SUN OIL COMPANY

TENSILE STRENGTH OF THE YELLOWKNIFE ICE SHEET

Report No. 742G-72-12
October, 1972

SUNOCO

SUNOCO E & P LIMITED
CALGARY, ALBERTA

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by
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SUNOCO E & P LIMITED
CALGARY, ALBERTA

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TENSILE STRENGTH OF THE
YELLOWKNIFE ICE SHEET

SUMMARY AND RECOMMENDATION

The tensile strength for the Yellowknife ice sheet is 413±50 psi. This value is based on Brazil tests conducted on 62 ice samples taken from the Yellowknife ice cover during the 1971-1972 winter. The spread of the data is so great that we can only make a general observation: the tensile strength increases with increasing sample density and increasing stress rate.

In recent years, studies on the small-scale testing of ice indicated that the Brazil test method is more applicable for strength measurements than the currently and extensively used ring tensile test method. Future sea ice testing for tensile strength should include both methods in order to obtain data which can be correlated with the functional equations relating the tensile strength to the brine volume. Our ultimate goal is to ascertain the proper testing method needed to obtain strength values suitable for use in predicting the safe load conditions on ice sheets.

INTRODUCTION

Petroleum exploration and production in northern Canada's marine areas require unique new methods to cope with the ice-clad seas. Sunoco E&P Limited is considering the adaptation of an air cushion vehicle to an offshore drilling vessel to provide an ecologically safe means of operating in the Canadian Arctic.

The feasibility of operating an air cushion vehicle through and over an ice sheet was evaluated in a test program conducted at Yellowknife, N.W.T., Canada, during the 1971-1972 winter. Yellowknife, shown in Figure 1, lies three degrees of latitude below the Arctic Circle. The test site annually experiences an arctic type environment during the ice season.

In support of the tests using an air cushion vehicle, an ice mechanics program was conducted at the test site to determine the engineering ice properties of the Yellowknife ice sheet. Various test methods were used to determine the following properties: tensile strength, modulus of elasticity, unconfined compressive strength, ultimate contact pressure and locked in stresses. The Foundation of Canada Engineering Corporation Limited (FENCO) was retained to conduct field tests for the ice mechanics program at Yellowknife and at Tuktoyaktuk [1]. A summary of their results is presented in Appendix A.

In addition to the tests performed by FENCO, Sunoco personnel subjected ice core samples to Brazil tests in order to determine the tensile strength of the ice cover. FENCO conducted their tests at the two sites shown in Figure 2. Ice samples for Brazil tests were taken at each probe station, at FENCO test site number 1, and at selected points in the ice sheet. A total of 62 ice core samples were tested. A comparison of the Brazil test results was made with the results of similar tests conducted by AMOCO on ice floes in the Beaufort Sea [2].

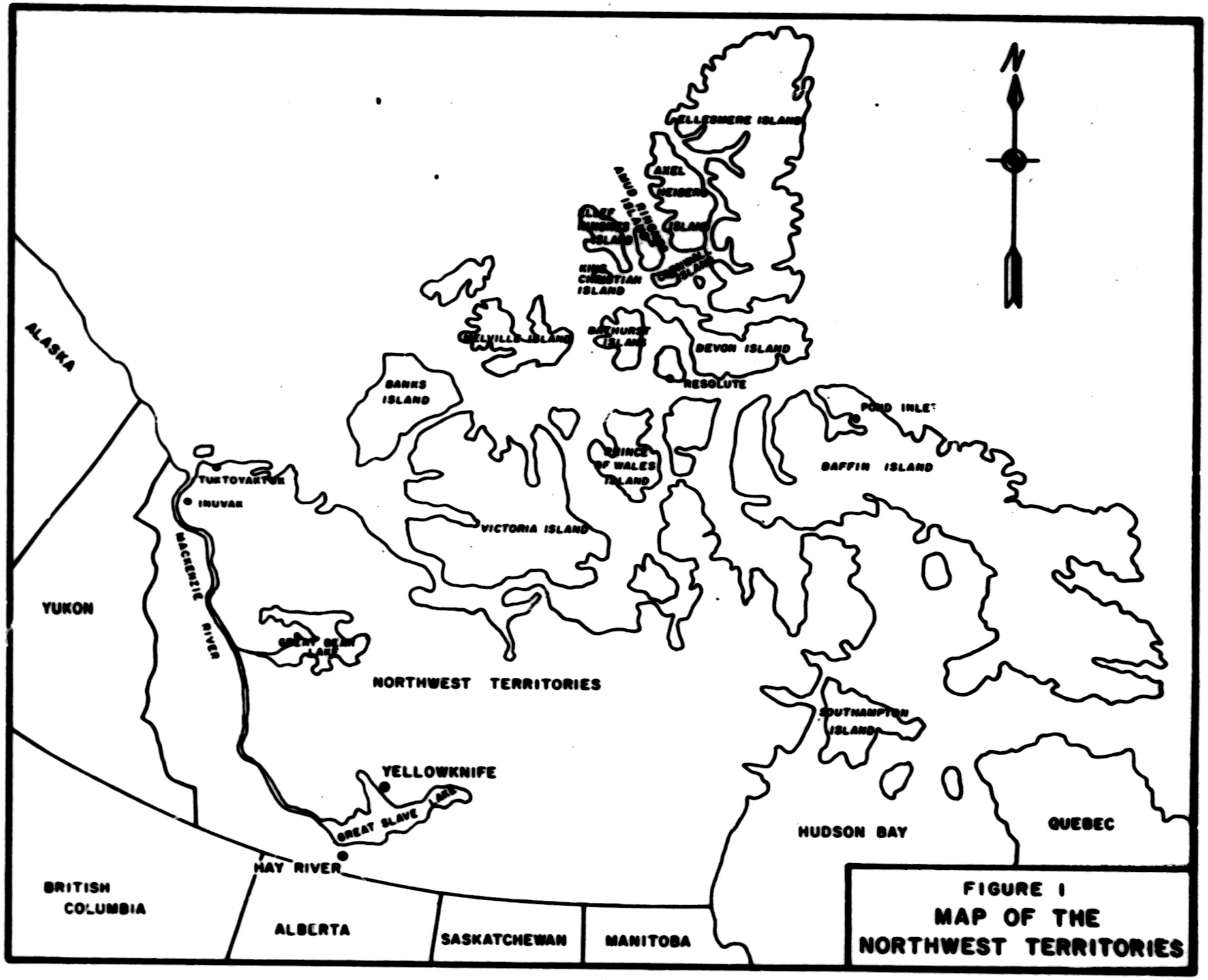

FIGURE I
MAP OF THE NORTHWEST TERRITORIES

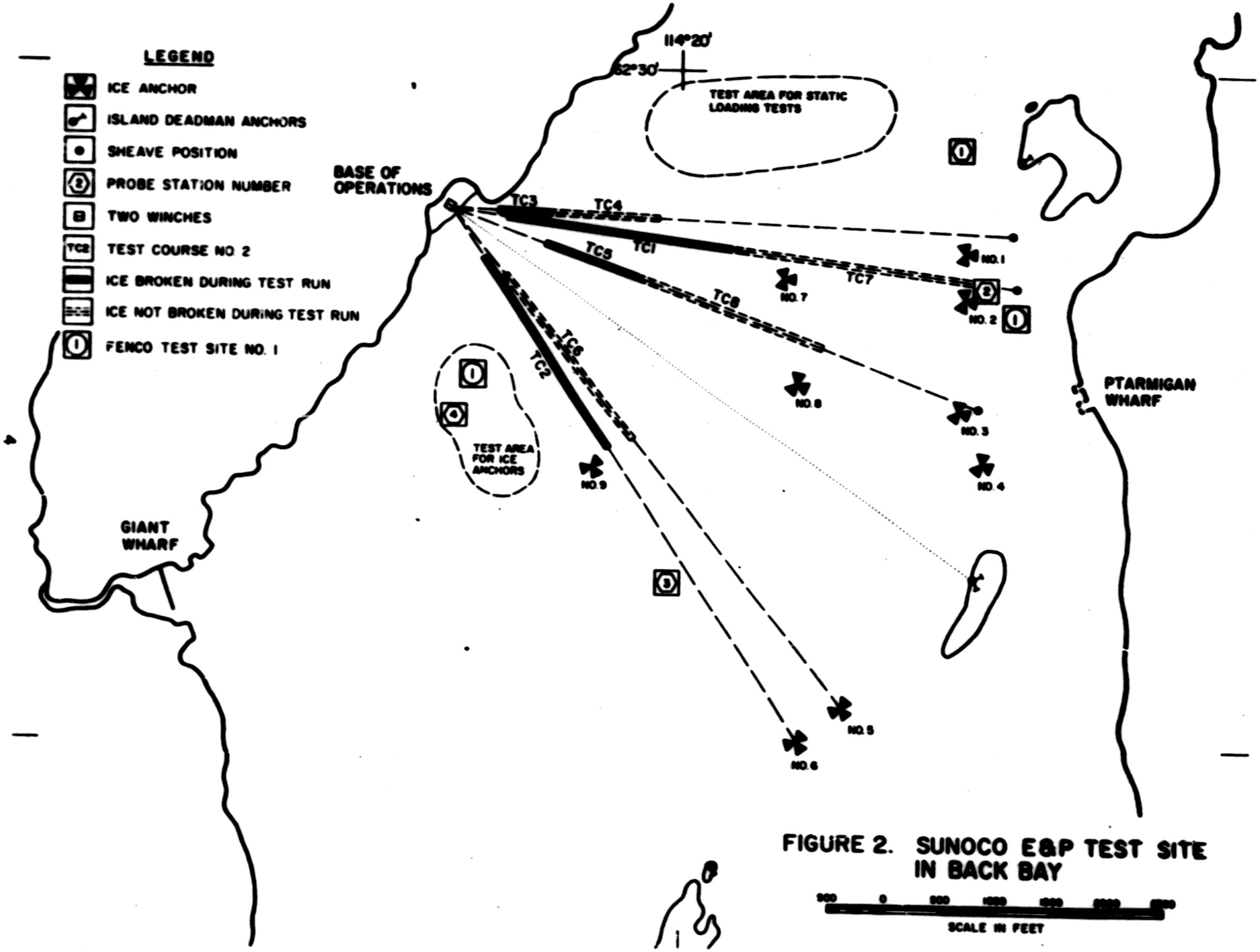

FIGURE 2. SUNOCO E&P TEST SITE IN BACK BAY

SCALE IN FEET

DISCUSSION OF TEST RESULTS

The tensile strength for the Yellowknife ice sheet is 413 ±50 psi. The Brazil test method was used to determine the value of the tensile strength. This method consisted of applying diametral compression between the platens of a compression testing machine to an ice cylinder having length shorter than its diameter. The load was increased until the sample broke in tension along a diametrical line connecting the two load points and passing through the center of the sample. A typical failure of an ice sample is shown in Figure 3. The stress distribution in the ice sample is shown in Figure 4. The tensile strength was calculated using the following equation:

$$\sigma_t = K\,\sigma_B = K\left[\frac{2F}{\pi DL}\right] \qquad (1)$$

where

σ_t = tensile strength, psi

σ_B = Brazil strength, psi

K = stress concentration factor, dimensionless

F = applied load at failure, lbs.

D = diameter of sample, inches

L = length of sample, inches

As shown in Equation 1, the tensile strength is the product of the Brazil strength and the stress concentration factor. For samples containing small holes the stress concentration factor is 6 [8]. Since the ice samples contained gas bubble inclusions, the stress concentration factor was taken as 6 for the Brazil tests conducted on the Yellowknife ice samples.

The test results are presented in Table I in terms of the Brazil strength values. These values are not biased with the stress concentration factor. Of the 62 samples tested, seven failed to break when subjected to the Brazil test. Some of these samples were too long thus requiring failure loads higher than the capacity of our compression machine. Other samples seemingly absorbed the loading energy and exploded apart when the load was released. The average Brazil strength for the remaining 55 samples was 68.8 psi with a standard deviation of 20.7 psi and a standard error [3] of 2.78 psi. A range of three standard errors establishes a 99.7% confidence level. Using a stress concentration factor of 6, one obtains the average tensile strength of 413 ±50 psi.

A comparison of the Yellowknife results can be made with Brazil tests conducted on zero salinity ice samples from ice floes in the Beaufort Sea. In September, 1970, AMOCO cored ice floes in the Beaufort Sea and subjected these cores to the Brazil test [2]. The results of the Yellowknife tests agreed quite well with the results of the Beaufort Sea tests. The distribution of the Brazil strength values from the Yellowknife tests can be seen in the histrogram presented in Figure 5.

FIGURE 3. ICE SAMPLE IN BRAZIL TEST

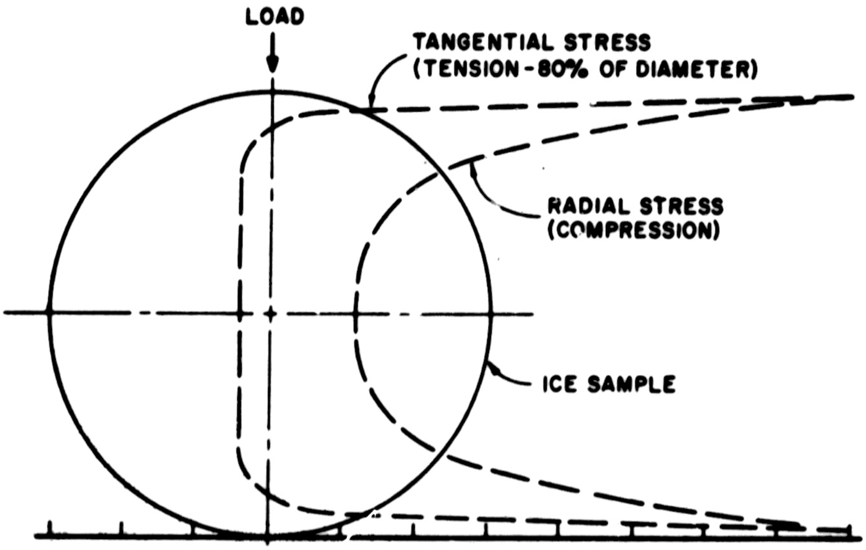

FIGURE 4. STRESS DISTRIBUTION IN ICE SAMPLE

FIGURE 3. ICE SAMPLE IN BRAZIL TEST

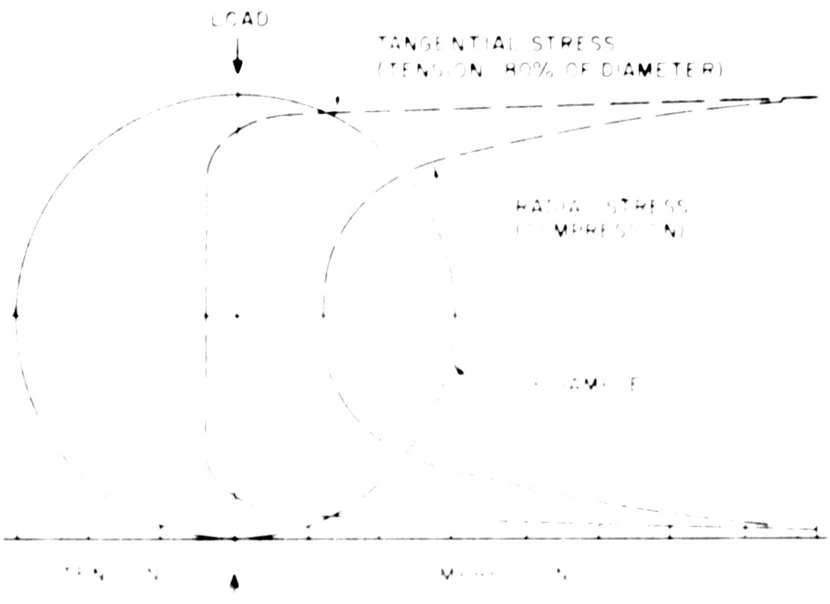

FIGURE 4. STRESS DISTRIBUTION IN ICE SAMPLE

TABLE I

RESULTS OF BRAZIL TESTS

Date	Location	Ice Sheet Thickness (inches)	Air Temp. (°F)	Depth to Core Top (inches)	Ice Temp. At Core Top (°F)	Sample Density (g/cc)	Stress Rate (psi/sec)	Brazil Strength (psi)
11-28-71	P1	15.7	16	3.50	25.5	0.77	2.93	88
	P2	16.1	16	5.75	25.0	0.78	3.06	52
	P3	17.3	16	5.88	25.0	0.73	8.30	83
	P4	16.5	16	4.00	24.0	0.76	4.79	91
11-30-71	P1	16.5	-17	5.50	28.0	0.79	5.14	36
	P2	16.5	--	----	----	----	----	--
	P3	17.7	-12	4.00	27.0	0.58	6.25	75
	P4	16.5	-12	2.75	28.0	0.76	7.83	47
12-1-71	P1	16.1	-16	3.50	27.0	0.83	10.00	80
	P2	16.9	-12	5.25	27.0	0.71	10.00	60
	P3	17.7	-16	6.50	27.5	0.72	9.20	92
	P4	18.1	-4	4.00	27.0	0.85	10.50	63
12-2-71	P1	16.1	17	4.13	27.0	0.74	12.40	62
	P2	17.7	17	6.00	27.5	0.80	7.50	30
	P3	17.7	17	1.88	----	0.79	----	--
	P4	18.9	17	4.25	----	0.80	----	--
12-3-71	P1	16.1	-7	5.00	----	0.77	----	--
	P2	17.3	-7	5.13	26.0	0.74	4.60	46
	P3	18.1	-7	4.00	26.0	0.77	16.60	83
	P4	18.9	-7	7.38	----	0.79	----	--
12-4-71	P1	17.3	-18	5.13	24.0	0.77	14.60	73
	P2	17.3	-18	5.50	23.5	0.77	8.20	41
	P3	18.1	-18	5.25	23.0	0.65	6.22	56
	P4	18.9	-18	9.25	27.0	0.79	9.17	55
12-5-71	P1	16.9	-24	8.50	24.5	0.78	6.67	60
	P2	17.3	-24	5.75	29.0	0.80	3.57	25
	P3	16.5	-24	4.50	28.0	0.72	8.13	65
	P4	16.5	-24	5.50	----	0.76	----	--
12-6-71	P1	18.1	-27	3.25	28.0	0.66	7.60	38
	P2	18.9	-27	6.50	28.0	0.72	6.09	67
	P3	19.3	-27	3.25	25.5	0.67	14.25	57
	P4	18.9	-27	3.63	28.0	0.74	8.00	40
12-8-71	P1	19.3	-13	8.5	24.0	0.75	12.04	65
	P2	18.9	-13	5.3	19.9	0.77	12.82	50
	P3	19.7	-13	10.88	24.5	0.79	11.14	49
	P4	19.3	-13	8.25	24.0	0.72	12.59	68

TABLE I (continued)

Date	Location	Ice Sheet Thickness (inches)	Air Temp. (°F)	Depth to Core Top (inches)	Ice Temp. At Core Top (°F)	Sample Density (g/cc)	Stress Rate (psi/sec)	Brazil Strength (psi)
12-9-71	P1	19.3	-18	9.13	25.0	0.91	10.71	75
	P2	18.9	-18	7.50	21.5	0.91	13.67	82
	P3	19.3	-18	10.00	23.0	0.99	11.71	82
	P4	19.3	-18	5.25	19.5	0.97	12.33	74
12-13-71	F1A	----	-40	1.25	----	1.01	20.00	80
	F1B	----	-40	8.50	----	0.93	13.73	103
	F1C	----	-40	3.20	----	0.92	22.00	99
	F1D	----	-40	----	----	0.88	21.40	107
	F1E	----	-40	----	----	0.86	23.86	105
12-15-71	P1A	21	-36	1.00	17.0	0.89	20.75	83
	P1B	21	-36	10.25	23.0	0.92	15.75	63
	P2A	22	-36	0.75	18.0	0.87	21.00	84
	P2B	22	-36	5.50	21.5	0.78	20.00	80
1-7-72	P1A	33	-41	2.50	----	0.85	17.60	88
	P1B	33	-41	10.00	----	0.92	18.25	73
	P1C	33	-41	19.00	----	0.89	17.60	89
	P3A	40	-41	2.00	----	0.91	24.62	64
	P3B	40	-41	11.00	----	0.90	21.90	46
1-12-72	TC2	32	-38	0.80	----	0.92	25.00	75
2-10-72	TC6A	39.6	+25	3.50	----	0.91	15.00	30
	TC6B	39.6	+29	20.00	----	0.92	-----	--
	TC6C	39.6	+29	3.00	----	0.93	22.25	89
	TC6D	39.6	+29	18.00	----	0.86	23.25	93
	TC6E	39.6	+29	18.00	----	0.93	25.25	101
	TC8A	40.0	+30	10.00	----	0.87	20.25	81
	TC8B	40.0	+31	22.00	----	0.88	23.16	44

Notes:

P1 -- Location at temperature probe No. 1
P2 -- Location at temperature probe No. 2
P3 -- Location at temperature probe No. 3
P4 -- Location at temperature probe No. 4
F1 -- Location at temperature probe No. 4
TC2 - Location at test course No. 2
TC6 - Location at test course No. 6
TC8 - Location at test course No. 8

HISTOGRAM OF BRAZIL STRENGTH DATA

BRAZIL STRENGTH DATA OBTAINED ON THE FRESH WATER ICE SHEET AT YELLOWKNIFE. NWT
STRESS FACTOR K = 1.0

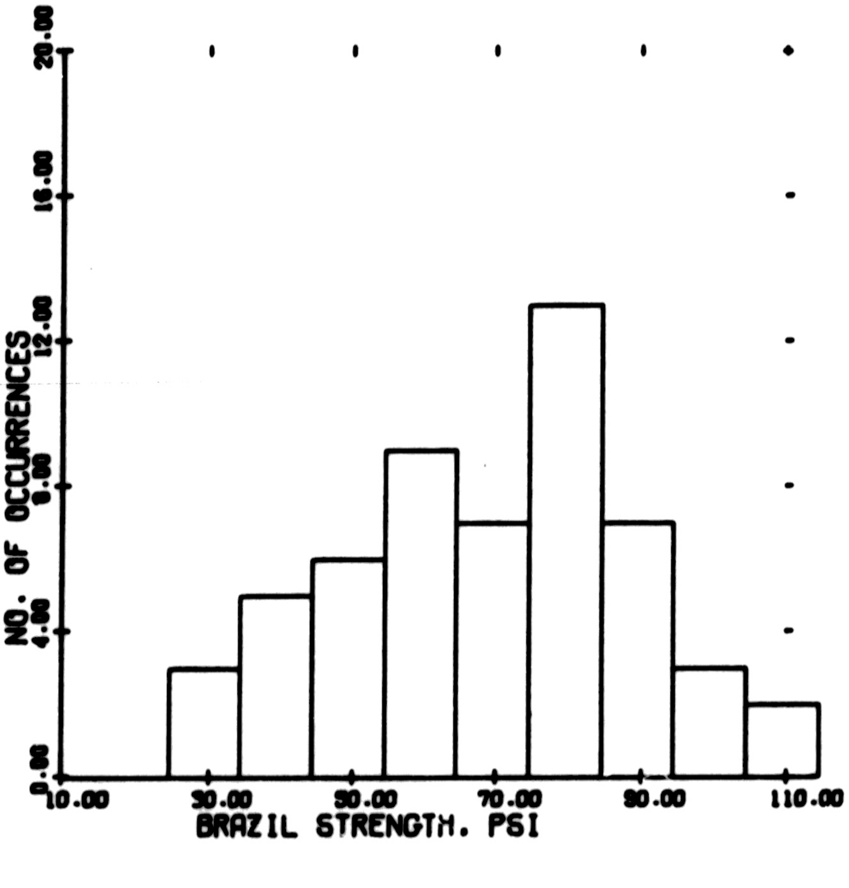

Figure 5. Histogram for Yellowknife Tests

[illegible] AND ARCTIC DRILLING [illegible].

Table II presents the tensile strength values of fresh water ice as reported by other investigators using similar test methods.

TABLE II

TENSILE STRENGTH VALUES

Strength (psi)	Concentration Factor	Investigator (Ref.)
413	6.0	Sunoco E&P Limited
428	6.0	Dykins [4]
412	6.0	Graystone and Langleben [5]
405	5.2	Frankenstein [6a]

An ice fabric study [7] was conducted as part of the ice mechanics program at Yellowknife. The most significant feature of the ice cover was the stratification of air bubble inclusions as shown in Figure 6.

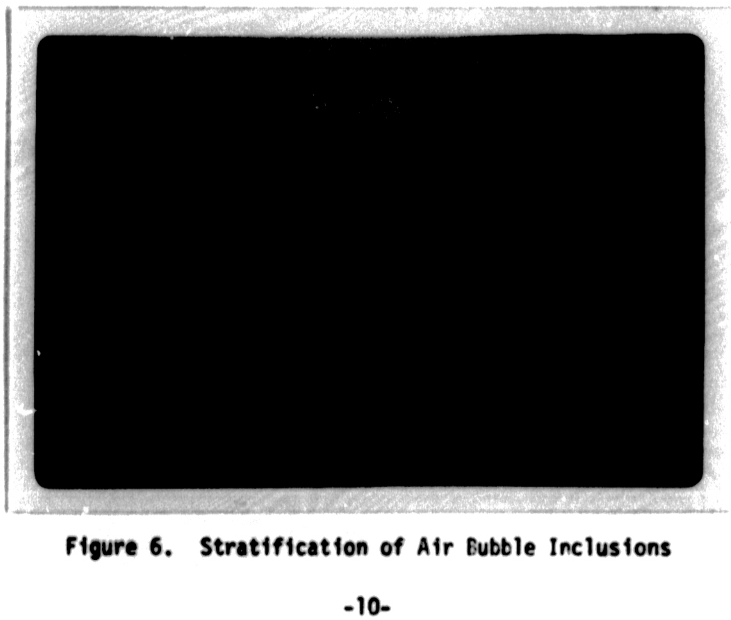

Figure 6. Stratification of Air Bubble Inclusions

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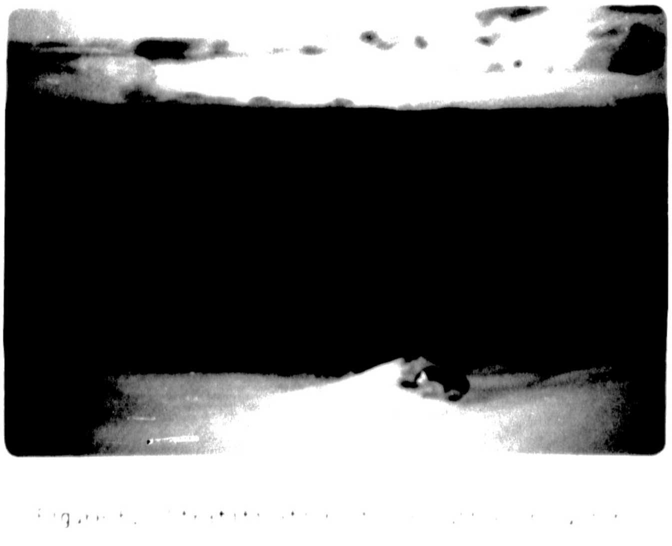


[illegible]

As one probes deeper into the ice sheet, the thickness of the inclusion layer increases but the number of inclusions decreases. At about 20 inches into the ice cover, the inclusion layer is four to five inches thick with air bubble inclusions spaced three to four inches apart. The ice sample shown in Figure 7 was taken from the upper portion of the ice sheet. One can readily see the numerous air bubble inclusions. In ice deeper than 20 inches, the air bubble inclusions are apparently not present or they are widely distributed. An ice sample from a depth of 20 inches is shown in Figure 8.

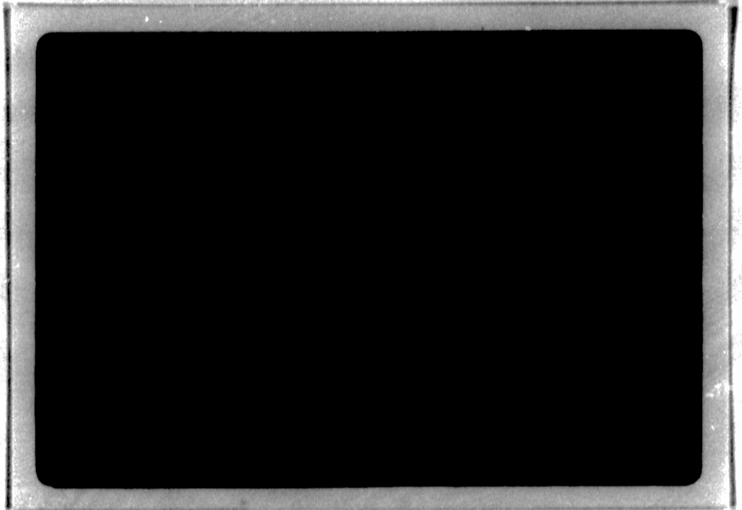


Figure 7. Ice Sample from Top Portion of Ice Sheet

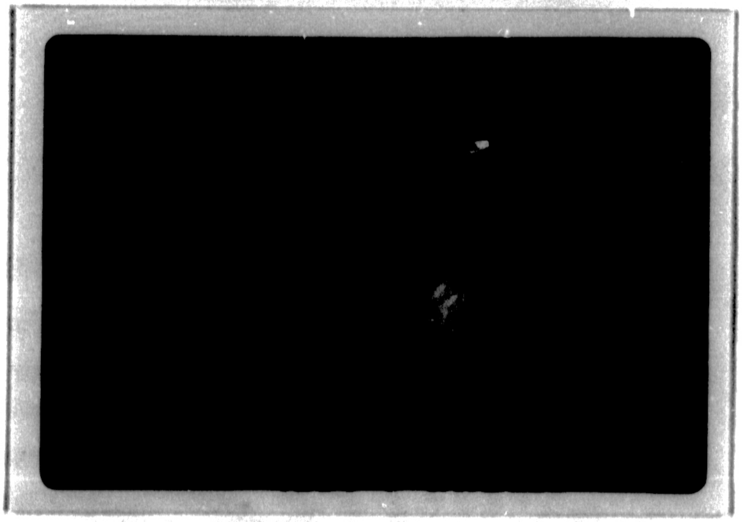
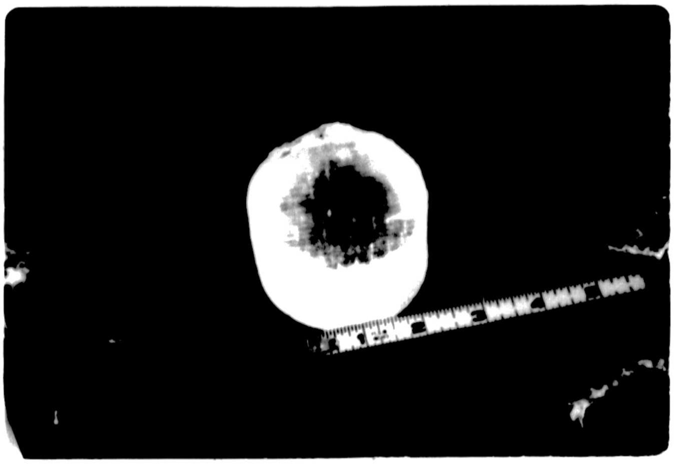


Figure 8. Ice Sample From Twenty Inches Deep




CORE #5
SIDE OF TEST

The major fabric variation in the ice sheet occurs in the upper few inches as one passes through the surface chill zone into the medium-to-coarse-grained crystal zone. The major change in the ice fabric below the chill zone was found to be an increasing complexity of the intercrystalline boundaries. These boundaries in the upper portion of the ice cover are simple, clearly defined planes. In the lower portion of the ice cover the intercrystalline boundaries are feathered one into the other.

The variations that occur through the ice will be reflected in the inherent strength of the ice. The large standard deviation in the determination of the Brazil strength eliminates any possibility of relating the ice strength to the vertical variation of the intercrystalline boundaries.

The effect of the air bubble inclusions is related to ice strength by the density of the ice sample subjected to testing. The ice sample with a low density will have a high void volume thus it will contain a higher number of air bubble inclusions. As with a perforated disk, the ice sample with a high number of holes (inclusions) will have a low strength value.

Figure 9 illustrates the effect of sample density on the Brazil strength of the sample. As would be expected, the Brazil strength decreases as the density decreases.

The value of the Brazil strength is currently thought to be independent of the stress rate for the range of 14 to 42 psi/sec [6b].

The values of the Brazil strength obtained in the Yellowknife tests are presented in Figure 10 as a function of the stress rate. The spread of the data is such that only a general observation can be made. It appears that the stress rate has some effect on the Brazil strength. The Brazil strength in general increases with increasing stress rate.

The temperature of the ice sample also has an effect on ice strength in that strength increases as temperature decreases. The temperature of the ambient air and the ice sheet temperature at the top of the core sample [12] are given in Table I. The ice samples were normally tested within 20 to 30 minutes after being removed from the ice sheet. The actual temperature of the ice sample at testing was less than the ice sheet temperature but certainly not that of the ambient air temperature. Generally speaking, the center temperature of the ice samples can be assumed to be within 5% of the original temperature if the test is performed within approximately 10 minutes after removal from the ice sheet. For the center temperature to reach 95% of the ambient air temperature, the ice sample must sit for approximately 3 hours. Because of the uncertainty of the ice sample temperature, a plot of Brazil strength as a function of temperature is not presented in this report.

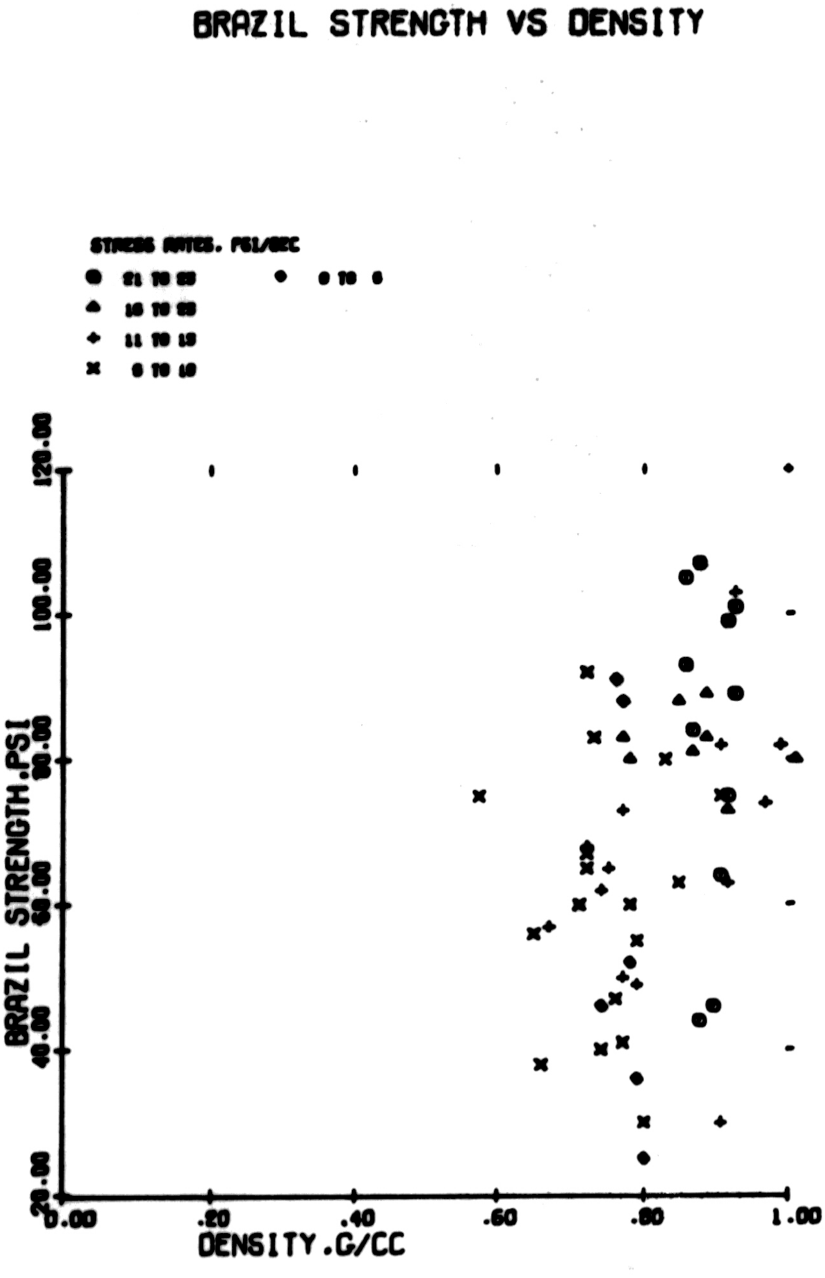


Figure 9. Brazil Strength vs. Density

BRAZIL STRENGTH VS STRESS RATE

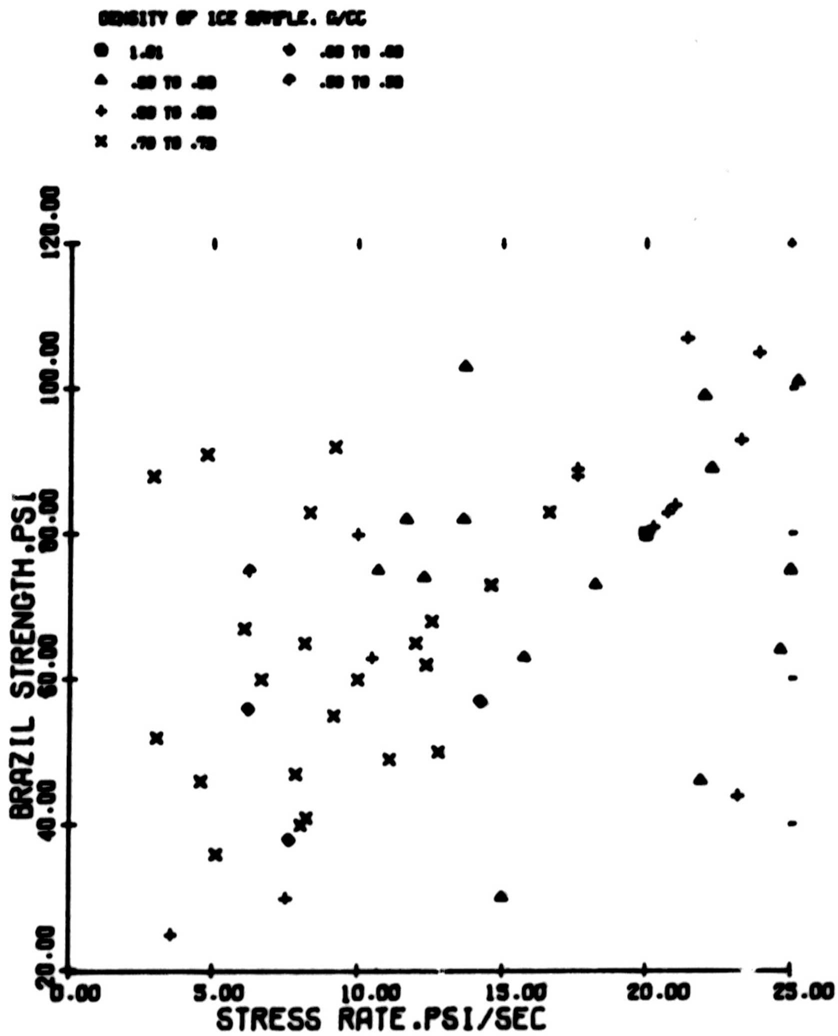


Figure 10. Brazil Strength vs. Stress Rate

DISCUSSION OF BRAZIL TEST METHOD

Theoretically the Brazil test method creates a tension stress over 80% of the diameter of the ice sample (see Figure 4). This method is a highly successful method in determining the tensile strength in rocks [8]. When properly conducted, the Brazil test gives a good approximation to the uniaxial tensile strength, at least in rocks. The Brazil test appears to be relatively insensitive to inelastic behavior and non-linearity. However, the Brazil test is not widely used in the study of ice strength. The ring tensile test has been extensively applied to studies of ice, especially sea ice [6c]. The ring tensile test is a Brazil test with a hole in the center of the sample.

The merits of the Brazil test and the ring tensile test have been compared by Mellor and Hawkes [9]. They concluded that there are several serious objections to the ring test which appear to completely invalidate it as a practicable test. The Brazil test fares no better in their judgement as they point out that the failure criterion of Griffith-type materials, which is the basis for the Brazil test theory, does not appear applicable to ice. Another comparison was made by Nevel [10]. Nevel concluded that the Brazil test is preferable for strength measurements and that the ring tensile test may be a potentially good test for determining Young's modulus. In a recent study on analysis of the small-scale strength testing of ice, Maser [11] points out that the ring tensile test provides a poor index for bulk ice strength, and its continued use for such a purpose is not recommended. Maser states that the potential use of the Brazil test is much more promising than has been generally assumed.

It appears that the Brazil test method even with certain inherent problems of interpretation has more merit for strength measurements than the ring tensile test method currently in extensive use. The average value of the Brazil strength for the Yellowknife ice cover provides an adequate basis for estimating the tensile strength of the ice even though the value of the stress concentration factor is the biasing number.

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APPENDIX A

SUMMARY OF FENCO'S RESULTS

SUMMARY OF FENCO'S TESTS

Table III presents a summary of the results obtained by FENCO [1]. Various test methods were used to determine the following properties: Tensile strength, unconfined compressive strength, elastic modulus and maximum contact pressure.

The two methods that were employed to obtain the tensile strength of the ice were the cantilever beam test and the encastré beam test. The cantilever beam test was difficult to perform because the beams usually cracked during the cutting process with the result that the beam fails prematurely after loading or simply dropped off into the water before loading. Because of the difficulty in obtaining uncracked specimens, the results showed considerable scatter rendering interpretation difficult and in some cases impossible. The encastré beam test was used to overcome the drawbacks of the cantilever beam tests. The encastré beam is simply a beam with both ends fixed. The results from the encastré beam tests were consistent and permitted the calculation of ice tensile strength and the modulus of elasticity. FENCO's analysis of the test results showed that the encastré beams were capable of carrying loads 3 to 4 times greater than those loads which caused the beams to crack in tension. The tensile strength value of 13 bars (188.5 psi) is approximately one-half the value of the strength determined by the Brazil test method. Perhaps the Brazil test is the quickest method to approximate the failure strength of an ice sheet.

The unconfined compressive strength was determined by jacking a triangular plate against the side of a rectangular pit cut into the ice. These tests are quickly prepared, easily executed and the results are reliable. The disadvantage of these tests is that they must be performed so that the hypotenuse of the triangular plate is flush with the upper surface of the ice sheet. In thick ice this method cannot be used to determine the variation of ice strength with depth.

The elastic modulus was evaluated directly from the encastré beam tests and indirectly from the pressure meter tests. The pressure meter test system consists of a pressure cell that is lowered into a borehole and expanded to contact and press against the borehole wall, registering the stress-strain sequence. The elastic and plastic ice properties are deduced from the pressure-relative volume change curves.

The maximum contact or bearing pressure was determined using rectangular plates and circular plates. The tests yielded results which are indicative of the strength which the ice is capable of developing when it is subjected to foundation type loading.

TABLE III

SUMMARY OF FENCO'S TESTS

Location	Physical Properties of Ice					
	Salinity (0/00)	Tensile[c] Strength (Bars)	Compressive[a] Strength (Bars)	Elastic Modulus (10^3 Bars)	Max. Contact Pressure	
					Strip (Bars)	Round (Bars)
Yellowknife	0.0	13	40.0	83.0	88.0	125
Tuktoyaktuk[b]						
Station D	2.1	--	32.3	62.5	78.6	--
Station F	4.6	--	36.7	26.0	84.1	--

a - Strength horizontal to ice sheet
b - Average ice temperature was - 17.5°C
c - Measured by the encastré beam technique