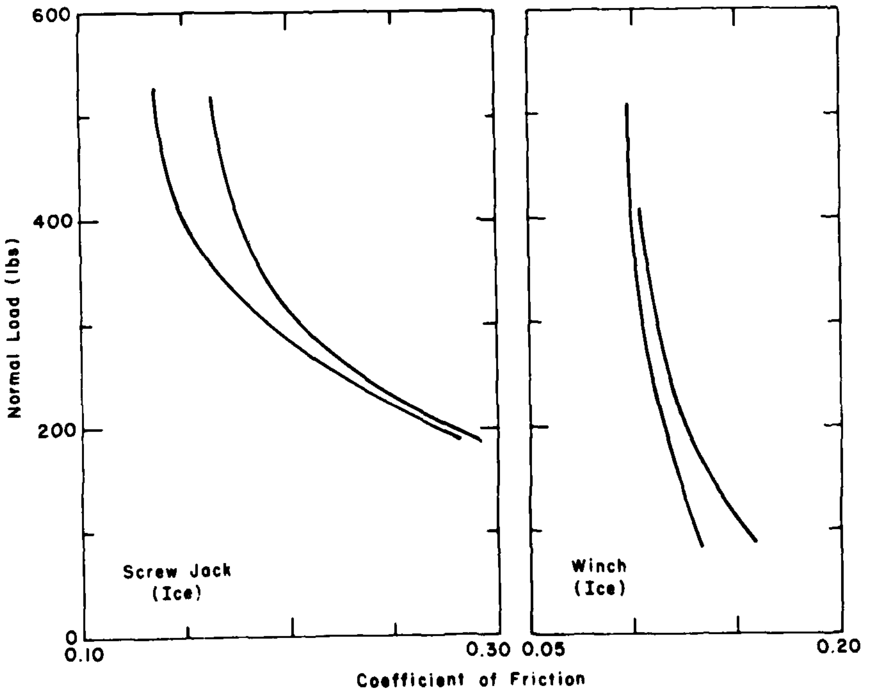


Figure A32. Dynamic coefficient of friction vs normal load for steel plate and ice, 15 March 1979.

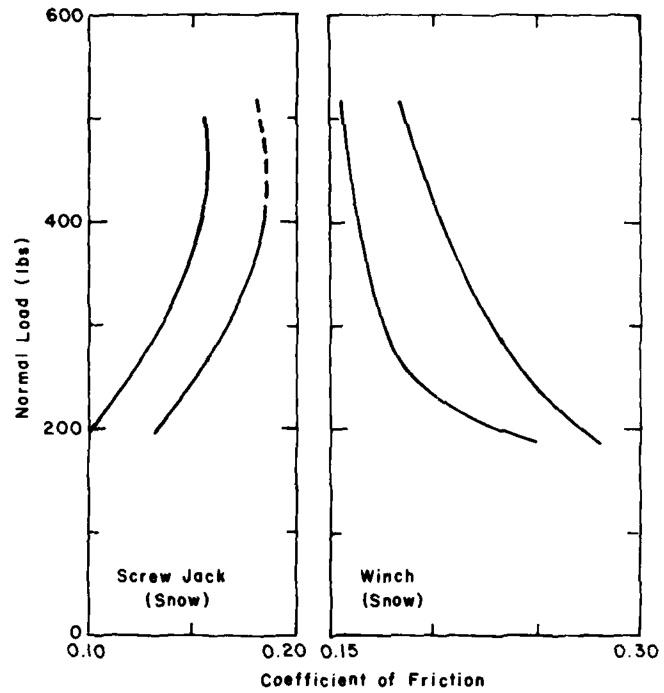


Figure A33. Dynamic coefficient of friction vs normal load for steel plate and snow, 15 March 1979.

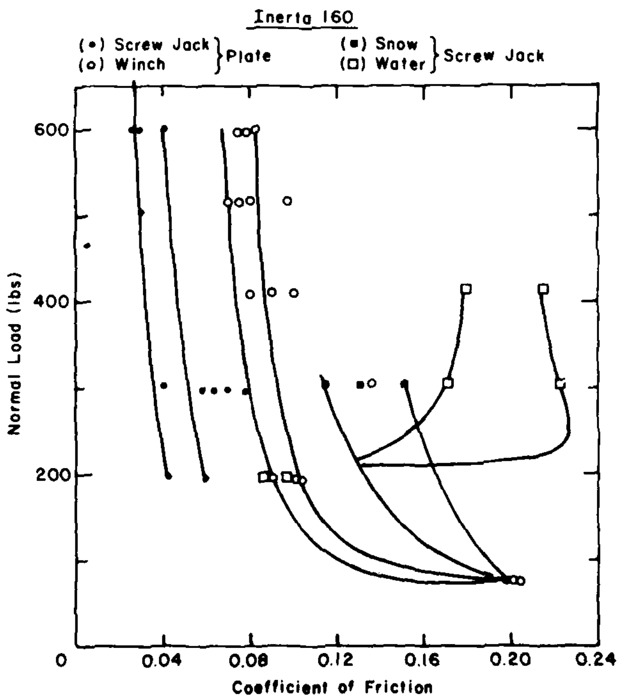


Figure A34. Static coefficient of friction vs normal load for Inerta 160, 10 and 12 February 1979.

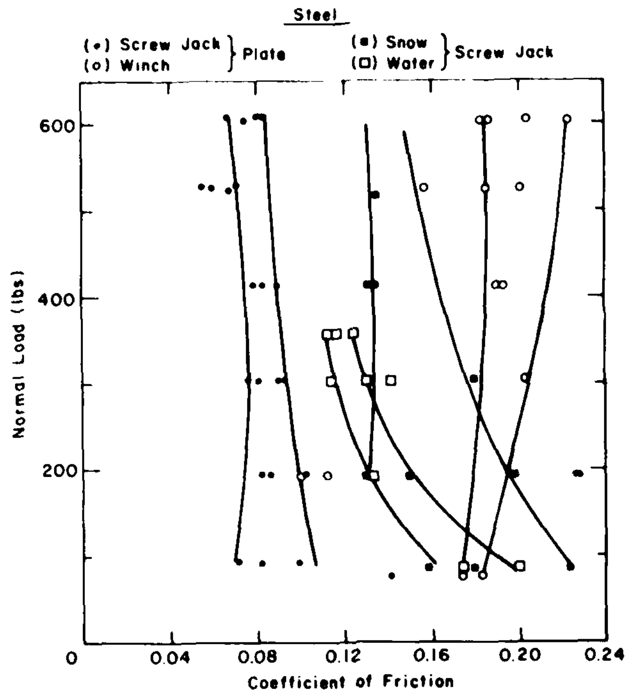


Figure A35. Static coefficient of friction vs normal load for steel plate, 10 and 12 February 1979.

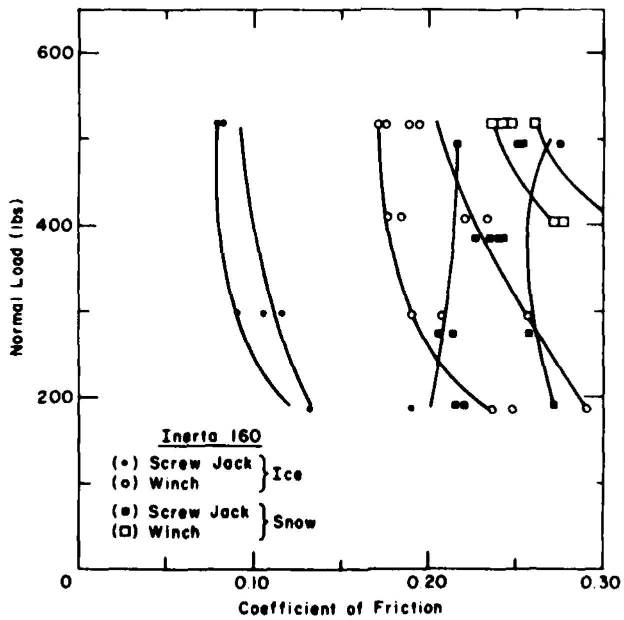


Figure A36. Static coefficient of friction vs normal load for Inerta 160, 15-16 March 1979.

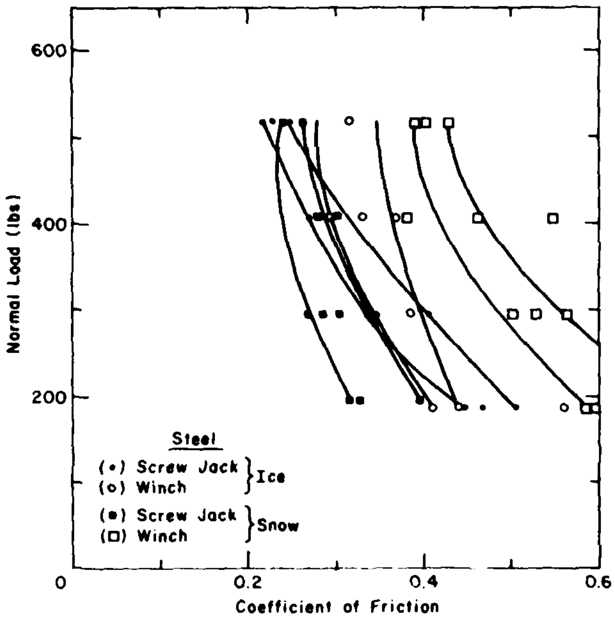


Figure A37. Static coefficient of friction vs normal load for steel plate, 15-16 March 1979.

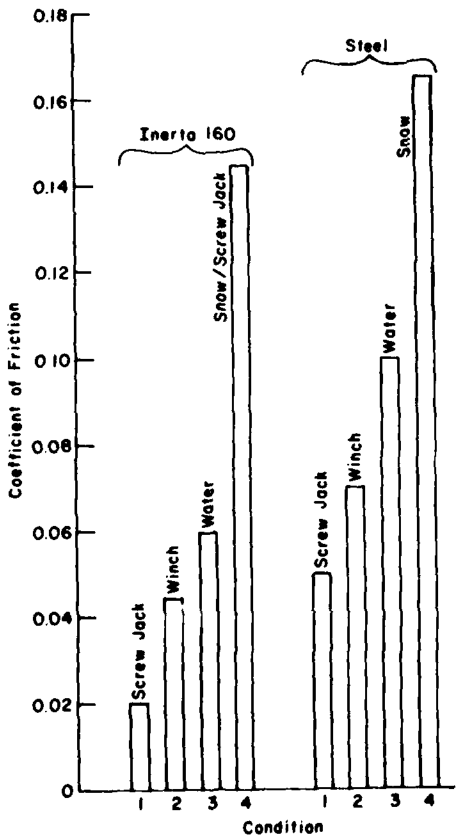


Figure A38. Dynamic tests, 10 and 12 February (V_w = 0.52 ft/sec, V_{ss}= 0.225 ft/sec).

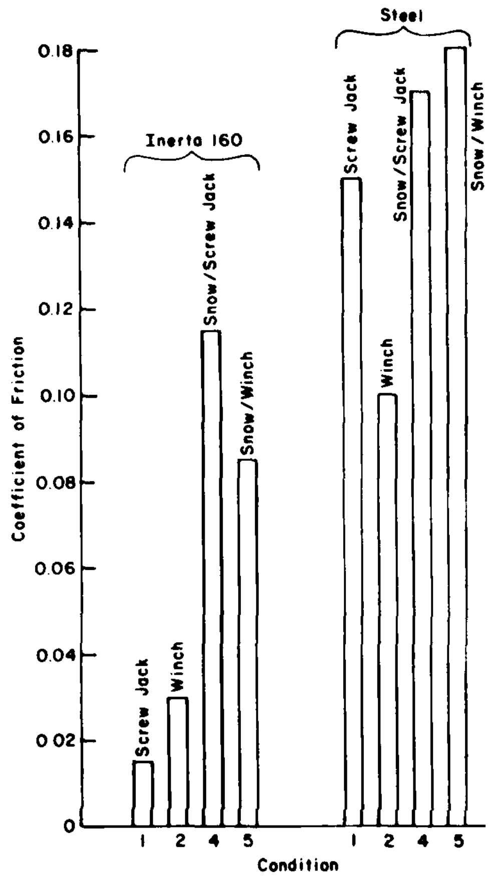


Figure A39. Dynamic tests, 15-16 March 1979.

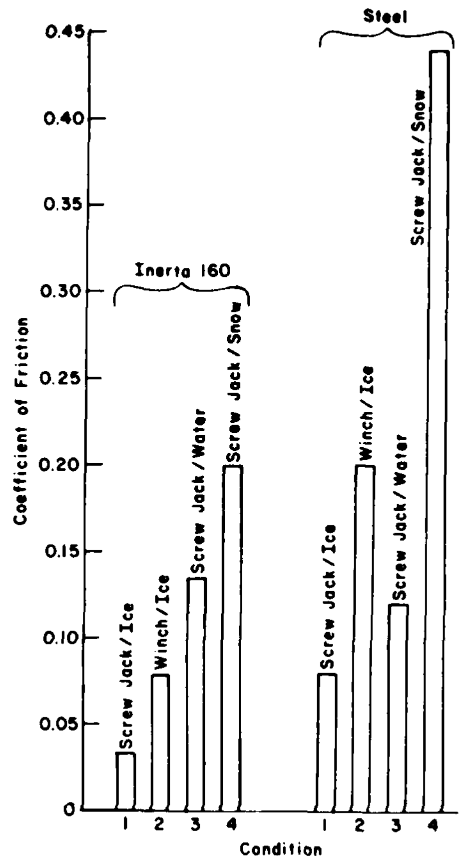


Figure A40. Static tests, 10 and 12 February 1979.

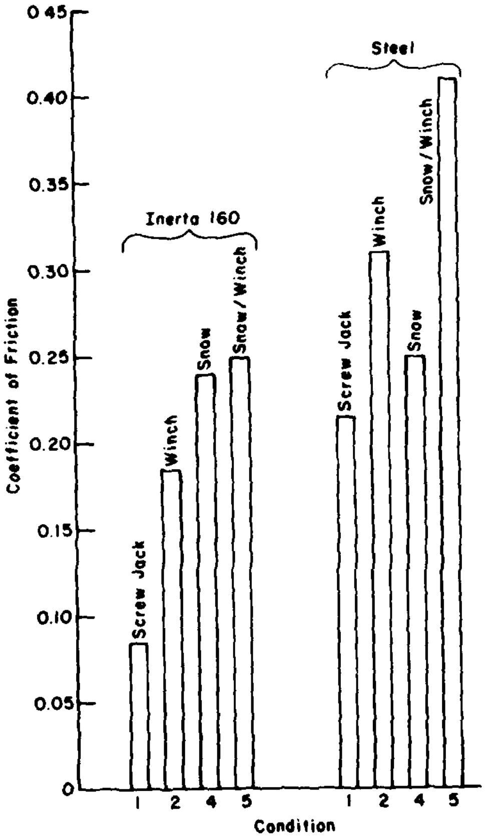


Figure A41. Static tests, 15 and 16 February 1979.

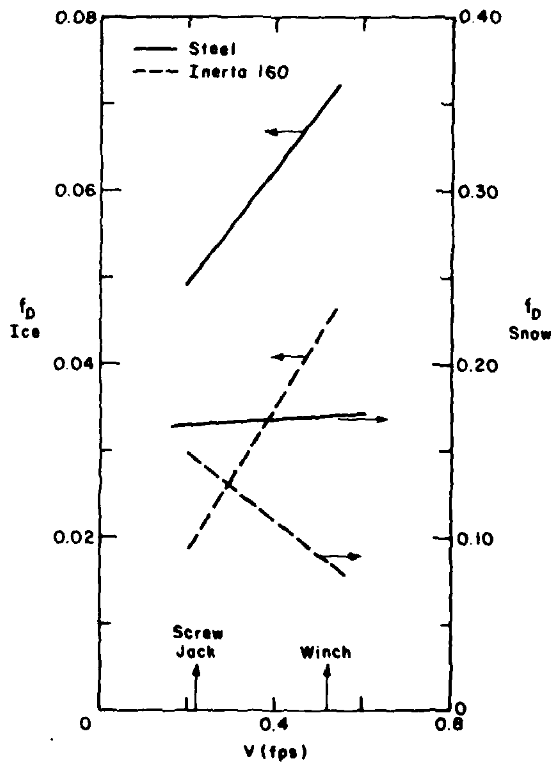


Figure A42. Dynamic coefficient of friction vs speed.