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Testing of an Oil Recovery Concept for Use in Brash and Mulched Ice

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TESTING OF AN OIL RECOVERY CONCEPT FOR USE IN BRASH AND MULCHED ICE

S.L. ROSS ENVIRONMENTAL RESEARCH LIMITED
OTTAWA, ONTARIO

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SUMMARY

A series of experiments was carried out to investigate the concept of mechanically submerging ice as a method of removing oil from brash and mulched ice. A device incorporating an inclined porous plane was found to submerge ice poorly and was rejected as a recovery concept. A device incorporating a rotating porous drum with paddles was more successful at processing oiled ice; it effectively submerged the brash ice and allowed the buoyant oil to flow up and into the porous drum. Recovery efficiencies up to 90%, with most values in the 40% to 65% range, were achieved for crude oil. Lower efficiencies (13% to 64%) were achieved in tests using viscous fuel oils.

RÉSUMÉ

Plusieurs expériences de submersion mécanique furent menées pour éprouver cette technique possible de nettoyage des sarrasins et des glaces concassées enduits de pétrole. Un appareil à plan incliné poureux submergeait mal la glace et fut rejeté. Un dispositif à tambour rotatif poreux muni de palettes traitait mieux les glaces huilées; il submergeait efficacement les sarrasins et le pétrole flottant remontait jusque dans le tambour. L'efficacité de récupération du pétrole brut variait surtout entre 40% et 65% mais pouvait atteindre 90%. Celle des fuels visqueux était plus faible (de 13% à 64%).

1.0 INTRODUCTION

While considerable technology exists for the cleanup of oil spills on open water and some methods have been devised for spills under complete ice cover, no techniques are available for dealing with oil spills amongst broken ice. Conditions of brash ice - defined as floes less than 2 m diameter - and pulp ice are common off Canada's east coast during the winter and spring months. Such conditions may also occur in the southern Beaufort Sea during periods of freeze-up and break-up. The anticipated oil production and accompanying oil spill risks in these two areas demand the development of novel techniques which will function in broken ice.

Several recent studies have addressed the problem of oil spill cleanup in broken ice. The first involved a brainstorming workshop (S.L. Ross, 1982) during which ideas were presented for responding to a major tanker accident in east coast brash ice. Two such ideas, a porous bottomed sled (with optional burner for disposal of recovered oil) (Figure 1) and a conventional oleophilic disc skimming head fitted with an ice protection screen (Figure 2), were the basis for further research.

As a follow-up to the workshop, a preliminary assessment was undertaken of the feasibility of these two and several other promising ideas (S.L. Ross, 1984). Small scale tests performed with porous surfaces showed that mechanical submergence with agitation of the oiled ice effectively permitted the buoyant oil to rise to the water surface for recovery. One problem noted was the tendency for oil, especially viscous fuel oils, to cling to the porous surface.

FIGURE 1 : POROUS BOTTOMED OIL RECOVERY SLED

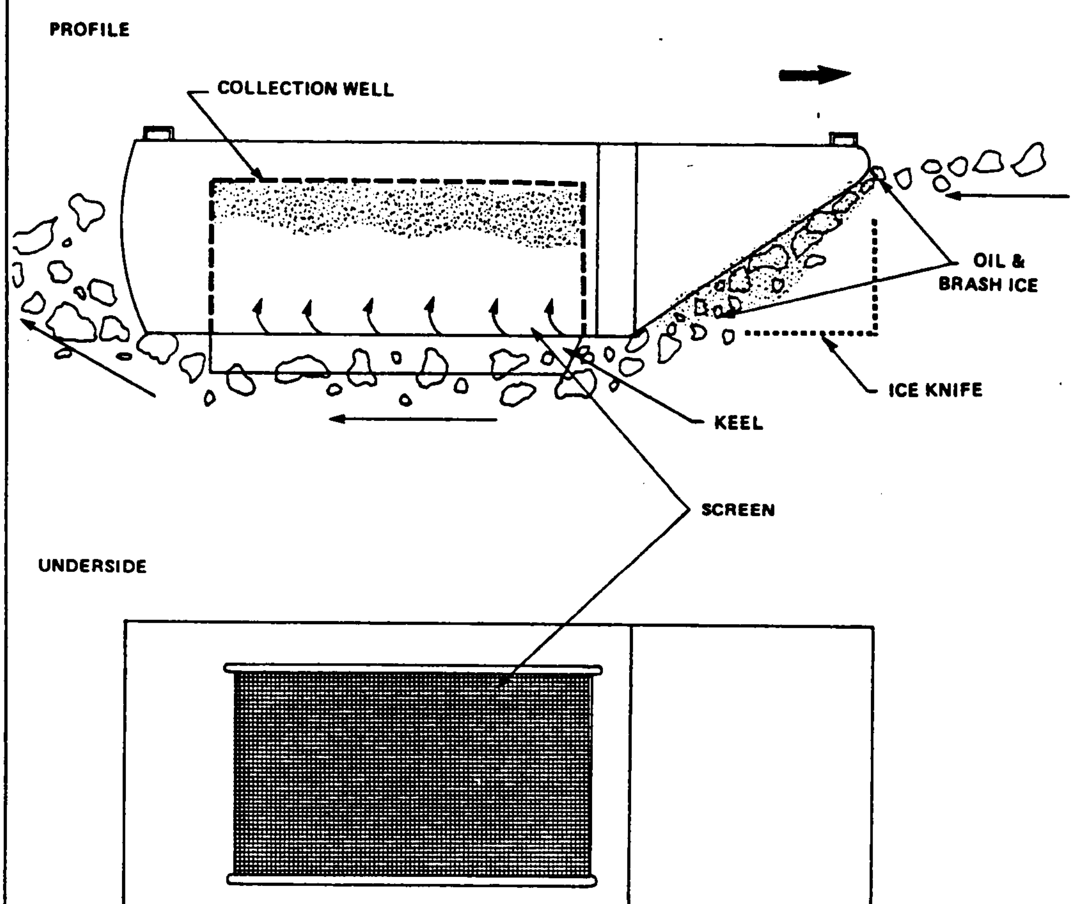
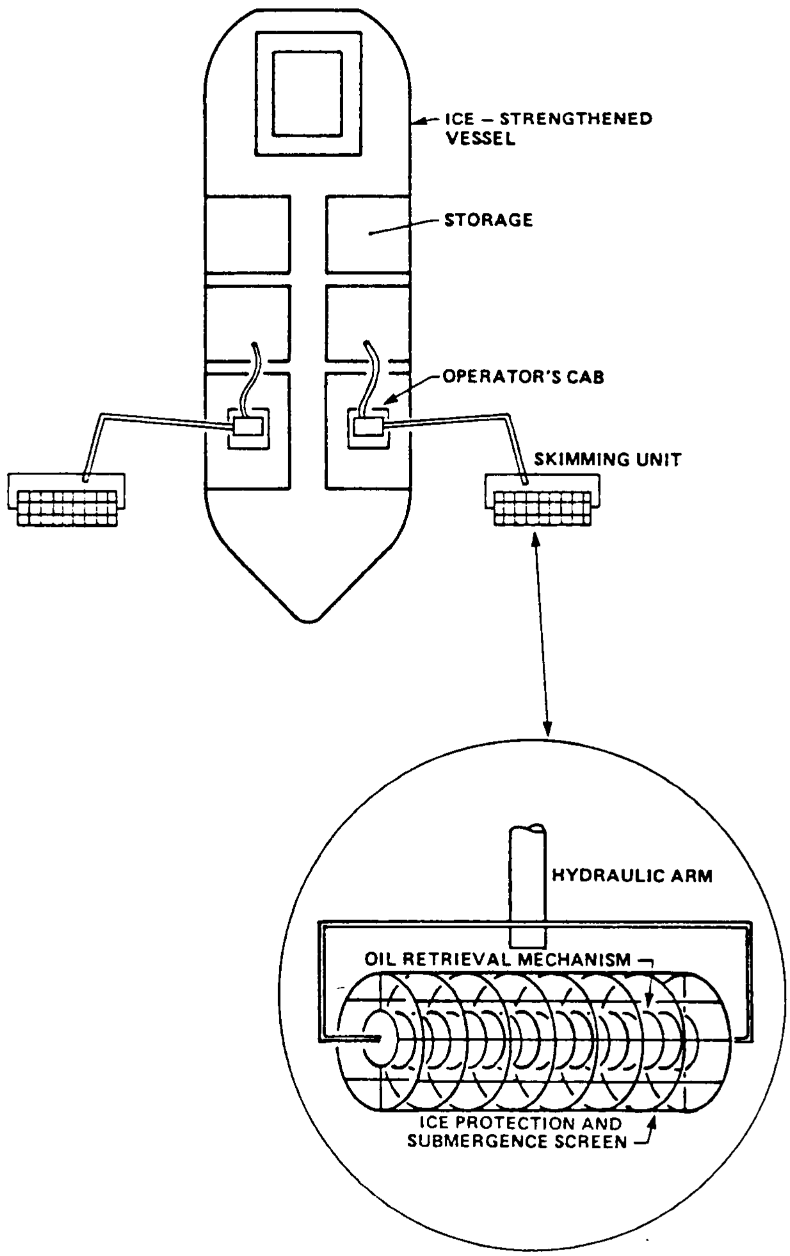


FIGURE 2 : CONVENTIONAL SKIMMER MODIFIED FOR OPERATION IN ICE



For the present study, larger-scale porous inclined plane and porous rotating drum systems were designed and constructed to further investigate the recovery concept. The porous plane incorporates porous bow, bottom and stern panels to allow the infiltration of oil. The bow panel is hinged to enhance ice processing as the device is advanced. The porous drum includes paddles which, along with the rotation of the drum, submerge the oiled ice.

This report describes the tank testing of these two oil recovery concepts in brash and mulched ice.

2.0 ICE CONDITIONS

Of interest in this study are conditions of brash ice which are defined as floes less than 2 m across, and pulp. Such conditions may be encountered at certain times of the year in the southern Beaufort Sea and off Canada's east coast.

The most common time for the occurrence of brash ice in the Beaufort Sea is during the period of freeze-up which usually begins in late September. As ice begins to grow in a level sheet, wind and wave action cause it to break into fragments, creating brash. When the disruptive forces cease, the ice fragments freeze together forming large floes. When the ice grows to a thickness of 30 cm or greater it is more resistant to fracture and usually forms ridges if broken. At this thickness, brash ice is limited to fragments of new ice forming in leads. Ambient air temperatures are likely to average between 0 and -10^{o}C during this period of freeze-up.

Brash ice is not likely to occur during winter months as the extremely low temperatures cause any fragments to quickly refreeze into a solid mass. Brash ice does not naturally occur in any significant concentration during spring break-up, though it would be possible to use ice breaking ships to create areas of brash.

Brash ice is more common off Canada's east coast due to the generally higher temperatures, which cause slower ice growth, in combination with the high sea states and frequent storms in the region. Brash ice may occur throughout the periods of freeze-up and winter, generally as a result of crushing and abrading forces between ice cakes and between the moving pack ice and landfast ice edge. During the period of "break-up" and pack ice retreat, brash ice is much more common because the floes in the pack continue to be fragmented and refreezing of the brash and pulp no longer occurs.

2.1 Experimental Ice Conditions

As originally proposed, the porous plane concept was intended for use in brash and pulp ice conditions. If larger floes were encountered the device would be unable to submerge them and release oil trapped in under ice depressions.

For this study it was originally proposed to consider two combinations of ice particle sizes: 100% fine ice pulp, and a mixture of 25% pulp, 25% large ice blocks (30 to 60 cm) and 50% medium sized chunks. Preliminary testing showed that although oil could be recovered from the fine ice pulp, a large amount of pulp also passed through the pores of the device. It was decided to limit the testing to a mixture of chunks and pulp as would more likely be encountered in a real spill.

Freshwater ice, broken by sledgehammers into chunks of the desired size, was used for the experiments. While obviously different than the naturally occurring saline ice, it was similar enough geometrically.

The concentration of ice pieces simulated $10/10^{ths}$ coverage with an overall ice thickness of approximately 30 cm. At the start of each day, new ice was added to the tank to make up for melting losses overnight. As well the top surface of the ice mixture, which had frozen together overnight, was broken up to ensure consistency between the first and succeeding test runs.

3.0 TEST DEVICE DESIGN

3.1 Porous Plane Device

This device was based on the initial concept proposed in the brainstorming workshop. Although its ability to process ice did not appear promising, its mechanical simplicity was felt to offer several advantages. For example, its submergence depth could be easily controlled, it had no moving parts and it could easily be towed or pushed.

A diagram of the test device is shown in Figure 3. The bow, bottom and stern surfaces were fitted with porous panels, replaceable to allow for three different pore sizes. Plexiglass was used for the side panels. The bow panel was hinged to allow a variable bow angle. The entire device was suspended from a cart by pieces of angle iron; adjustments were possible for controlling submergence depth and bottom panel inclination. The cart was a steel frame, welded on one side and mounted on bearings on the other side. The bearings rode along a 1-inch rod which was fixed along the upper edge of the tank wall.

3.2 Porous Drum Device

This device was similar in concept to the porous plane, with the advantage of drum rotation to increase its ability to process ice.

A photograph of the test device is shown in Figure 4. The drum comprised a rolled angle-iron frame to which a sheet of porous steel was bolted. The porous sheet was replaceable to allow the use of three different pore sizes and drums of three diameters (500, 750 and 1000 mm). Paddles were bolted to the drum to aid in ice entrainment. Plexiglass panels were bolted to the drum sides to keep ice out and collected oil within the drum. The panels were easily removable to enable collection and measurement of the contained oil.

FIGURE 3 : POROUS PLANE DEVICE

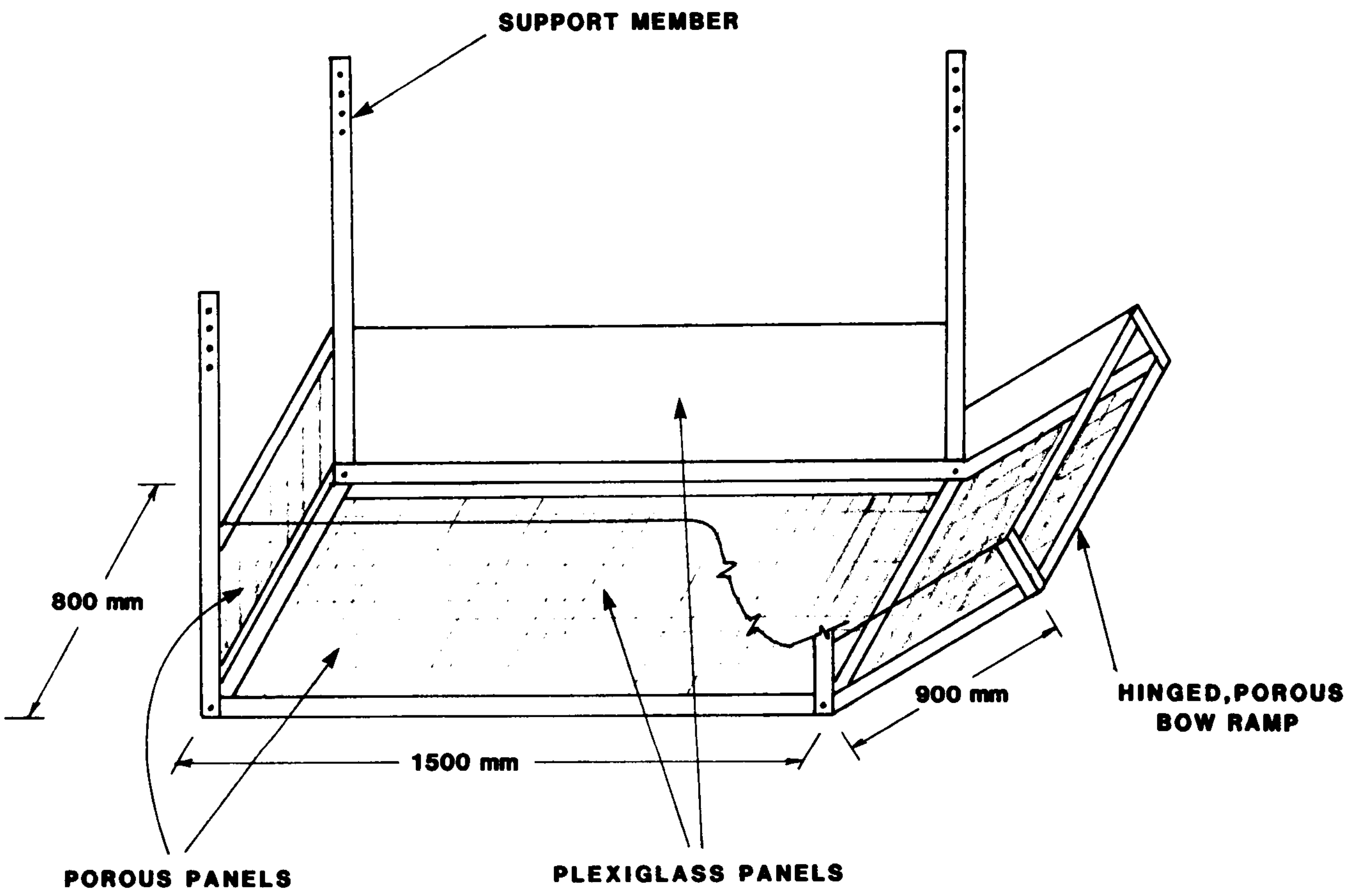
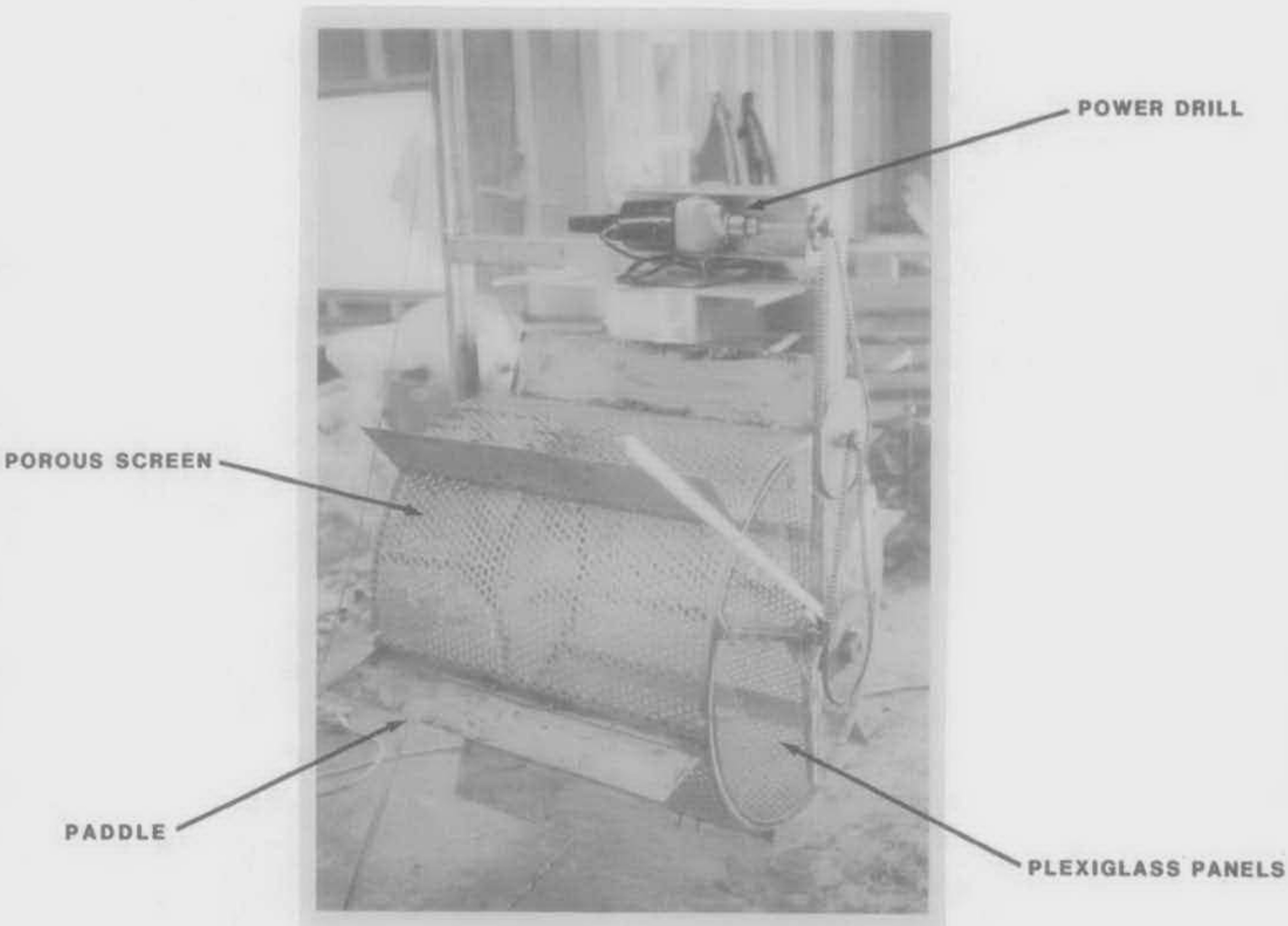


FIGURE 4 : POROUS DRUM DEVICE



The drum apparatus was suspended from the same cart as used for the porous plane; the support connections could be varied to change the submergence of the drum. Drive for the drum rotation was provided by a variable speed drill with a chain and gear arrangement with 30:1 gear reduction.

3.3 Porous Surface

The material used for the porous surface panels on both the plane and the drum was perforated sheet steel. It was noted in the earlier preliminary feasibility study that the overall porosity should be maximized as some of the oil - especially in tests with the more viscous fuel oil - tended to stick to the submerging screen rather than rise up through the pores as desired. However, for these test prototypes, it was desirable for economic reasons to use commercially available materials. The overall porosity for the porous surfaces is calculated in Appendix A; it varies from 40% to 48% depending on the pore size. Considering the problem of oil clinging to the metal rather than rising through the pores, greater porosity would have been desirable and is recommended for subsequent full-scale designs. Greater porosity could be achieved with a custom designed surface which derived its required flexural strength from frame members rather than from the surface itself.

3.4 Device Positioning and Towing

The porous plane and porous drum devices were each designed to be mounted on a towable cart. One side of the cart was supported by two wheels which rode along the top edge of the tank wall. The other side was guided and supported by two bearings which rode along a rod fixed along the top edge of the other tank wall. A cable, driven by a 3 HP electric motor, pulled the cart along the test tank. The drive motor was continuously variable allowing forward speeds ranging from 0.08 to 0.5 m/s (0.16 to 1.0 knots).

4.0 EXPERIMENTAL CONDITIONS

The tank used for the experiments is shown in Figures 5 and 6. Its dimensions are length: 11 m, width: 1.2 m and depth: 1.2 m. The glass walls of the central tank section allowed unobstructed viewing of the devices as they passed.

The water in the tank was of approximately 32 parts per thousand salinity. Its temperature was fairly constant at 0^{o} to $1^{o}C$. The ambient temperature in the laboratory ranged from 0^{o} to $8^{o}C$ during the experiments.

For all test runs, brash and mulched freshwater ice was used with an overall thickness of 200 to 300 mm. Individual ice pieces ranged in size from fine pulp to roughly 150 mm in diameter.

4.1 Oils Used and Their Properties

Four oils were used in the experiments; their properties are listed below.

1.	Light crude oil	Alberta Sweet Mixed Blend (ASMB) density: 0.84 g/ml viscosity: 9.2 cp @ $15^{o}C$ pour point: $-20^{o}C$
2.	Medium weight oil	No. 4 Fuel Oil (prepared by mixing 60% No. 6 F.O. and 40% No. 2 F.O.) density: 0.93 g/ml viscosity: 46.4 cp @ $20^{o}C$ pour point: $-7^{o}C$

FIGURE 5 : VIEWING WINDOW OF TEST TANK

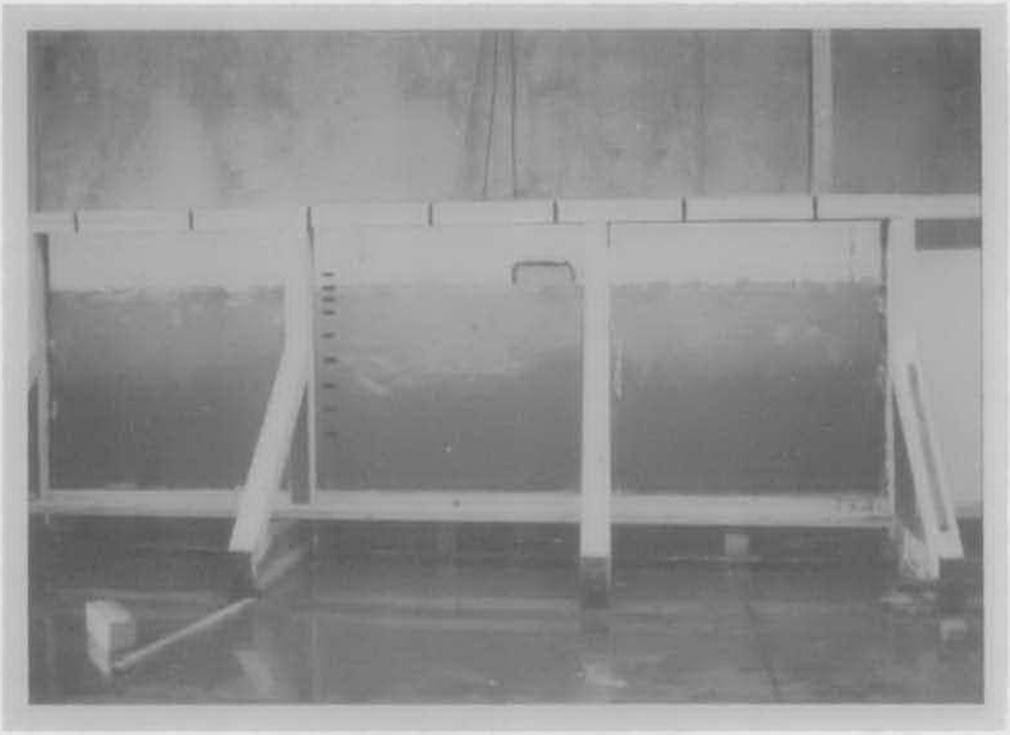


FIGURE 6 : TYPICAL PRE-TEST AREA OF OILED ICE

3.	Heavy oil	No. 5 Fuel Oil density: 0.95 g/ml viscosity: 598 cp @ 20^oC pour point: -9^oC
4.	East Coast crude oil	density: 0.86 g/ml viscosity: 33.2 cp @ 20^oC pour point: 15^oC

5.0 EXPERIMENTAL METHODOLOGY

Prior to testing either device with oil, the porous plane and porous drum were each qualitatively tested for their ice processing capability. Small pieces of wood, numbered for identification of their relative locations, were placed in the broken ice ahead of the test devices. Each device was towed through the tank several times, varying the submergence depth, the forward speed and rotation speed and noting their effects on each device's ability to effectively submerge ice. Through these tests the optimum test parameters were determined for testing with oil.

The testing methodology was essentially the same for the porous plane and porous drum. A measured volume of oil was mixed into the ice ahead of the test device and its temperature allowed to equilibrate. The oiled area was approximately 3 m long and 1 m wide. Figure 6 shows a typical pre-test area of oiled ice.

For the tests with fuel oils, the oil was spread over a narrower area (approximately 0.5 m wide) due to its greater equilibrium thickness. Had this oil been spread over the normal width it would have been very patchy so it was decided to concentrate the patches in the centre of the track.

Before each test run the submergence depth was measured. For the plane, the fore and aft submergence was measured (fore depth at the base of the bow ramp and aft depth at the aft end of the plane, Figure 3) as well as the angle of the bow ramp from horizontal. The drum submergence was measured from the bottom of the drum perimeter to the waterline.

Oleophilic and hydrophobic sorbent pads were used to collect and measure the recovered oil at the end of each test run. Prior to each run, four sorbent pads were distributed on the water surface inside the test device. In this manner the pads sorbed the oil as it entered the test device, preventing the collected oil from seeping out. With the porous plane a length of wood spanning the inner collection area kept the sorbent pads in place. With the porous drum the pads remained in position and flat on the water surface as the drum rotated.

The test device was then towed along the tank. Each run was recorded on videotape with a timer display. These recordings were later used to measure the forward and rotational speed for each run (v and w respectively). The submergence time, the time that a given piece of ice was submerged by the drum, was calculated using the measured rotational speed and drum submergence (calculation method is shown in Appendix B).

Upon completing a test run, the sorbents were removed from the test device and weighed. The difference between this weight and the previously measured dry weight was used to calculate the recovered oil volume using the densities noted in 4.1. The oil recovery efficiency was calculated as the percentage oil volume recovered of that spilled. For several test runs the volume of oil coating the exterior drum surface was estimated by sorbing the oil from a one-sixth drum section. As well, the amount of oil in the ice track was estimated for several runs by manually recovering this oil with sorbents, and then weighing the sorbents. Following the measurements, the ice was manually cleaned using sorbent pads in preparation for the succeeding run.

6.0 RESULTS AND DISCUSSION

There are two requirements for mechanically removing oil from brash ice using a submerging porous surface. First the ice has to be submerged with as little lateral ice movement as possible; otherwise the device would simply plough through the ice cover, pushing ice pieces ahead and to the sides. Secondly, the oiled ice has to be submerged for enough time to allow the buoyant oil to rise into the submerging device. The merits of each device are discussed below in the context of these two requirements.

6.1 Porous Plane Device

Preliminary tests with the porous plane (without oil) indicated that the best ice processing was achieved with minimal plane submergence. Also, ice processing was enhanced by raising the aft end slightly such that the advancing plane was downward sloping at the forward end (the bow ramp) and slightly upward sloping at the aft end.

The porous plane showed a poor ability to process ice. In the preliminary tests without oil and in the tests with oil the plane produced a build-up of ice at its leading edge which prevented ice chunks from flowing under the plane. In general, had the ice not been confined by the side and end walls of the test tank, the device would have simply ploughed through the ice cover and not submerged any ice. Even with a shallow submergence depth, an excessive amount of ice built up under the leading edge of the plane; in several cases it was in danger of grounding the ice build-up against the tank bottom. An example of this ice build-up is shown in Figure 7 (the plane has just completed its run and the leading edge is on the right).

Given the confinement provided by the tank walls, ice would accumulate at the bow of the device as it was towed until an equilibrium was reached

FIGURE 7 : ICE BUILD-UP AT LEADING EDGE OF POROUS PLANE

between the forward force of the device and the reaction force of the ice. Only when this equilibrium was reached did the plane both submerge an appreciable amount of ice and collect any oil.

Due to the ineffective ice processing only a limited number of tests were performed with oil. The results, including oil recovery efficiency, are listed in Appendix C. The measured recovery efficiency ranged from 50% to 92%, with four of the six results in the 62% to 71% range. This indicates that there is little correlation between recovery efficiency and any of the varied parameters (submergence depth, forward speed and pore size). In any case, the results are of little practical value due to the excessive and non-repeatable ice build-up. A single test with No. 5 Fuel Oil resulted in a low recovery efficiency due to the oil's greater viscosity and greater tendency to adhere to the ice.

In conclusion, there are two main reasons for rejecting the porous plane as a oil recovery device in brash ice:

1) while the recovery efficiency results appear to be good, this is deceptive because to achieve those results, ice was, in effect, forced under the device by the confining side and end walls of the tank; and
2) in the real world, the excessive ice build-up at the leading edge of the plane would result in very little oiled ice being submerged by and flowing under the plane.

6.2 Porous Drum Device

The porous drum was much more successful at processing ice. As the device advanced, the rotation of the drum and paddles effectively submerged the brash ice as it was encountered with little lateral movement of the ice and no noticeable ice build-up.

Due to the low torque limit of the variable speed drill, slow rotational speeds were necessarily accompanied by slow forward speeds. For such conditions, the ice force resisting the forward motion of the device provided the moment required to turn the drum. Normal and fast rotational speeds were not a problem for the drill.

The complete test results with oil are listed in Appendix D and are summarized in Table 1. The recovery efficiency ranged from 26% to 90% for crude oil, with most in the 40 to 65% range, and from 13 to 64% for the viscous residual fuel oils.

During the test program, the submergence time was thought to be the most important variable governing the recovery efficiency. The submergence time, the time that a piece of oiled ice was submerged by the porous drum, was varied by changing the submergence depth and the rotational speed. In the preliminary feasibility tests (S.L. Ross, 1984) submergence times in the 2 to 15 s range were used successfully; the same range was used for these tests. As noted previously, the other significant finding in the preliminary feasibility tests was the importance of providing sufficient agitation to release the oil from the ice and allow it to flow through the porous surface.

The following two sections discuss the effect on recovery efficiency of varying submergence time by changing the rotational speed and the submergence depth. Discussions of the other parameters follow in individual sections. Finally the major factors affecting the variability of the results are presented.

6.2.1 Rotational Speed

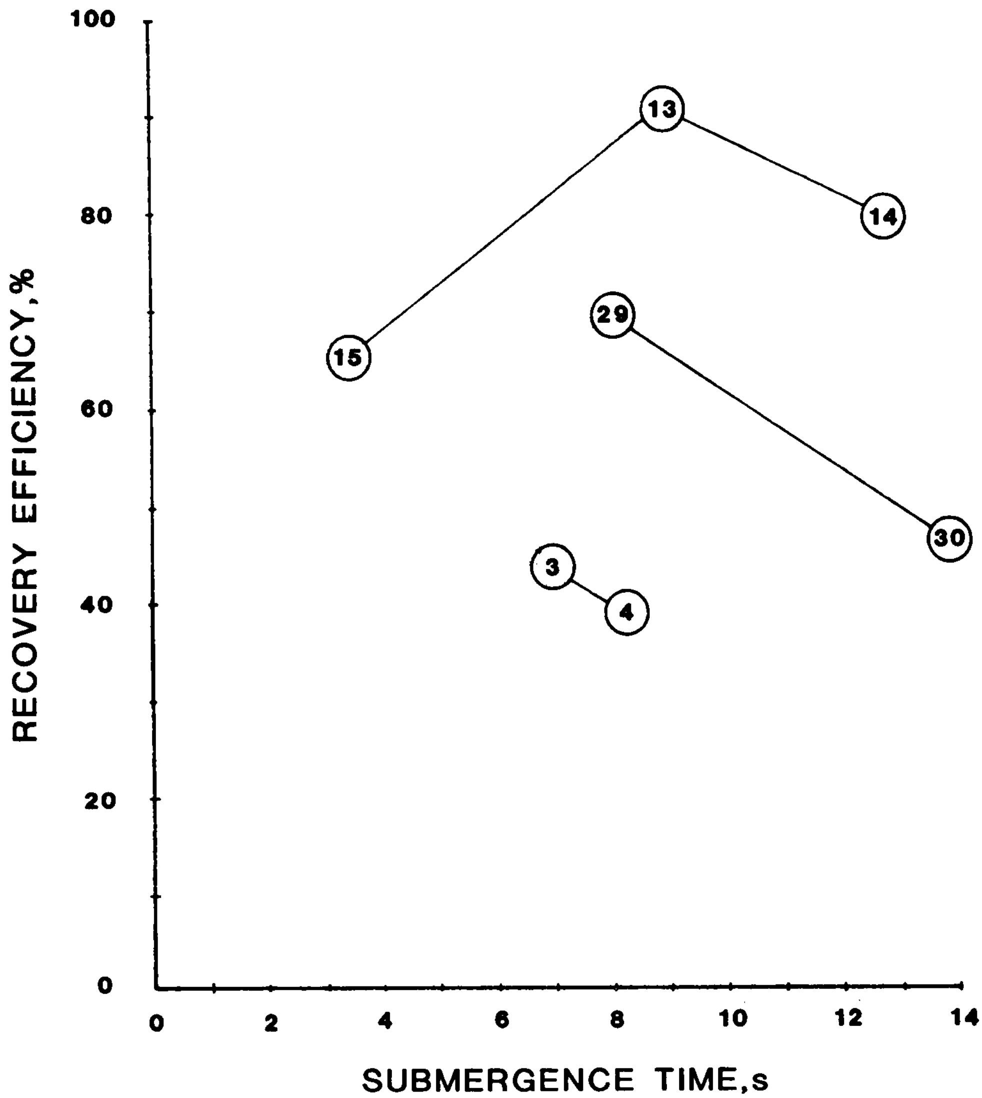
While it was generally true that greater submergence times resulted in greater recovery efficiencies, attempts to provide long submergence times through slow rotational speeds resulted in decreased efficiencies. The significance of varying rotational speed is shown in Figure 8. Three sets of tests were performed; in each set the only parameter that was varied was the rotational speed, and in each case, while the slower rotational speed provided more submergence time, the result was a decrease in recovery efficiency. A possible explanation is that at slower rotations, the agitation is insufficient to release the oil from the ice and allow it to flow through the porous drum. Similarly, at excessively high rotational speeds, lower efficiencies resulted due to oil being swept past the drum before it has a chance to be collected. The

TABLE 1: SUMMARY OF POROUS DRUM TEST RESULTS WITH CRUDE OIL

TEST	ROTATIONAL SPEED (rad/s)	SUBMERGENCE DEPTH (mm)	PORE SIZE dia, (mm)	SUBMERGENCE TIME (s)	RECOVERY EFFICIENCY (%)
D1	0.35	210	6.35	5.4	32
D3	0.31	267	6.35	7.0	43
D4	0.27	267	6.35	8.2	39
D6	0.25	210	12.7	7.7	26
D7	0.33	267	12.7	6.6	43
D8	0.30	267	12.7	7.3	59
D10	0.87	267	12.7	2.5	56
D11	0.29	267	12.7	7.5	41
D12	0.79	267	12.7	2.7	39
D13	0.31	394	12.7	8.9	90
D14	0.21	394	12.7	12.7	79
D15	0.81	394	12.7	3.4	65
D16	0.32	210	25.4	5.9	69
D17	0.34	210	25.4	5.6	57
D18	0.33	267	25.4	6.6	57
D19	0.30	267	25.4	7.2	58
D20	0.81	267	25.4	2.7	44
D21	0.33	394	25.4	8.1	48
D22	0.35	394	25.4	7.8	61
D25*	0.27	127	12.7	6.4	51
D26*	0.26	318	12.7	10.8	68
D27*	1.06	318	12.7	2.7	38
D28*	0.41	127	25.4	4.1	56
D29*	0.35	318	25.4	8.0	69
D30*	0.21	318	25.4	13.8	46

* denotes tests done with drum of diameter 750 mm; all other tests with drum of diameter 1000 mm.

FIGURE 8 : SIGNIFICANCE OF VARYING ROTATIONAL SPEED



TEST NO./RECOVERY EFFICIENCY

ROTATION	-FAST	-NORMAL	-SLOW	PORE SIZE	DRUM SIZE	SUBM. DEPTH
1.	D15/65%	D13/90%	D14/79%	M	L	MAX.
2.	-	D29/69%	D30/46%	L	M	MAX.
3.	-	D3/43%	D4/39%	S	L	MED.

normal rotation speed, which proved to be optimum, was that which provided a tangential velocity (linear velocity of the porous surface) which approximately matched the forward speed.

6.2.2 Submergence Depth/Time

The test results with the light crude oil are shown graphically in Figure 9, with recovery efficiency plotted as a function of submergence time. The graph excludes the tests done at slow rotational speeds (as discussed above) and the three tests done with the smallest pore size (discussed below under "Pore Size").

There is considerable scatter but the graph does indicate a general increase in recovery efficiency with increasing submergence time. A linear regression, with a regression coefficient of 0.66, is shown on the graph.

The poorest results are three (D12,20,27) of the five tests performed at fast rotational speeds; the recovery efficiencies for these three tests ranged from 38% to 44%. The other two tests (D10,15) at fast rotation had anomalous results (56% and 65% recovery), the higher result partially explainable by the deeper submergence.

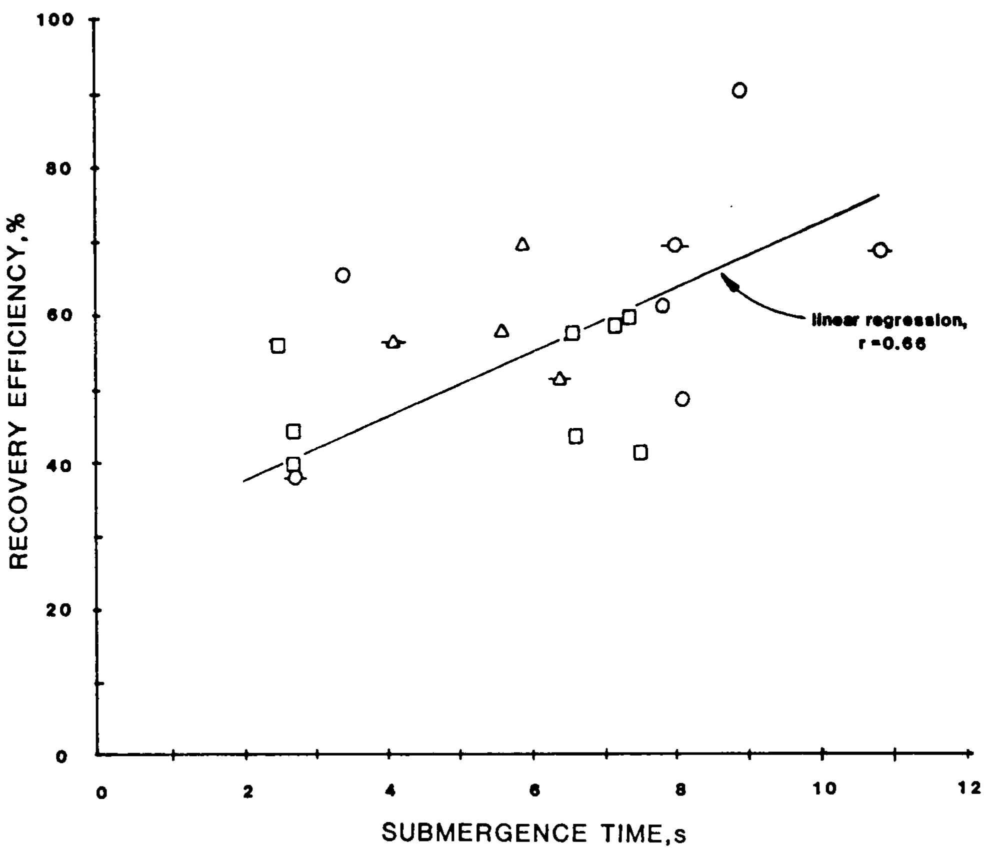
The best result, with 90% recovery, was achieved with the large drum at maximum submergence depth (D13). The rotational speed of 0.31 rad/sec proved to be near optimum.

The central portion of the graph exhibits considerable scatter. Nonetheless, of those data points with submergence times in the range of 4.0 to 8.5 s, eight of the twelve (67%) are within ±10% efficiency of that predicted by the linear regression.

6.2.3 Pore Size

Three pore sizes were available for the test programme, 25.4, 12.7 and 6.35 mm (1, 1/2 and 1/4 inch). The overall porosities for the porous surfaces

FIGURE 9 : POROUS DRUM RESULTS
RECOVERY EFFICIENCY vs. SUBMERGENCE TIME



LEGEND
- ○ large drum,max. submergence (D13,15,21,22)
- □ large drum,med. submergence (D7,8,10,11,12,18,19,20)
- △ large drum,min. submergence (D16,17)
- -○- med. drum,max. submergence (D26,27,29)
- -△- med. drum,min. submergence (D25,28)

were 48% for the largest pore size and 40% for the small two (calculations shown in Appendix A). Only three tests (D1,3,4) were performed with the smallest pore size and the light crude oil. The average recovery efficiency for those three tests was 38%, substantially lower than that achieved with the medium and large pores. Further testing with the small pore size, especially with the more viscous residual fuel oils, was unlikely to be profitable and was not done.

No difference in recovery efficiency was noted between the tests with medium and large pore size. This is not too surprising as the overall porosity is only 20% greater for the large pore size. Nevertheless, for the tests with the more viscous fuel oils only the large pore size was used as it was felt that the larger pores would more easily allow the infiltration of oil.

The only difference between the tests using medium and large pores was that more pulp ice was collected inside the drum in the tests with large pores; obviously the large pores allowed more of the fine ice pieces to enter the drum. During the test runs this ice was no more than a nuisance although it is a factor to be considered in a full scale design.

6.2.4 Paddle Size

Paddles, bolted to the outside drum surface to assist in drawing ice under the drum, were available in two sizes: 76 and 152 mm (3 and 6 inches). No difference in recovery efficiency was noted between the two sizes. For the sake of continuity, all tests following D10 (except for D16,17,18) were performed with the large paddles.

6.2.5 Unrecovered Oil

To ensure the validity of the measurements of recovered volumes several oil balances were attempted. Measurements were made of the amount of oil coating the drum and the amount left in the ice. The results are summarized below in Table 2.

TABLE 2: SUMMARY OF UNRECOVERED OIL VOLUMES

TEST NO.	OIL TYPE	OIL COATING 1/6th DRUM (l)	OIL LEFT IN TANK (l)	OIL RECOVERED (l)	TTL. OIL ACCOUNTED FOR (l,%)
D4	Lt. Crude	0.13	------	1.16	------------
D6	Lt. Crude	0.10	------	0.79	------------
D11	Lt. Crude	0.17	------	1.24	------------
D19	Lt. Crude	0.080	------	1.73	------------
D24	#5 F.O.	0.081	1.75	0.50	2.74 (91 %)
D25	Lt. Crude	0.054	0.75	1.53	2.60 (87 %)
D32	#4 F.O.	0.067	0.53	1.91	2.84 (95 %)
D33	#4 F.O.	-----	0.55	1.45	------------

For light crudes, the amount of oil coating the drum is generally higher than for the fuel oils. This is due to a change in the experimental procedure; for the fuel oils the oil was not spread laterally across the ice as much as for the light crude oil. As a result the entire drum width was not coated with fuel oil. Had the ice been saturated with fuel oil it is likely that more oil would have coated the drum.

For the three oil balances that were performed approximately 90% of the oil was accounted for. The remaining 10% would be made up of two major components: oil left in tank but not recovered by sorbents for measurement, and inexact estimation of exterior coating volume using only 1/6th of drum. Oil coating the interior drum surface was observed to be minimal.

6.2.6. Heavy Oils

Five tests were performed using heavy oils: two with #5 Fuel Oil (D23,24), two with #4 Fuel Oil (D31,32) and one with an East Coast crude oil (D33). The results are summarized below, and presented fully in Appendix D.

TABLE 3: SUMMARY OF POROUS DRUM TEST RESULTS WITH HEAVY OILS

TEST	ROTATIONAL SPEED (rad/s)	SUBMERGENCE DEPTH (mm)	PORE SIZE dia, (mm)	SUBMERGENCE TIME (s)	RECOVERY EFFICIENCY (%)	OIL TYPE
D23	0.30	394	25.4	9.1	13	#5 fuel oil
D24	0.32	394	25.4	8.6	17	#5 fuel oil
D31	0.35	210	25.4	-	41	#4 fuel oil
D32	0.35	394	25.4	7.8	64	#4 fuel oil
D33	0.26	394	25.4	10.4	48	East Coast crude

All tests done with drum of diameter 1000 mm.

The device showed a poor ability to collect #5 Fuel Oil, as only 13% and 17% recovery efficiencies were attained, respectively, in the two tests. An oil balance performed on the second test indicated that, of the spilled volume, approximately 16% was stuck to the outside surface of the drum and 58% was left in ice following the test run. Hence the poor recovery efficiency cannot be solely blamed on the oil sticking to the porous surface (the major problem noted in the preliminary feasibility tests). Compared with the crude oil tests, the decreased buoyancy and/or the increased viscosity of the #5 Fuel Oil resulted in less oil being freed from the ice and flowing through the porous surface.

The tests with the #4 Fuel Oil resulted in better recovery efficiencies, 41% with the drum 20% submerged and 64% when the submergence was doubled. The density of the #4 Fuel Oil is roughly the same as that of #5 Fuel Oil but the viscosity is an order of magnitude less, indicating that viscosity is a more important factor than density. This was substantiated by the single test with the East Coast crude oil, an oil with a viscosity similar to that of the #4 Fuel Oil.

6.2.7 Recovery Rate

The results of these experiments have been expressed as recovery efficiencies rather than as recovery rates as a skimmer operating in brash ice, more than an open water device, is severely limited by its oil encounter rate. For example, a skimmer with a 2 m wide swath, advancing at a rate of 0.5 m/s (1 knot) through brash ice containing oil with an overall average thickness of 1 mm, encounters oil at a rate of only 3.6 m^3/hr. With such a low encounter rate, which is also the maximum possible recovery rate under those conditions, recovery efficiency is more relevant to the evaluation.

6.3 Factors Affecting Variability of Results

As there was considerable variability in the measurements of recovery efficiency, it is worth noting the major factors which may have affected the variability.

1. Oil Flowing Out of Drum During Processing Run

   While a full scale design of the porous drum concept would include a pump or skimmer to continuously remove oil from inside the drum, no such device was used for this experimental prototype. However, observations during the test runs confirmed that any outflow of collected oil was minimal due mainly to the presence of the sorbent pads (within the drum) which sorbed the oil as it was collected.

2. Variability of Oil Coating Exterior Drum Surface

At the completion of each run the drum was coated with a volume of oil which had not penetrated the porous surface. The decision was made not to clean the device after each run as it was felt that over the long run this volume would remain relatively constant. In fact, measurements of the volume coating a 1/6th portion of the drum exhibited considerable variability; the average coating volume (five measurements with the light crude) corresponded to 22% of the spill volume, while individual measurements range within 11% to 35% of the spill volume.

3. Method of Measuring Recovered Volume

When sorbing the recovered volume at the end of each test run, care was taken to not include both oil seeping into the drum after the run and oil dripping from the porous surface. As well the sorbents used were hydrophobic, minimizing the amount of free water included in the sorbed mixture; other investigators have measured the free water uptake with these sorbents to be less than 3% by weight (Robertson, 1978). Emulsification was assumed to be negligible due to the slow speeds of the drum, an assumption corroborated by visual observation and the oil balances discussed in 6.2.5.

7.0 FULL SCALE DESIGN CONSIDERATIONS

Central to a full scale design would be the inclusion of a pump or skimmer inside the drum to remove collected oil. As noted in the Introduction, the original proposal of the porous drum concept included oleophilic discs inside the drum. This would be a reasonable approach although the discs would not be able to cope with the continuous infiltration of pulp ice. In fact, the pulp ice - pieces smaller than the selected pore size would limit the contact of oil to the discs. A more practical approach would be to use a weir/auger system which would be able to handle the collected oil and any ice which infiltrated the drum. Other options would be the use of an oleophilic belt or rope mops, both of which can tolerate some debris in the collection area.

A significant amount of oil coated the exterior drum surface after each run, especially with the heavier oils. A system to remove this oil from the drum surface on each rotation would increase the recovery efficiency accordingly.

As was evidenced in several test runs, ice jamming the moving parts can be a problem. In particular, ice pieces were carried out of the water by the paddles and, on several occasions, jammed against the support arms. Close tolerances must be avoided in any further designs to prevent this problem. Especially for the more viscous oils, the recovery efficiency could be increased by the addition of a scraping system to clean the exterior surface of the drum on each rotation.

The drum required very little torque to turn it. A motor capable of turning it in open water without forward movement is sufficient.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Tank testing of two devices - the porous plane and the porous drum - for the recovery of oil in brash ice has led to the following conclusions and recommendations.

8.1 Conclusions

1. The porous plane showed a poor ability to submerge ice. In a real-world application, without the benefit of the tank walls confining the ice, the porous plane would simply plough through the ice cover; its effectiveness at submerging ice and capturing the oil entrapped in the ice would be very low.

2. The porous drum was much more successful in processing ice. The rotation of the drum and paddles effectively submerged the ice and allowed the oil to float up through the porous surface.

3. Tests using the porous drum to recover light crude oil resulted in recovery efficiencies ranging from 38% to 90% of the volume spilled.

4. The main independent parameter for recovery efficiency was submergence time. Although the correlation between the two was weaker than expected, the best results were obtained with the largest drum submerged to its maximum depth.

5. Increasing the submergence time by slowing the drum rotation resulted in lower recovery efficiencies. The optimum rotational speed was that which produced a tangential velocity which approximated the forward speed of the device.

6. In tests with more viscous fuel oils, lower recovery efficiencies - in the range of 13% to 64% - resulted due to the greater tendency of the oil to adhere to the ice.

7. A significant volume of oil stuck to the outer drum surface rather than rising through the pores. Had the drum surface been of greater porosity, or had the device incorporated a scraping system to remove this oil, the recovery efficiencies could have been increased by 10-20% of the spill volume.

8.2 Recommendations

1. The concept of a rotating porous drum warrants continued consideration as a method for recovering oil from brash and mulched ice.

2. A hybrid device, using the drum to initially submerge the ice followed by a submerged plane to provide greater submergence time, or alternatively a porous rotating belt should be considered as a possible improvement for greater recovery efficiency.

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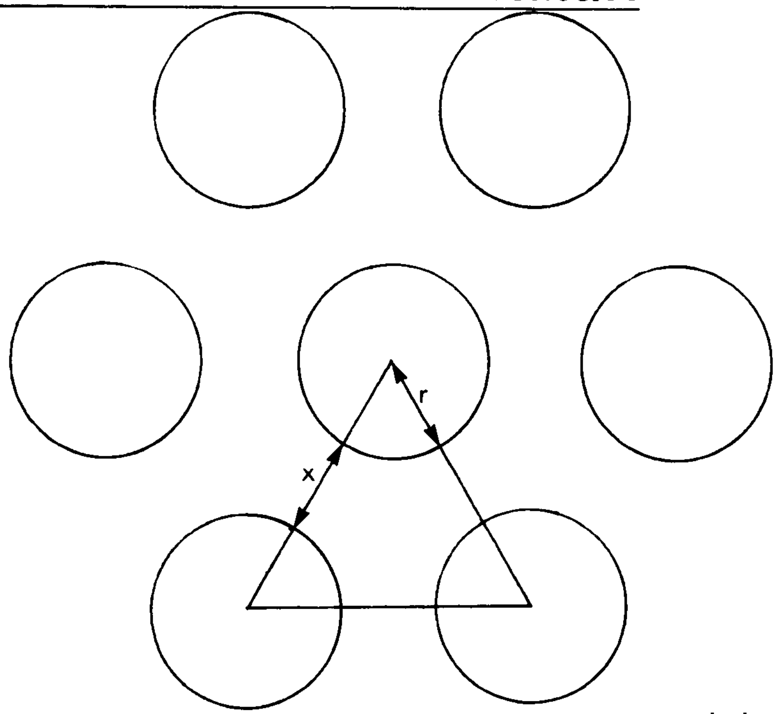
APPENDIX A

POROUS SURFACE:

CALCULATION OF POROSITY

POROUS SURFACE: CALCULATION OF POROSITY



x - hole spacing

r - hole radius

Holes punched in the pattern of a series of equilateral triangles.

1. Area of triangle

$$A_T = 1/2\ (\text{base})(\text{height})$$
$$= 1/2\ (x + 2r)[(\sqrt{3}/2)(x + 2r)]$$
$$= \sqrt{3}/4\ (x+2r)^2$$

2. Area of Holes

$$A_H = \text{three } 1/6\text{th portions of circle, each of radius } r$$
$$= (3)(1/6)(\pi r^2)$$
$$= \pi r^2/2$$

3. Porosity

$$P = (\text{Area of holes})/(\text{Area of Triangle})$$
$$= (\pi r^2/2)/(\sqrt{3}/4)(x + 2r)^2$$

$$= \frac{2\pi r^2}{\sqrt{3}\ (x + 2r)^2}$$

i) holes of diameter 1 inch, spacing 3/8 inch

$r = 0.5$ in., $x = 0.375$ in.

$p = 0.48$

ii) holes of diameter 1/2 inch, spacing 1/4 inch

$r = 0.25$ in., $x = 0.25$ in

$p - 0.40$

iii) holes of diameter 1/4 inch, spacing 1/8 inch

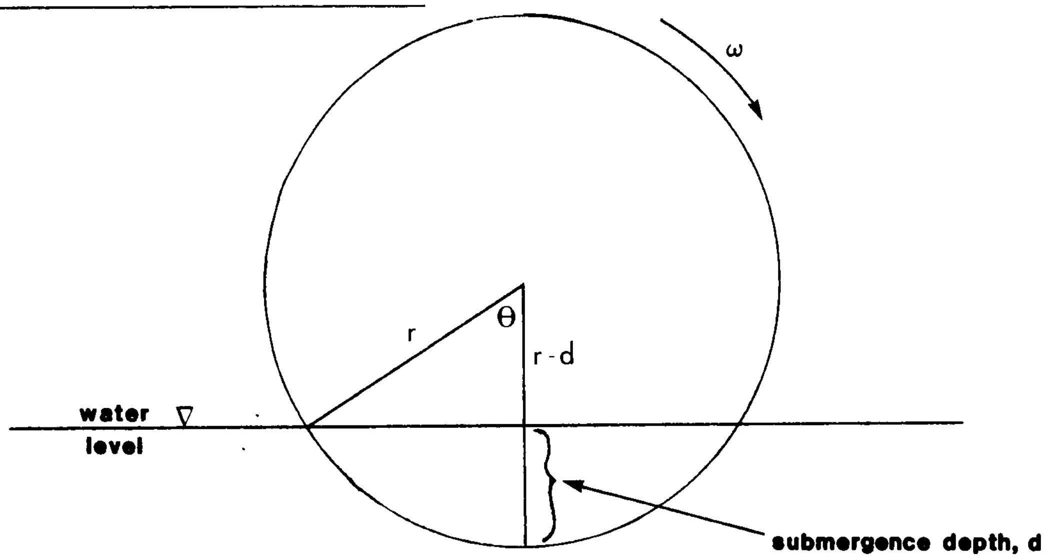
$r = 0.125$ in., $x = 0.125$ in.

$p = 0.40$

APPENDIX B

SUBMERGENCE TIME CALCULATION

SUBMERGENCE TIME CALCULATION



- Wetted 'Angle' $A_w = 2\Theta$ Θ,radians

$$\Theta = \cos^{-1}\left(\frac{r-d}{r}\right)$$

$$A_w = 2\cos^{-1}\left(\frac{r-d}{r}\right)$$

- Submergence Time $t = A_w/\omega$ ω ,rad/sec

$$= \frac{2}{\omega}\cos^{-1}\left(\frac{r-d}{r}\right)$$

- for example, D8

ω = 0.30 rad/s

r = 500 mm

d = 267 mm

$t = (2/0.30)\cos^{-1}[(500-267)/500]$

= 7.3s

APPENDIX C

POROUS PLANE TEST RESULTS

Test	Depth(mm) fore d	Depth(mm) aft h	Bow Ramp Angle (from horiz.)	Speed V (m/s)	Pore size dia(mm)	Subm time (sec)	Amount of oil in tank l/type	Amount of oil recov (l)	Recovery efficiency %
P3	121	51	11°	0.15	6.35	15.8	3	2 (approx.)	67
P4	121	51	11°	0.31	6.35	7.6	3	2.133	71
P5	76	51	8°	0.29	6.35	8.1	3	1.512	50
P6	64	64	7°	0.15	25.4	15.7	3	2.754	92
P7	64	64	7^{0}	0.29	25.4	8.3	3	1.925	64
P8	108	64	10°	0.26	25.4	9.1	3	1.880	62
P9	64	64	7°	0.17	25.4	14.3	3 /#5F.O.	0.748	25

APPENDIX D

POROUS DRUM TEST RESULTS

Test	Depth d (mm)	Speeds v (m/s)	Speeds w (rad/s)	Drum size Radius (mm)	Paddle Size length (mm)	Pore size dia,(mm)	Subm. time (sec.)	Amount of oil in tank (l)/type	Amount of oil recov. (l)	Recovery efficiency (%)
D1	210	0.17	0.35	500	76	6.35	5.4	3	0.944	32
D3	267	0.17	0.31	500	76	6.35	7.0	3	1.302	43
D4	267	0.098	0.27	500	76	6.35	8.2	3	1.163	39
D6	210	0.17	0.25	500	76	12.7	7.7	3	0.792	26
D7	267	0.16	0.33	500	76	12.7	6.6	3	1.289	43
D8	267	0.17	0.30	500	76	12.7	7.3	6	3.529	59
D10	267	0.17	0.87	500	76	12.7	2.5	3	1.681	56
D11	267	0.16	0.29	500	152	12.7	7.5	3	1.243	41
D12	267	0.16	0.79	500	152	12.7	2.7	3	1.160	39
D13	394	0.17	0.31	500	152	12.7	8.9	3	2.696	90
D14	394	0.095	0.21	500	152	12.7	12.7	3	2.360	79
D15	394	0.32	0.81	500	152	12.7	3.4	3	1.939	65
D16	210	0.17	0.32	500	76	25.4	5.9	3	2.060	69
D17	210	0.14	0.34	500	76	25.4	5.6	1.5	0.848	57
D18	267	0.17	0.33	500	76	25.4	6.6	1.5	0.858	57

Test	Depth d (mm)	Speeds v (m/s)	w (rad/s)	Drum size Radius (mm)	Paddle Size length (mm)	Pore size dia,(mm)	Subm. time (sec.)	Amount of oil in tank (l)/type	Amount of oil recov. (l)	Recovery efficiency (%)
D19	267	0.17	0.30	500	152	25.4	7.2	3	1.731	58
D20	267	0.17	0.81	500	152	25.4	2.7	3	1.311	44
D21	394	0.17	0.33	500	152	25.4	8.1	3	1.451	48
D22	394	0.18	0.35	500	152	25.4	7.8	6	3.669	61
D23	394	0.16	0.30	500	152	25.4	9.1	3 /#5F.O.	0.362	13
D24	394	0.16	0.32	500	152	25.4	8.6	3 /#5F.O.	0.477	17
D25	127	0.16	0.27	375	152	12.7	6.4	3	1.533	51
D26	318	0.17	0.26	375	152	12.7	10.8	3	2.042	68
D27	318	0.17	1.06	375	152	12.7	2.7	3	1.148	38
D28	127	0.17	0.41	375	152	25.4	4.1	3	1.682	56
D29	318	0.18	0.35	375	152	25.4	8.0	3	2.060	69
D30	318	0.068	0.21	375	152	25.4	13.8	3	1.375	46
D31	210	0.17	0.35	500	152	25.4	—	3 /#4F.O.	1.214	41
D32	394	0.19	0.35	500	152	25.4	7.8	3 /#4F.O.	2.911	64
D33	394	0.15	0.26	500	152	25.4	10.4	3 /East Coast	1.448	48