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CUTTING ICE WITH HIGH PRESSURE WATER JETS

Malcolm Mellor, et al

Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

16 July 1973

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16. Abstract

This report describes high pressure water jet ice cutting experiments conducted in support of the Coast Guard Domestic Icebreaking Program.

The test objectives were to determine power requirements for cutting two feet of fresh water ice at a speed of advance of 5 knots.

The results of the tests show extremely high power requirements even when using state-of-the-art equipment pumping at 100,000 p s i

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CUTTING ICE WITH HIGH PRESSURE WATER JETS

FINAL TECHNICAL REPORT

MAY 1973

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UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20590

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This report has been submitted in fulfillment of MIPR Z-70099-3-31741 and is promulgated subject to the following qualifications:

The contents of this report reflect the views of U.S.A.CRREL HANOVER NEW HAMPSHIRE 03755 which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Coast Guard. This report does not constitute a standard, specification, or regulation.

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Objective: To conduct large scale field experiments to determine the power requirements of cutting ice with high pressure water jets.

Purpose: To compare water jet ice cutting with other methods of ice disaggrigation.

Summary Of Results:

A water jet ice cutting system capable of slicing through 2 ft. of ice at a traverse speed of 5 knots, operating at near 100,000 psi would require approximately 1500 hydraulic horsepower corresponding to about 3,000 prime mover horsepower with present state of the are equipment.

Conclusions:

Continuous ice cutting with high pressure water jets is not a feasable method of ice disaggrigation due to:

1. Excessively high power requirements
2. Unreliable state of the art high pressure water jet pumping equipment.

JET-CUTTING AS AN ICE-BREAKING AID

Preliminary Report on Field Tests for U. S. Coast Guard

Malcolm Mellor and Francis Gagnon

Introduction

Recent developments in high pressure technology have stimulated interest in the use of high pressure water jets, both pulsed and continuous, for cutting and breaking. Many diverse applications have been proposed, sometimes with more enthusiasm than discrimination.

It appears that water jets were proposed as supplementary cutters for ice-breaking vessels in Russia a few years ago, but no substantive reports are available. A 1971 paper on the subject by Shvayshteyn summarizes some well-known properties of water jets, but reaches only trivial conclusions about their efficacy for cutting ice. The idea of using water jets for cutting ice has been bandied around in the United States for the past two years, and over the past year or so a number of commercial organizations and contract research institutions have shown definite interest. However, as far as is known, only USACRREL has made any systematic experiments.

USACRREL interest in high pressure water jets dates from about 1966, and over the past six years or so a variety of studies have been made, mainly directed towards excavation of frozen ground (see Mellor, 1972a, for a review of work up to the end of 1971). In all of these studies, access to high pressure equipment has been by contract arrangement or by collaboration with other institutions. This approach has proved beneficial in that it has been economical, it has provided experience with a variety of equipment, and it has avoided enslavement to one particular type of capital equipment. During the course of tests on frozen soils, a few experiments were made on ice blocks (Summers, 1971; Mellor and Harris, 1972) and the results were used to evaluate the material constants needed for analytical design methods (Mellor, 1972a, 1972b).

In the autumn of 1972 USACRREL received informal inquiries from the U. S. Coast Guard about the possibilities of using water jets as ice-breaking aids on inland waters. At that time, design estimates based on results of small-scale laboratory experiments indicated that a jet capable of slicing through 2 ft of floating ice at a traverse speed of 5 knots would make unreasonably high power demands (Mellor and Harris, 1972). However, recognizing that no field tests had been made, and that new equipment capable of pressures up to 100,000 lbf/in^2 was being offered, it was conceded that it would be prudent for the Coast Guard to include jet-cutting tests in its FY73 research program. Consequently, USACRREL submitted a proposal for field evaluation of what appeared to be the most advanced continuous-jet unit in existence at that time.

Test Program

Technical plans drawn up in November 1972 called for one week of systematic field tests on a small lake near the USACRREL laboratories in

Hanover, N. H., the tests to begin on 19 February 1973. A 100,000 lbf/in^2 jet unit developing 200 hydraulic horsepower was to be leased from the Illinois Institute of Technology Research Institute (IITRI), and the unit was to be operated by a senior engineer and a technician from IITRI. The test matrix was designed to investigate the variation of jet penetration with nozzle pressure, nozzle diameter, and traverse speed.

Due to administrative delays the IITRI contract was not awarded until after the planned starting date for the tests, and by this time the IITRI unit was being reconstructed in the third version of the prototype, so that further delay ensued. The jet unit was not ready for shipment until 19 March, and by this time abnormally early spring conditions had caused serious deterioration of the lake ice in New England. A rapid survey of ice conditions indicated that early breakup was general in the northern states, but a decision was made to attempt field tests at the Keweenaw Field Station, Houghton, Michigan, where the required 2 ft of ice still existed in apparently sound condition.

The IITRI high pressure unit arrived at Houghton late on Wednesday, 21 March, and was off-loaded on Thursday, 22 March. There were logistic difficulties in preparing the unit for operation and in moving it to the test site (among other things, the unit sank in the mud and the bulldozer broke down), but by mid-morning of Friday, 23 March, the unit was on the ice and ready for testing (Fig. 1).

Since it seemed possible that there might be trouble with both the ice and the equipment, the original test plan was discarded and the program was started with the grand finale, i.e. full hydraulic horsepower, maximum pressure, maximum nozzle size, and operational traverse speeds.

At the start, the power trailer and intensifier skid were towed across the ice by means of a winch and cable, but this improvised arrangement only gave speeds up to about 1 knot, and the motion was unsteady. A direct tow with a light oversnow vehicle was then attempted, but this 2½-ton machine was unable to move the 7½-ton IITRI unit. It was then decided that a tow by the HD-5 Traxcavator (about 6-ton) would have to be risked. Two good test runs were then made at almost 3 knots before the tractor broke through the ice and sank (Fig. 2), at which time tests on floating ice were terminated by decree of the equipment superintendent. Appendix A gives some notes on this bearing strength problem.

All equipment was retrieved and returned to the Keweenaw Field Station on Friday afternoon, 23 March, and preparations for tests on ice blocks were made. On the morning of Saturday, 24 March, the intensifier unit was set up on blocks and a simple traversing track for ice blocks was laid beneath the fixed nozzle (Fig. 4). Ice blocks were cut from a nearby pond with a chain saw, and were carried to the test rig in a Weasel. Soon after start-up, the high-pressure seals failed on one cylinder of the intensifier, and repairs had to be made. Two traversing tests were then run at 100,000 lbf/in^2 and the seals again failed, this time on both cylinders, so that testing was terminated for the day. On Sunday morning the replaced seals failed again immediately after the first run-up to 100,000 lbf/in^2, and after further repairs the intensifier was still leaking. However, by limiting pressure to 60,000 lbf/in^2 and limiting nozzle diameter to 0.016 in. it was possible to operate, and some traversing tests, static penetration tests, and jet length measurements were made.

By the end of Sunday, 25 March, the intensifier was leaking profusely and spares and morale were running low. There seemed little likelihood of obtaining much more useable data, and therefore the test program was terminated.

Test Results

Before giving any test data it must be pointed out that the IITRI unit does not give a continuous jet when operating at its maximum pressure and flow rating, and the writers are not yet convinced that it actually delivers 100,000 lbf/in^2 when fitted with a 0.02 in. diameter nozzle. The unit spurts at about 0.8 beats per second under high-pressure operation because there is no surge chamber on the delivery side of the intensifier. Delivery pressure is uncertain because there is no pressure gauge on the high pressure end of the system - pressure is read from the low-pressure circuit, and is then multiplied by the area ratio of the intensifier, but the system has not been calibrated. When the maximum-performance jet traverses, penetration varies cyclically from zero to a maximum value as the nozzle pressure fluctuates.

In all of the traversing tests, penetration varied cyclically from zero to a maximum value, and it was assumed that maximum penetration corresponded with maximum delivery pressure. In Tables I and II maximum penetration is tabulated alongside the nominal delivery pressure, i.e. the pressure of the low-pressure hydraulic circuit multiplied by the effective intensification ratio of 20 (which makes some allowance for friction in the intensifier). Traverse speed in the lake tests was measured by timing a 50-ft run with a stopwatch, and in the block tests it was measured by timing the travel of a block (approximately 52 in. long) through the jet. Nozzles were described as "Leach and Walker 13° nozzles," i.e. they were of the design attributed by Leach and Walker to Nikonov and Shavlovskii, with 13° entry cone and a parallel exit section having a length/diameter ratio of 2.5 to 3.0. Traversing data are given in Tables I and II and in Figure 5.

Table I

Traversing tests on floating ice

Test	Nozzle dia. (in.)	Nominal Nozzle pressure (lbf/in^2)	Traverse Speed (ft/min)	Max. Penetration (in.)	Remarks
1	0.02	100,000	69.1	6.5	
2	"	"	99.3	7.0	Jerky travel
3	"	"	303	5.0	
4	"	50,000	280	2.0	One cylinder of intensifier faulty.

Standoff distance approximately 1 in.

Table II

Traversing tests on ice blocks

Test	Nozzle dia. (in.)	Nominal Nozzle Pressure (lbf/in^2)	Traverse Speed (ft/min)	Max. Penetration (in.)	Remarks
1	0.02	100,000	250	3.75	
2	"	"	357	6.0	Jerky travel
3	0.012	60,000	189	2.75	
4	"	"	83.3	3.0	Jerky travel
5	"	"	58.9	4.5	
6	0.016	"	92.0	5.0	
7	"	"	69.6	6.5	Jerky travel
8	"	"	66.0	6.5	

Standoff distance approximately 0.75 in. for 0.012 in. nozzle and 1.0 in. for 0.016 in. nozzle.

Static penetration tests were run in order to set an upper bound for penetration as traverse velocity tends to zero. For a penetration test, an ice block was set up with its long dimension parallel to the nozzle axis (Fig. 6), the nozzle was brought up to operating pressure with a steel deflector protecting the ice, and then the jet was allowed to attack the ice for 20 seconds. In some of these tests the jet broke out through the side of the block, since the ice on one side of each block was very weak due to grain-boundary melting. In all cases the cavity cut by the jet tended to increase in diameter with increasing depth for about 90% of the total depth. The few results obtained are given in Table III; it appears that static penetration for small standoff is about 2000 nozzle diameters.

Table III

Static Penetration Tests

Test	Nozzle Dia. (in.)	Nominal Nozzle Pressure (lbf/in^2)	Penetration (in.)	Penetration + Standoff (in.)	Penetration+Standoff / Nozzle diameter
1	0.012	40,000	22.9	23.9	1992
2	"	60,000	28.1	29.1	2425
3	0.016	60,000	29	30	1875
4	"	80,000	34.5	35.5	2219

With a nozzle diameter of 0.016 in. and the feedwater pressure of 600 lbf/in^2, the jet was allowed several minutes to erode a groove along the surface of a 0°C block; it eroded to a total distance of 51.5 in.

Some attempt was made to determine free-air jet length by simple means. As near as could be ascertained by direct observation, the coherent jet core was about 1000 nozzle diameters long. However, the dispersed fringe of the jet extended more than 3000 nozzle diameters. When a wooden board was moved backwards and forwards at the extremity of the jet there was a fairly distinct transition from low impact force to a force of the order of 1 kgf, and the distance from the nozzle at which this transition occurred was measured, results being listed in Table IV. The apparent increase in dynamic length with increase in nozzle pressure can probably be attributed to the method of measurement; it would be more consistent to take as a lower limit of force some percentage of the nozzle exit force. For most practical purposes, however, it can be assumed that dynamic length is about 3000 nozzle diameters.

Table IV

Total dynamic length of jet in air

Test	Nozzle dia. (in.)	Nozzle Pressure (lbf/in^2)	Dynamic length (in.)	Dynamic length / Nozzle diameter
1	0.012	20,000	35	2917
2	"	40,000	38	3167
3	"	60,000	39	3250
4	"	80,000	40	3333
5	"	100,000	49	4083
6	"	"	52	4333
7	0.016	20,000	44	2750
8	"	40,000	44.5	2781
9	"	60,000	46	2875
10	"	80,000	54	3375
11	"	100,000	55	3438
12	0.020	80,000	48	2400

Evaluation of Results

Prior to these tests some performance estimates were made on the basis of earlier experimental work, and it is now instructive to compare the estimates with measured values. Penetration ℓ_u was estimated from the equation (Mellor, 1972b):

$$\ell_u = \ell_o \left[1 - \exp\left(-K_2 p_o^2 \, d/u\right) \right]$$

in which p_o is nozzle pressure (lbf/in^2), d is nozzle diameter (in.), u is traverse speed (ft/min), and ℓ_o and K_2 are parameters determined experimentally. The values taken for the parameters were:

$$\ell_o = 1000d - s$$
$$K_2 = 9.2 \times 10^{-7} \ (\mathrm{lbf/in^2})^{-2} (\mathrm{in.})^{-1} (\mathrm{ft/min})$$

where s is standoff distance in inches. Table V gives the comparison of predicted values with actual values.

Table V

Comparison of actual and predicted penetration for traversing jet

Nozzle dia. (in.)	Nominal nozzle pressure (lbf/in^2)	Traverse speed (ft/min)	Actual penetration (in.)	Predicted penetration (in.)
0.02	100,000	69.1	6.5	17.7
"	"	99.3	7.0	16.0
"	"	303	5.0	8.7
"	50,000	280	2.0	2.9
"	100,000	250	3.75	10.0
"	"	357	6.0	7.75
0.012	60,000	189	2.75	2.1
"	"	83.3	3.0	4.3
"	"	58.9	4.5	5.5
0.016	"	92.0	5.0	6.6
"	"	69.6	6.5	8.0
"	"	66.0	6.5	8.3

With one exception, the actual measured values of maximum penetration are all lower than the predicted values, and the most glaring discrepancy occurs at the highest level of nominal hydraulic horsepower (Fig. 7). The reason for plotting the comparative data against traverse velocity in Figure 7 is that there ought to be reasonable agreement between predicted and actual values at the extremes of velocity ($u \rightarrow 0$ and $u \rightarrow \infty$), with poorest agreement in the mid-range of velocities. However, there are not enough results to test this hypothesis.

One thing that comes out of the static penetration tests at Houghton is that the previously assumed value of ℓ_o is too low for physical reality, although it may well be reasonable as a curve-fitting parameter for the data available up to this time. In order to examine this question, $-\ln(1-\ell_u/\ell_o)$ has been plotted against $(p_o^2 d/u)$ for three different assumed values of ℓ_o, and the Houghton data, <u>excluding</u> the results for the nominal 220 hydraulic horsepower, have been added (Fig. 8). It should be noted that logarithmic scales are used only for convenience and clarity, and a linear relationship between $-\ln(1 - \ell_u/\ell_o)$ and $(p_o^2 d/u)$ <u>must</u> have a slope of 1:1 on this type of plot. Figure 8 clearly shows that this type of parameter determination is quite insensitive to the assumed value of ℓ_o unless the data involve values of ℓ_u that approach the value of ℓ_o. Although these results have not yet been checked by regression analysis, it appears that the best fit is obtained with a value of ℓ_o that lies between (1000d - s) and (1500d - s). In any event, the situation with respect to the Houghton data remains unchanged, in that all results except one are low in comparison with previous results according to this type of plot.

Actually, there are some indications that the analytical function (p_o^2 d/u) may give too much emphasis to nozzle pressure, with the result that predictions extrapolated to pressure ranges higher than the data range are systematically overestimated. What this means in the present case is that our predictions for very high pressure equipment (100,000 lbf/in^2) have perhaps been too optimistic.

While our design analyses may be in need of some refinement, they are still perfectly adequate for making planning estimates, and it is worth looking again at the probable requirements for a jet that will cut 2 ft of ice at a traverse speed of 5 knots. The simplest and least controversial way to do this is to select various nozzle sizes and then calculate the minimum pressure that will just give a 2-ft penetration at 5 knots; Table VI gives some results for calculations of this type.

Table VI

Minimum requirements for single jet slicing 2 ft of ice at 5 knots

(assuming $\ell_o = 1500d - s$, $K_2 = 5.0 \times 10^{-7}$, $s = 1$ in.)

Nozzle dia. (in.)	Nozzle pressure (lbf/in^2)	Hydraulic power of jet (h.p.)
0.05	89,700	1160
0.10	42,200	1510
0.15	27,700	1800
0.20	20,500	2050

Conclusions

In spite of all the setbacks, this project succeeded in making an adequate evaluation of the IITRI high pressure jet unit as it presently exists. The following conclusions can be drawn:

1. There is absolutely no indication that the high pressure jet unit can exceed the performance estimates made prior to these tests. There is a strong possibility that mechanical inadequacies in the jet system reduced its performance somewhat at high power levels, but elimination of these problems would not be likely to do more than improve the agreement between predicted and actual performance. In fact, it may well be that the performance predictions for very high pressures are too optimistic.

2. A water jet system capable of slicing through 2 ft of ice at a traverse speed of 5 knots would make exorbitant power demands. At the practical pressure limit of available large pumps, a single jet nozzle would develop about 2000 h.p., while at the absolute pressure limit of current pump technology a single nozzle would develop about 1000 h.p. These are values of <u>hydraulic</u> horsepower; the input engine horsepower could be as much as twice these values. For a 3-nozzle cutter system the installed engine power would thus be of the order of 10,000 h.p., which seems preposterous for a vessel working the Great Lakes or the St. Lawrence Seaway.

3. In its present form, the IITRI jet unit does not appear suitable for sustained operation at full output pressure. There is very little likelihood of it operating hour-after-hour and day-after-day, as would be required for shipboard tests.

Acknowledgements

The writers are grateful to the staff of the Keweenaw Field Station, Michigan Technological University, for their help in carrying through the abruptly relocated field tests, and to Mr. L. E. Finlayson, Illinois Institute of Technology Research Institute, for preparing and operating the high pressure unit. They would also like to express their appreciation to Mr. Albert F. Wuori, USACRREL, for clearing administrative blockages, and to Mr. Norman Ehrlich, USCG, for his patience and forebearance.

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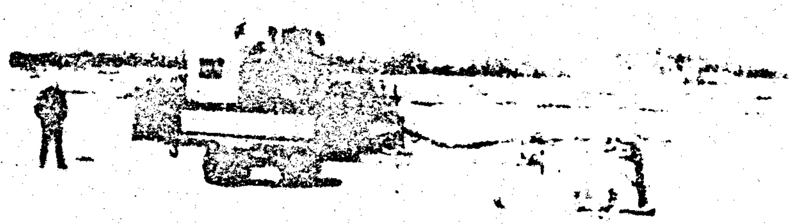


Figure 1 Power trailer and intensifier skid on the ice.

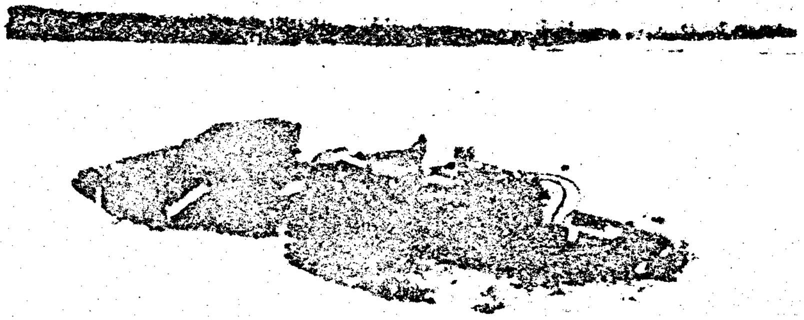


Figure 2. HD-5 Traxcavator in trouble.

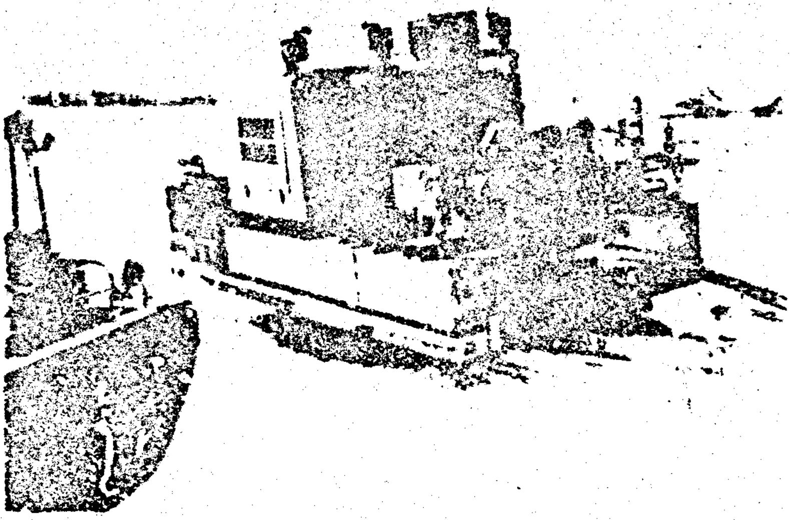


Figure 3. Power trailer in difficulty.

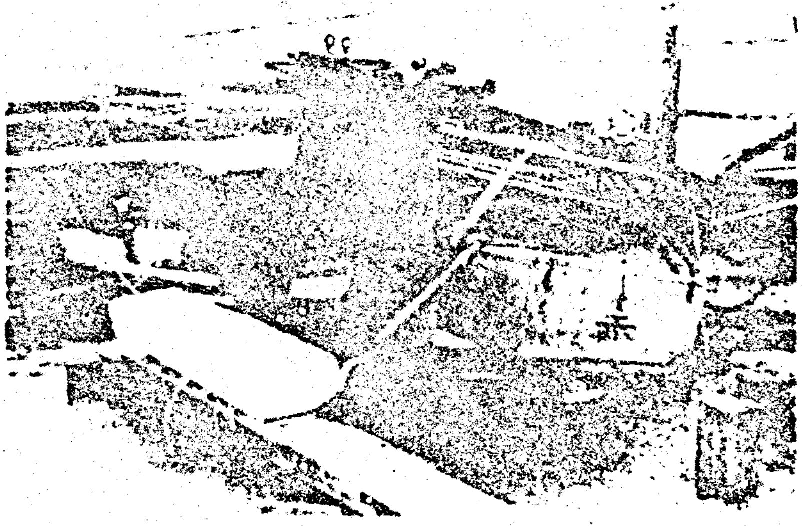


Figure 4. Improvised arrangement for traversing tests on ice blocks.

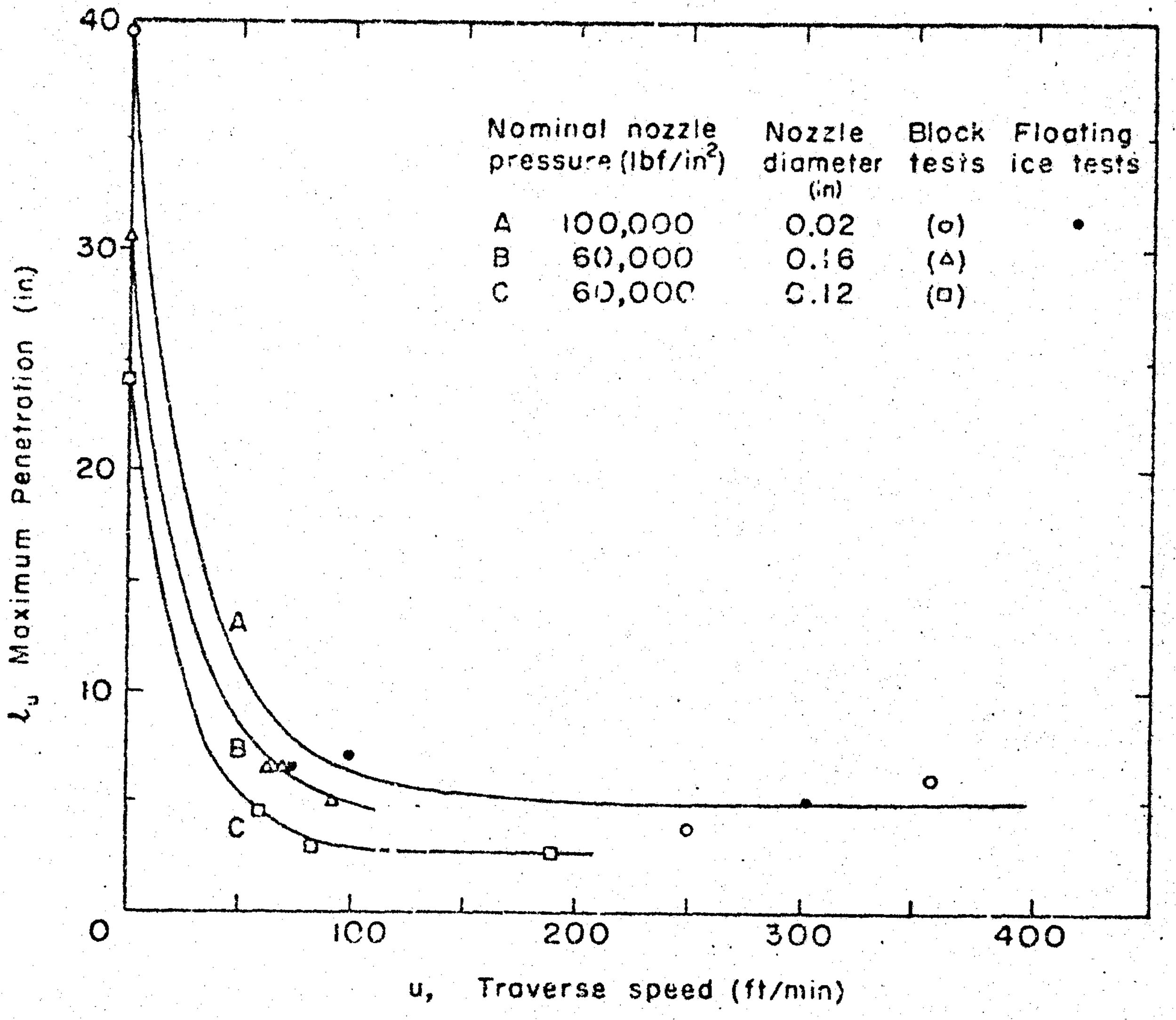


Figure 5. Jet penetration as a function of traverse speed.

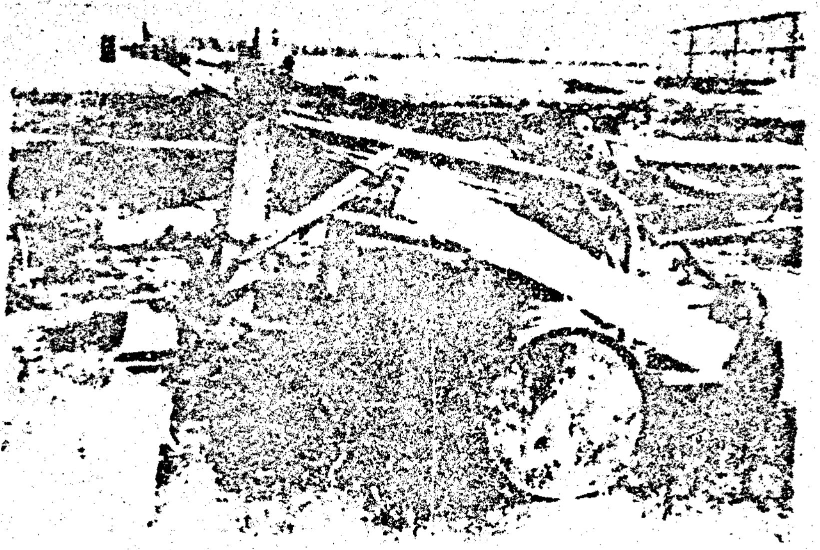


Figure 6. Improvised arrangement for static penetration tests on ice blocks.

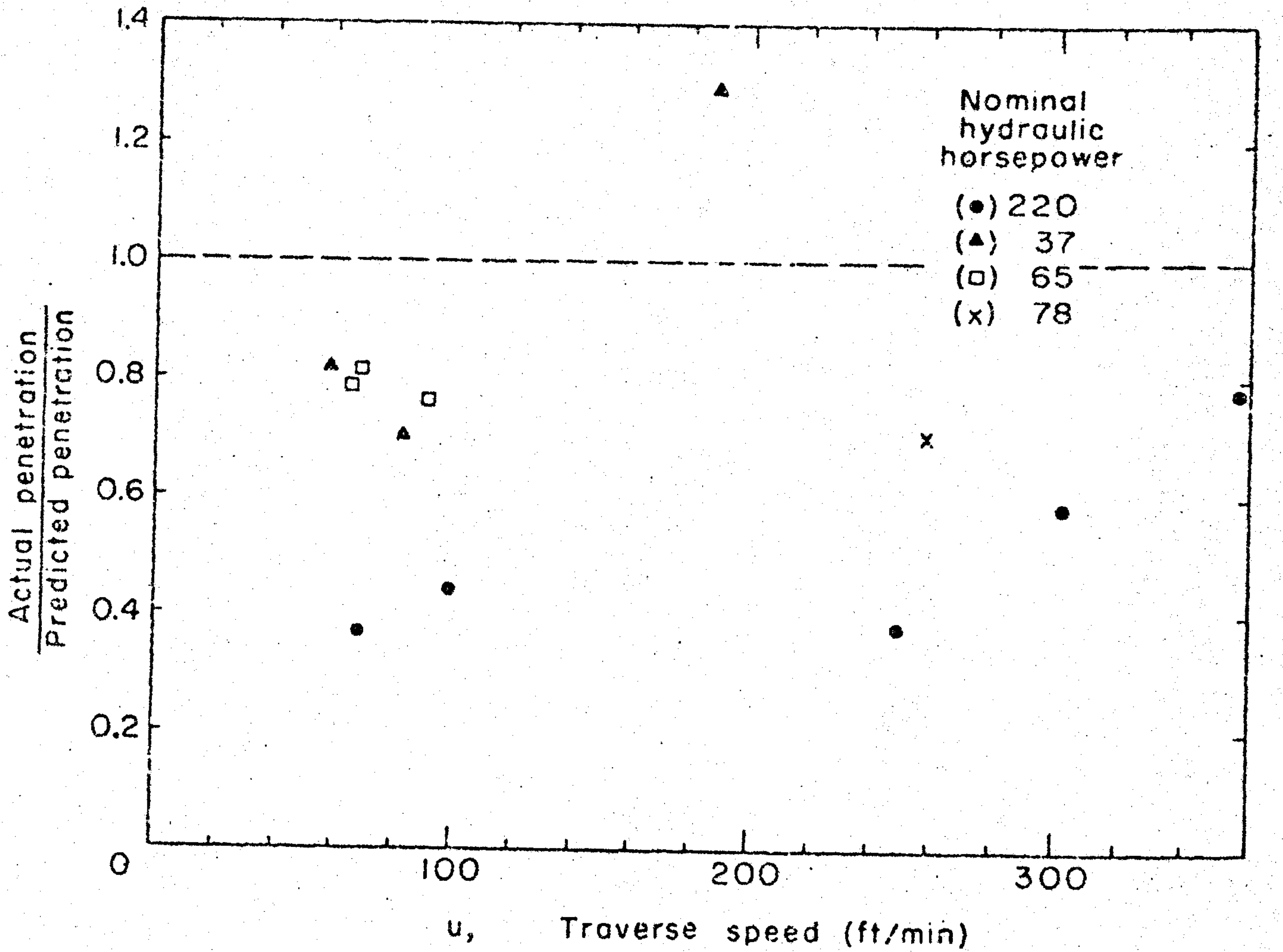


Figure 7. Ratio of actual penetration to predicted penetration plotted against traverse speed.

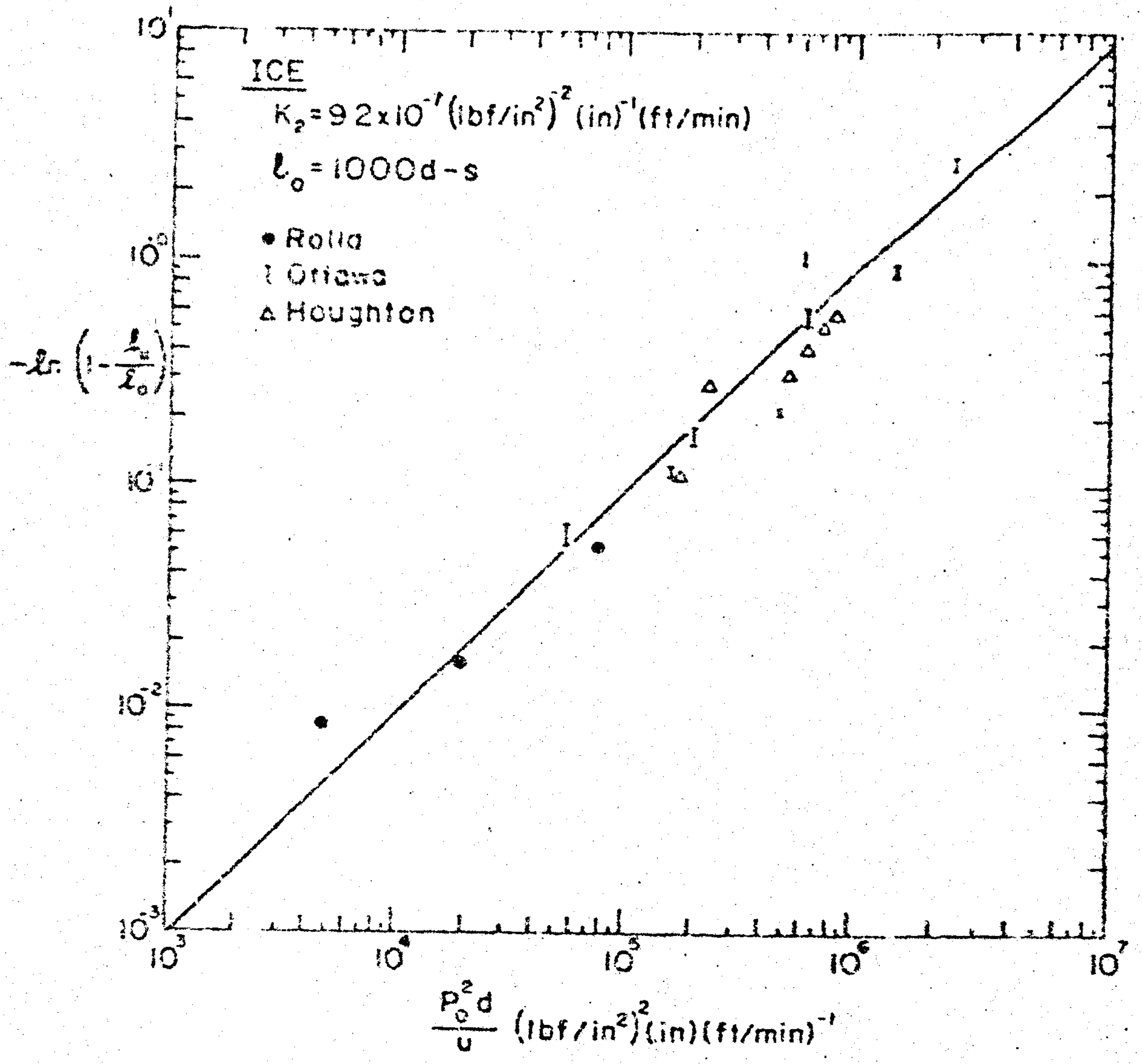
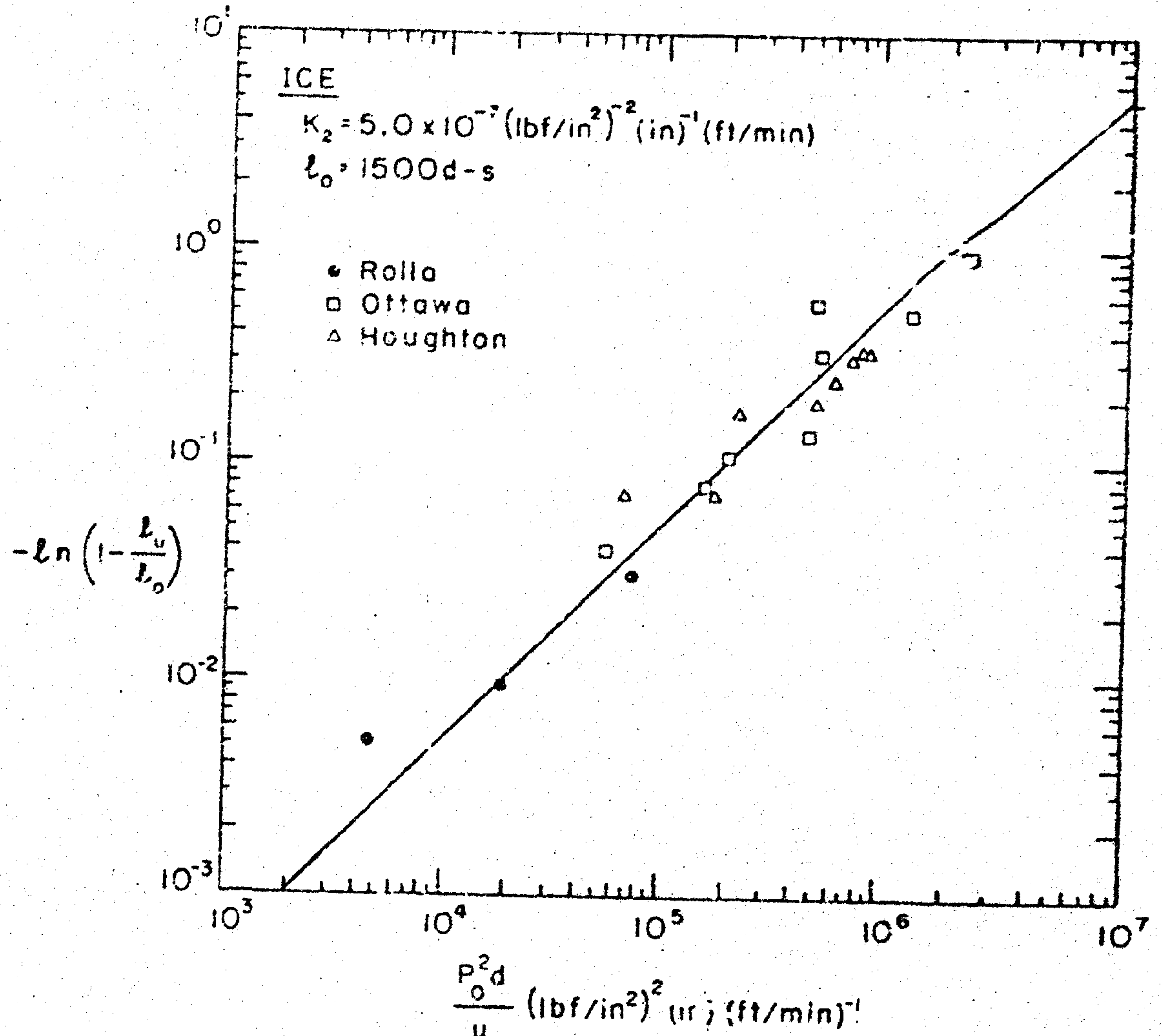


Figure 8. Logarithmic plot of – ln $(1-\ell_u/\ell_o)$ against p_o^2 d/u for three different assumptions on ℓ_o.



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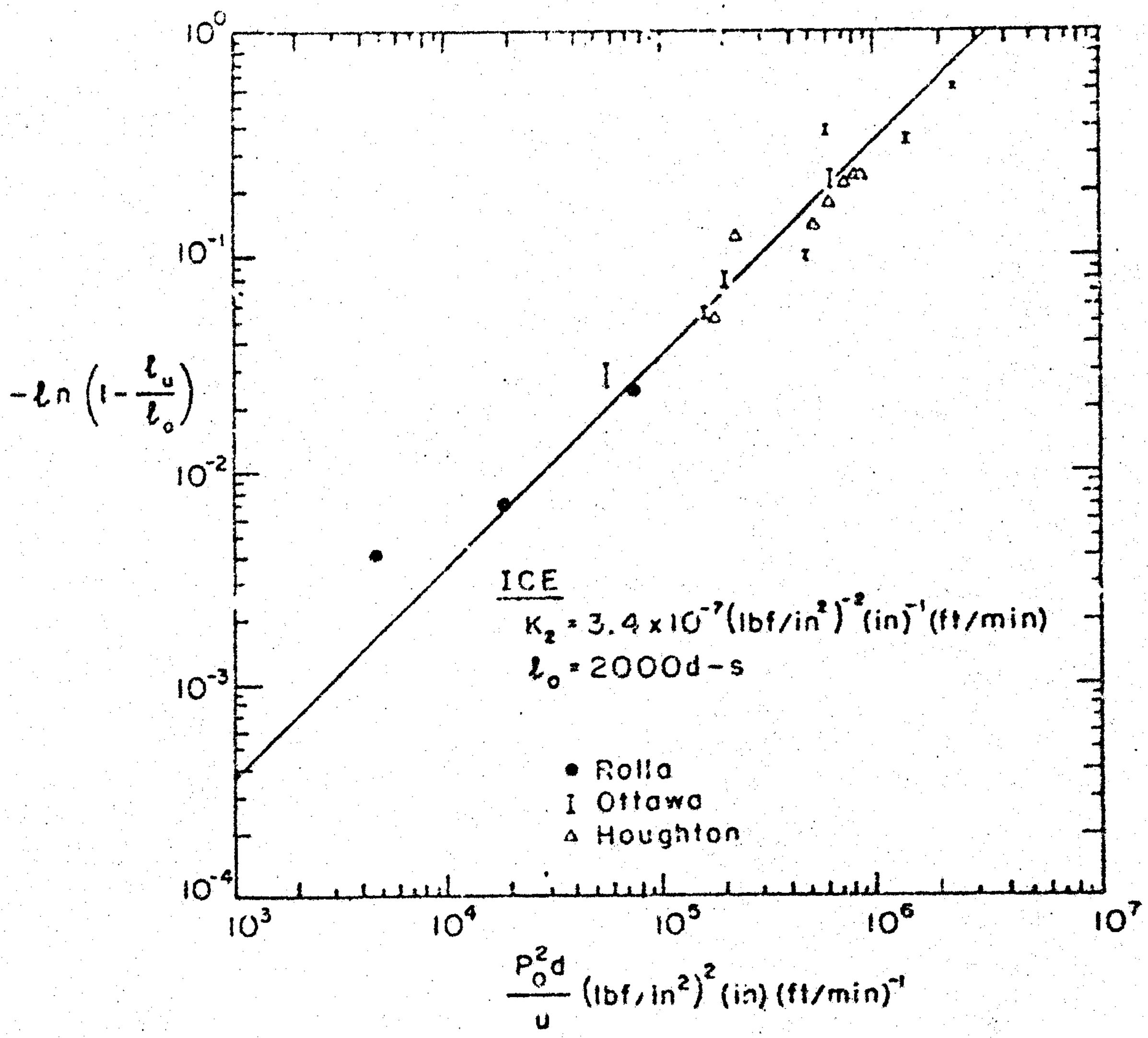

Figure 8. Logarithmic plot of – ln $(1-\ell_u/\ell_o)$ against $p_o^2\ d/u$ for three different assumptions on ℓ_o.

APPENDIX A

Problems with ice bearing strength

At the time the tests started, the main body of lake ice at the test site was about 24 in. thick, but there was a 2 in. layer of very weak slush 7 in. below the upper surface. The uppermost 7 in. of ice was snow-ice. Night temperatures were below freezing, and the ice surface was dry, with high albedo. Cores drilled out of the ice showed no sign of internal deterioration by grain boundary melting (apart from the slush layer). There was a band of transition ice around the shoreline that was thinner than main body of ice, and on one side of the pond the ice had been thinned by inflow of a small stream.

At the beginning, attempts were made to tow the power trailer onto the ice with a D-7 tractor, but the ice was incapable of supporting this machine (Fig. A-1). The power trailer was then pushed out onto the ice, and was moved around with a winch cable. If parked for 10 minutes or so, the power trailer (15,000 lb on a dual-wheel, single-axle, trailer) caused the ice to creep into a bowl-shaped depression, about 1 ft deep at the center. Whenever this happened a state of controlled panic ensued, and the trailer was swiftly transferred to another parking place.

When it became necessary to tow the jet unit directly with the HD-5 there was some concern, since too many loads were being placed in close proximity, and the vehicle tracks induced vibratory loads. The train of loads (Fig. A-2) consisted of the intensifier skid (1000 lb), the power trailer (15,000 lb), and the tractor (11,500 lb). The plan was to make a test run across the ice, and then return to a safe parking place near the shore while preparations were made for the next test. However, it was impractical for the equipment to cross the shoreline transition ice, and so the train was parked over what was believed to be shallow water.

After the second towing test, the train had been parked for about 5 minutes when the ice under the tractor began to sag increasingly at a perceptible rate, and water flooded the depressed ice surface. The coupling between the tractor and trailer was released and an attempt was made to drive the tractor away, but as soon as the tractor moved the ice gave way.

The trailer was moved onto the transition ice over very shallow water, where its wheels broke through.

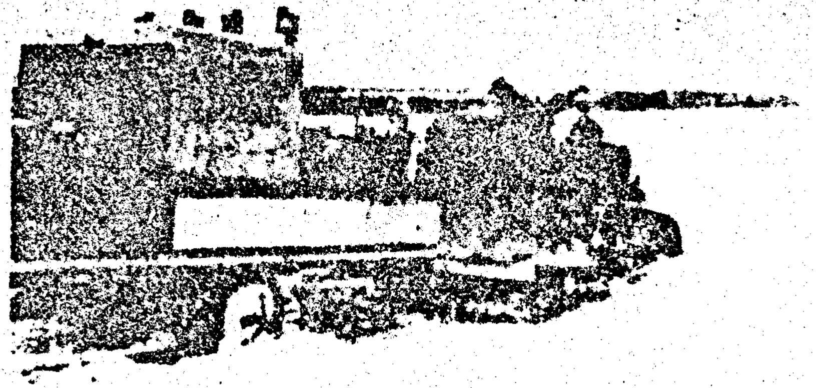

Figure A-1. D-7 tractor and power trailer breaking through the ice.

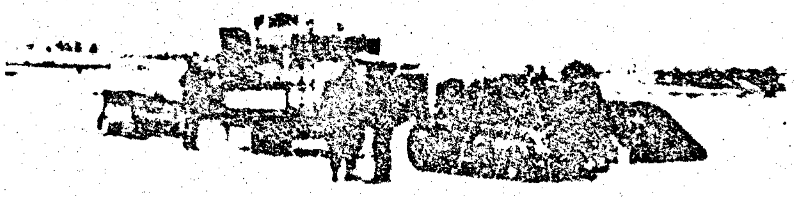

Figure A-2. Jet unit coupled to HD-5.