SINTEF REPORT

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TITLE

The Program for
MECHANICAL OIL RECOVERY IN ICE-INFESTED WATERS (MORICE)

PHASE 3

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CLIENT(S)

Statoil, Saga Petroleum, Norsk Hydro, Exxon Prod. Res. Comp., HSVA, Alaska Clean Seas, US MMS

REPORT NO.	CLASSIFICATION	CLIENTS REF.	
STF 22 F99213	Confidential		
CLASS. THIS PAGE	ISBN	PROJECT NO.	NO. OF PAGES/APPENDICES
Unrestricted		22D095	28 / 5
ELECTRONIC FILE CODE		PROJECT MANAGER (NAME, SIGN.)	CHECKED BY (NAME, SIGN.)
Phase 3 report, July 1999		Hans V. Jensen	
FILE CODE	DATE	APPROVED BY (NAME, POSITION, SIGN.)	
	1999-07-07	Torbjørn Sotberg	

ABSTRACT

This report describes the work conducted in Phase 3 of the Program for Mechanical Oil Recovery in Ice-Infested Waters (MORICE). The objective of the program is to develop technologies for more effective recovery of oil spills in ice. Phase 3 of the program focused on carrying out a quantitative evaluation of two concepts conceived and qualitatively tested during previous phases, the Lifting Grated Belt and the Brush Drum concept. This has been done through tank tests in ice-infested water conditions at the Hamburg Ship Model Basin (HSVA).

The main conclusion from the testing is that prototypes of both concepts tested should be designed, constructed and tested in the next phase of the program. Upon completion of this phase of the program it is believed that a well-designed, appropriately scaled mechanical recovery system is a feasible option for combating oil spills in ice-infested waters. It is believed that subsequent development efforts can lead to improved products.

Before finalising the designs of the prototypes for the next phase of the program, continued laboratory development is recommended for some of the components, both for the Lifting Grated Belt and the Brush/Drum. An evaluation of methods to prevent freezing of the Air Conveyor system is also recommended.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Environment	Miljø
GROUP 2	Oil spill recovery	Oljevern
SELECTED BY AUTHOR	Oil-in-ice	Olje i is
	Skimmer	Skimmer
	Ice	Is

ACKNOWLEDGEMENTS

The authors would like to thank the project participants for their financial support and valuable input throughout the course of this project.

Funding for Phase 3 of MORICE has been provided by:

- Statoil
- Saga Petroleum
- Norsk Hydro
- Exxon Production Research Company
- U S Mineral Management Service
- Alaska Clean Seas
- Hamburg Ship Model Basin
- The European Communities DG XII Science, Research and Development under the "Access to Large Scale Facilities Activities of the TMR Programme"

The MORICE Phase 3 Technical Committee consisted of the following members:

- Hans Jensen, SINTEF
- Tony Lorenzo, SINTEF
- Laurie Solsberg, Counterspil Research
- Fred McAdams, Alaska Clean Seas
- Andrie Chen, Exxon Production Research Company
- Karl-Ulrich Evers, Hamburg Ship Model Basin

A special thank you goes to the HSVA staff for their hospitality and the significant contribution they made to this program during the work conducted at their Hamburg facilities.

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SUMMARY

This report describes the work and results of Phase 3 of the Program for Mechanical Oil Recovery in Ice-infested Waters (MORICE). MORICE was initiated in 1995 and was aimed at developing technologies for more effectively recovering oil spills in cold climate waters where ice is also present in the recovery area. After a thorough literature review and assessment of current technology, several concepts were conceived and suggested during Technical meetings in Phase 1. After further assessment of these suggested concepts, Phase 2 saw the design, construction and qualitative testing of small test units of the most promising of these concepts; the Lifting Grated Belt, Submerging Grated Belt, the Brush/Drum, the Grated Plough, the Auger Drum, and, as an offloading device, the Air Conveyor. These test units consisted strictly of the mechanical components that related to the ice processing and oil recovery operation and did not consider such components as the support vessel and other major auxiliary equipment.

The objective of Phase 3 was to further develop and evaluate a reduced number of the concepts recommended from Phase 2, namely the Lifting Grated Belt and the Brush/Drum. In this phase, the concepts were redesigned to a larger scale and tested at the Hamburg Ship Model Basin (HSVA) in a more extensive and quantitative manner.

After preparing and shakedown testing of the test units in Trondheim in July 1998, the units were then shipped to HSVA in Hamburg for three weeks of quantitative testing. This large test facility proved to be ideal for the type of evaluations required in this phase of the MORICE Program.

The quantitative tests carried out in this phase were successful in providing a progressive step towards the development and improvement of the concept technologies being evaluated for oil recovery in ice infested waters. Following is a summary of results from these tests.

Lifting Grated Belt

Ice Processing
The Lifting Grated Belt used as an ice deflection method has demonstrated that it is capable of effectively deflecting a wide range of ice sizes from a recovery path to facilitate an oil recovery operation. The larger unit tested in this phase was capable of deflecting ice floes as large as 1.5 m x 2.0 m x 0.2 m. The design is mechanically sound, requiring only minor refinements to provide greater reliability in future prototype units.

Oil Flushing
The flushing mechanism initially installed proved to be ineffective with this oil type and in these conditions. However, a more direct flushing method that was evaluated proved to be more effective, which indicates that flushing can provide effective cleaning of deflected ice pieces and thus increase the overall oil recovery rate. Indeed, additional evaluations of a flushing system are required to determine the effects of variations in pressure, flow rate and/or heat input to clean oil from the ice and rakes. Such an evaluation is necessary at the initial stages of the next phase, before finalisation of the prototype design.

Oil Recovery
As a first attempt at designing an oil recovery unit for the collection area of the LGB, a system comprised of three small oleophilic drums was designed and used. Several methods of operating this unit proved promising to separate and collect the oil from the slush and water in this collection area. The most promising method of operation used techniques to create and contain pools of oil between drums, and subsequently collect this oil through periodic controlled reversal

of the drum rotation direction. The prototype unit to be designed for field evaluations in subsequent phases will further investigate the feasibility of this oil recovery system within the LGB collection area.

The oil recovered in the troughs is often mixed with slush and/or ice pieces that make offloading difficult. The use of auger conveyors together with added heat in the collection troughs should be considered to help offloading the collected product.

Brush/Drum

Ice Processing
The ice deflection operation of the Brush Drum system was effective with the 1. 0 m diameter drums as long as the forward drum was operated at an angle of incidence less than 37 degrees and at a low rotation speed.

Oil Recovery
The first configuration, consisting of two large drums operated in series and relying strictly on a one-pass oleophilic process, was not very effective at recovering the highly viscous oil used in these tests.

The second Brush Drum configuration, using one large and one small drum, was very effective at recovering both the high and medium viscosity oils and thus should be used in the prototype unit of Phase 4. This design will provide the greatest recovery performance in very viscous and less adhesive oils since the process does not rely strictly on an oleophilic recovery process, as does the first configuration.

The minor oil losses observed from this configuration can be reduced or eliminated by incorporating containment walls at the sides of the drum where the oil pool is formed.

1. INTRODUCTION

1.1 Background

The program for Mechanical Oil Recovery in Ice-infested Waters (MORICE) was initiated in 1995 to develop technologies for the more effective recovery of oil spills in ice-infested waters. Several northern countries face the potential of an oil spill in waters where ice is present, either permanently or during parts of the year.

MORICE is a multinational effort involving Norwegian, Canadian, United States and German researchers. While research activities in this field have generally not been co-ordinated on an international level in the past, a collective international effort is considered essential to achieve a significant improvement in the capability of dealing with oil spills in ice.

Phase 1 of the MORICE Program (Johannessen, B.O. et al, 1996) involved an extensive literature review to identify available information from previous efforts to develop oil-in-ice recovery technologies. Information collected also relates to oil behaviour, ice conditions, historical oil spills in cold areas, and operational experience gained during the recovery of oil in these conditions. Following this review, a series of brainstorming sessions and technical discussions was held to evaluate past work and generate new ideas for potential solutions to the problem. A number of concepts were proposed. The MORICE Technical Committee discussed ten of these ideas in detail.

MORICE brainstorming sessions and technical discussions have focused on the following ice conditions:

- Broken ice
- Up to 70% ice concentration on a large scale; locally up to 100%
- 0 - 10 m ice floe diameter
- Small brash and slush ice between ice floes
- Mild dynamic conditions (current, wind)
- Oil within a wide viscosity range

Phase 2 of the program (Johannessen, B.O. et al, 1998) involved qualitative laboratory testing of six of the ten concepts recommended from Phase 1. These concepts included; the Lifting Grated Belt, the Submerging Grated Belt, the Brush/Drum, the Grated Plough, and the Auger Drum. The Air Conveyor was also evaluated as a material transfer unit. This phase started in February 1997 and was completed late February 1998.

The continuation of the program was planned to include the following phases:

Phase 3	Quantitative testing of two concepts in the Arctic Environmental Test Basin at HSVA, namely the Lifting Grated Belt and the large Brush/Drum system.
Phase 4	Development of prototype units, testing in laboratory or under outdoor controlled conditions
Phase 5	Field testing of prototypes in experimental oil spills in ice

The detailed work requirements of each phase are decided upon after completion of the previous phase.

1.2 Objectives

The overall objective of MORICE is to develop technologies for the recovery of oil spills in ice-infested waters.

The objective of Phase 1 was to identify and address the fundamental problems involved in oil recovery in ice and to suggest technical solutions to the problems. The work resulted in a number of suggested concepts for oil-in-ice response.

The objective for Phase 2 of the MORICE Program was to evaluate, at a qualitative level, the feasibility of the concepts recommended in Phase 1. This has been done through testing and evaluations of concepts with oil in ice-infested water conditions in an ice tank at SINTEF.

In Phase 3, the objective has been to evaluate two concepts, namely the Lifting Grated Belt and the Brush/Drum system, through quantitative testing in the Arctic Environmental Test Basin at the Hamburg Ship Model Basin.

1.3 MORICE Phase 3 Activities

Phase 3 officially commenced in May 1998, although some preparations had started before this.

Where appropriate, technical drawings were prepared for the construction of the test units. Also the set-up of the testing facility was planned, specifying requirements for test equipment such as transfer pumps, storage tanks, hoses, hydraulic power units and other ancillary equipment. Since the models were relatively large, the dimensions and weight of the units had to be matched to the capacity of the test tank.

In July 1998, the different components of the models were examined during a two-week shakedown test period at SINTEF, followed by some final modifications before the models were transported to Hamburg.

During a three-week period in September and October, tests were carried out at the Arctic Environment test tank at the Hamburg Ship Model Basin. By way of these tests, the Technical Committee evaluated the ice processing and/or oil recovery capabilities of each test unit. On some occasions, changes and improvisations were made to the units based on the Committee's assessments of these tests.

Steering Committee meetings and Technical meetings were held to provide progress updates to the funding participants and to receive their technical input. One meeting was held during the tests in Hamburg, while the other was held several weeks after finishing the tests.

2. PHASE 3 WORK DESCRIPTION

2.1 Model Design and Test Planning

The recommendation from Phase 2 was to proceed with two of the concepts; the Lifting Grated Belt (ice deflection) and the Brush/Drum system (oil recovery), see Figure 2.1 and Figure 2.2, respectively. As a second priority it was decided to test the Grated Plough Shaped Deflector with relatively low ice concentration in the tank at HSVA, if time permitted.

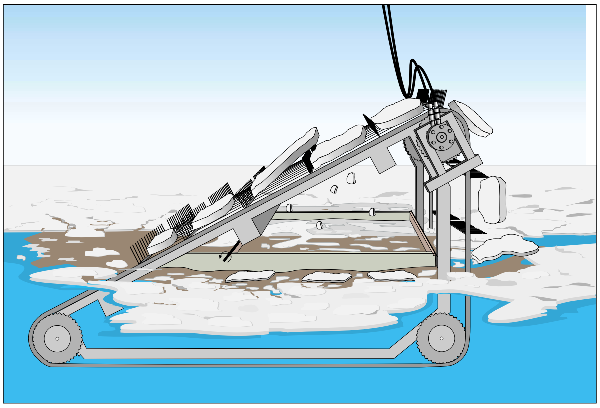

Figure 2.1 Lifting Grated Belt concept from Phase 2.

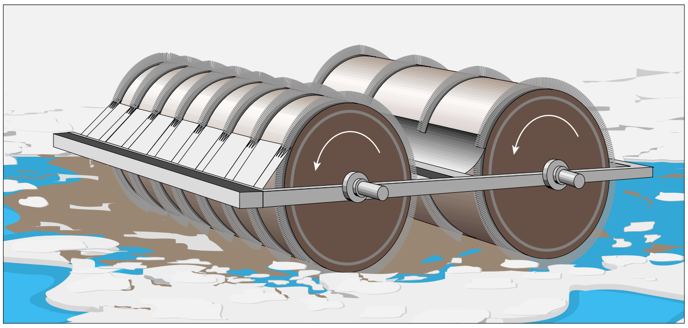

Figure 2.2 Brush/Drum concept from Phase 2.

In Phase 2, designs were kept as simple as possible and test units were constructed to allow quick modifications and/or improvisations that were often required during the testing period. However, for this phase, the units had to be more carefully designed to allow for a quantitative evaluation. To make it possible to quantify the performance of the LGB as more than just an ice deflection unit, an oil recovery unit had to de designed and incorporated under the belt unit.

2.2 Construction and Shakedown Testing of Units

New units were designed for both the Lifting Grated Belt and the Brush/Drum system:

Lifting Grated Belt (LGB)
For these larger scale tests a wider and longer LGB was designed with overall dimensions of 4.5 m length, 1.7 m width, and a total height of about 1.7 m. The same firm that constructed the LGB tested in Phase 2 also constructed this modified unit.

Under the belt, a small brush/drum oil recovery unit was positioned comprising of three small drums, each with a diameter of approximately 32 cm, individually powered by electric motors with reduction gears. Each of the drums had its own scraper and trough to collect recovered product. An air conveyor was used to transfer the recovered product from the trough to a temporary storage container.

Brush/Drum system
In Phase 2, the Brush/Drums used had a diameter of 0.6 m and a length of 0.8 m. In order to keep a low angle of incidence between the oncoming drum surface and the water surface, the diameter of the new drums was increased to 1.0 m. This also resulted in an increase in the buoyancy/weight ratio, which might reduce or possibly eliminate the need for separate pontoon floatation since these would significantly increase the resistance of the unit when moving through the ice field. The length of the drums was 1.50 m.

Drums were fabricated of two different materials, composite and stainless steel. All drums had the same dimensions, but the composite drums weighed 40 kg while the steel drums weighed 85 kg. Both drum types had a 25 mm diameter steel shaft going all the way through their centres.

Each of the large drums was equipped with a hydraulic motor, a scraper mechanism and a trough, all mounted on an individual aluminium frame. These drums, with their individual frames, were then supported on a larger main frame, which facilitated changing from one drum type to another or to allow the distance between the drums to be varied within certain limits. The smaller individual frames were clamped to the main frame to secure the drums in place (Figure D.2).

More details on the design and construction of the individual concepts are given in Chapter 3.

These test units were constructed in May and June, while the shakedown testing period commenced in July for a duration of two weeks. During this latter period, preparations were made on each test unit, including preparation of the flushing system for the LGB, reinforcement of the composite drums and preparation of combs and scrapers for the Brush/Drums, and set up and testing of the hydraulic power system. Subsequently, the operation of the test units was evaluated by means of "dry" and "wet" tests at the SINTEF Cold Laboratory. Wet tests with ice and oil were performed with the Brush/Drum units and the oil recovery unit for the Lifting Grated Belt. The LGB ice deflector itself was not wet tested since the unit is too large for this laboratory.

After the shakedown tests were completed, necessary modifications and final preparations were carried out on each unit before the equipment was transported from Trondheim to Hamburg.

2.3 Quantitative Testing at the HSVA Test Facility

Quantitative testing at the HSVA test facility began in Mid-September and lasted one month, including mobilisation and demobilisation. The first week was spent preparing the lab and models for testing and included such tasks as mounting the LGB on a support frame and installing auxiliary equipment such as pumps, storage containers, hydraulic power pack and a water flushing tank.

After filling the test tank with water, another week was required to prepare the ice sheet. At the end of this week a Steering Committee meeting was held at the HSVA premises. Time was also spent discussing technical matters, and preparations were made for a proposal on Phase 4 of the Program. Since results from the quantitative testing were not available at the time, the Steering Committee meeting was partly used to discuss the continuation of the project in more detail.

Despite some delays experienced during the preparation of the ice sheet, 20 tests in total were carried out during the testing period and the objectives of the testing were fulfilled upon completion of the work. However, there was not enough time to test the Grated Plough Shaped Deflector since this would have required another two to three days in the lab.

2.4 Test Facility at HSVA

Evaluations of the concepts took place in the Arctic Environmental Test Basin at the Hamburg Ship Model Basin. This tank, formerly used for ice testing, measures 30 metres in length, 6 metres in width, and 1.2 metres in depth (see sketch in Figure 2.3). The water level for these tests was 1.1 metres.

The tank is located in an insulated room that is cooled by heat exchangers covering the whole ceiling. Under optimum conditions this enables control of the air temperature down to -25°C. However, most of the tests in this project were performed at temperatures just below 0°C. Ice was prepared by freezing the water surface to form an ice sheet of a desired thickness. The test tank can be equipped with wave-makers and a current-generating system. However, none of these systems were required for the tests. A motorised main carriage extends across the tank and can travel the length of the tank with speeds adjustable from 0 to 2 m/s. The main carriage was also equipped with a crane.

The models to be tested were supported by two I-beams spanning from the main carriage to a smaller carriage (Figure D.2 in Appendix D). Due to the size of this support structure, the doors to the main tank area could not be completely sealed during the freezing of the ice sheet. This resulted in a minimum possible temperature of -15°C instead of -25°C, and therefore the time required preparing the 20 cm-thick ice sheet required more time than anticipated.

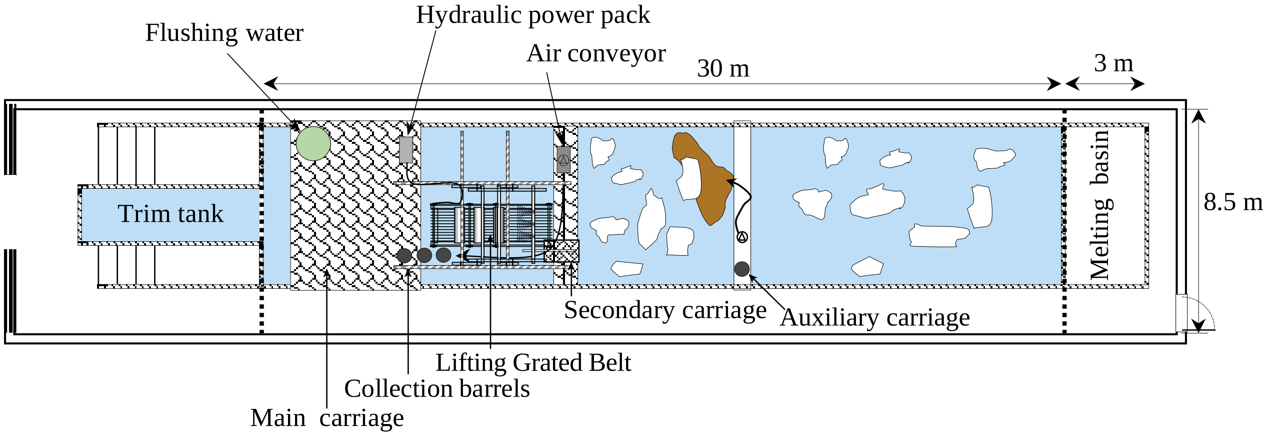

Figure 2.3 Overview of the HSVA facility used for these tests.

2.5 Methodology

In the previous phase of MORICE, simple models were prepared to provide a basic understanding of the operational characteristics of the selected oil-in-ice response concepts. To assess a reasonable number of concepts without getting into prohibitively costly testing, these evaluations were kept strictly at a qualitative level.

In the present phase, the objective was to carry out more quantitative experiments with two or perhaps three of the most promising concepts identified in the earlier work. This required more carefully designed and constructed models. It also called for a slightly more sophisticated test set-up, although still only concept components, not complete prototypes, were tested.

The air conveyor from Phase 2 was used to transfer the recovered product from the troughs of the oil recovery drums to separate temporary storage containers. These containers consisted of a number of standard 200-litre steel drums with detachable tops. On the suction line of the air conveyor, flexible hoses were connected to the top of the container covers. By using a manifold with ball valves for each container top, recovery product could be independently transferred from one trough to its separate storage container. The capacity of this air conveyor did not allow for transfer of product from all troughs simultaneously.

The following sections describe the general preparations and methods used for testing of the units in the HSVA facility. Specific test set-ups for the individual units are described in more detail in Chapter 3.

Salt water preparation

Using the same ice for carrying out experiments during two to three weeks requires ice being hard enough to resist the grinding due to ice–ice interaction without it deteriorating too quickly into slush. Although the hardest ice is made of freshwater, ice with porosity typical of saltwater ice was preferred since oil has a different adhesion to such ice.

During previous laboratory work, water with a salinity of up to 3.5 % was used, but the weaker porous ice formed at this salinity resulted in the formation of excessive amounts of slush during testing. Later the water salinity was decreased to about 2.0 %, reducing the slush problem. In Hamburg, water with a salinity of 0.85% was used to further reduce the slush problems. Water with this salinity proved to provide the appropriate ice hardness for the duration of the tests.

Ice preparation
After filling the tank with water to the required level for the Lifting Grated Belt, the ice preparation process was started. The insulating end wall of the tank could not be closed due to the size of our test set-up. This caused the temperature in the room to stay at about –15^{o}C during the freezing process, and it took about one week to prepare the ice sheet of approximately 20 cm thickness. Subsequently, the ice sheet was cut using a chain saw and broken manually to form ice ranging in size from small brash to pieces with a maximum length of 2 metres. Some slush was inevitably formed during this ice-breaking process. This mixture of ice of various sizes was used during all the tests.

A 4-metre wide straight path was cut in the ice sheet to form a broken ice situation in the test tank, leaving a 2-metre wide section of level fast ice along one side of the tank. To reduce the ice concentration in the path, some of the broken ice was pushed underneath this fast ice.

Preparation of test oil and distribution in the tank
A non-emulsified oil blend of heavy bunker and gas oil (IFO30-Intermediate Fuel Oil 30, viscosity 30 cP at 50^{o}C) was used as delivered to conduct most tests. Although the same blend rating (IFO30) was used in the previous phase, the viscosity of the oil used in Hamburg, when measured at 0^{o}C, was much higher than previously experienced. The viscosity of this IFO30 blend was between 12000-14000 cP at 10s^{-1} at the temperature of the water in the test basin, see Appendix E.

Towards the end of the testing period, some final tests were performed with a lower viscosity oil blend which was prepared using the delivered IFO30 oil further blended to a 70/30 ratio with diesel oil. This blending was carried out by circulating each batch of test oil in a barrel with a gear pump while slowly adding diesel to the suction side of the pump. The original IFO30 oil was delivered from a bunker station in Hamburg, and stored in a tank located outdoors of the test lab. Another storage tank was located adjacent to this one for storing the used oil after each test.

The first time oil was deployed into the test basin, it was pumped through a horizontally held PVC pipe boom with holes evenly distributed along its length. The boom was used from a small manually operated carriage in the tank. With this distribution method, most of the oil was applied to the top of the ice pieces. This oil having at least 10^{o}C higher temperature than the ice in the tank prior to deployment proved to adhere tenaciously to the ice. It was realised that pouring warmer oil on the ice like this would make some ice melt and strongly bond the oil to the ice. For the remaining tests the oil was deployed from the moving carriage through a hose and manually distributed between the ice pieces.

Typically, 130 litres of oil were deployed along a 20-metre long testing path prior to each test. It was observed that overnight, when there was no work done in the tank, a very thin sheet of ice would form on the surface of the tank water. The following morning, prior to distribution of new oil, this thin ice sheet was broken up to ensure that the conditions were similar from one test to another.

Operation of tested units
The test basin is equipped with a large motorised towing bridge extending across the width of the tank. A smaller carriage was connected to the main carriage by two I-beams, forming a rectangular area where the units were supported. With this arrangement, access was provided to the models from all sides, although at times somewhat difficult.

Advancing speed was kept low in all the tests to allow for careful examination of the interaction between the test unit and the oil and/or ice. The intention was to increase the advancing speed after the first few tests. However, the low speed was maintained throughout all the tests after realising that operation in the field probably would be performed at a similar speed as used in the tank. The advancing speed was typically 2-4 cm/s.

The small drums were operated electrically, and the rotational speed of each drum could be varied individually. The Lifting Grated Belt and the large drums were operated hydraulically. Hydraulic adjustment valves were controlled from the main carriage. Parameters to be varied were belt speed, drum rotation speed, unit draft etc. The recovered product was scraped or combed into collection troughs from where it was subsequently transferred by means of an air conveyor unit into separate storage containers for each recovery drum.

Quantitative assessments of performance

Testing included visual examination and careful assessment of the operation of each unit. Video recordings permitted the Technical Committee to review the individual tests when required. Testing procedures and the test matrix sequence remained flexible to allow for variations based on preceding tests.

Ice deflection performance was assessed only through visual observations of the interaction between the test unit and the ice, and its ability to separate large ice forms from smaller ice pieces. Oil recovery performance was evaluated through visual observations of oil adhesion to the skimmer surfaces and from measurements of the amount of oil recovered for each individual recovery drum in their respective collection barrels.

After each test the filled collection barrels were moved out to the workshop for accurate measurement of oil, ice and water. Total volume of recovered material and volume of ice were recorded immediately after each test. The ice was then melted and the volume of water measured again to find out how much ice was collected together with the oil and water.

3. TEST RESULTS AND DISCUSSION

3.1 Lifting Grated Belt

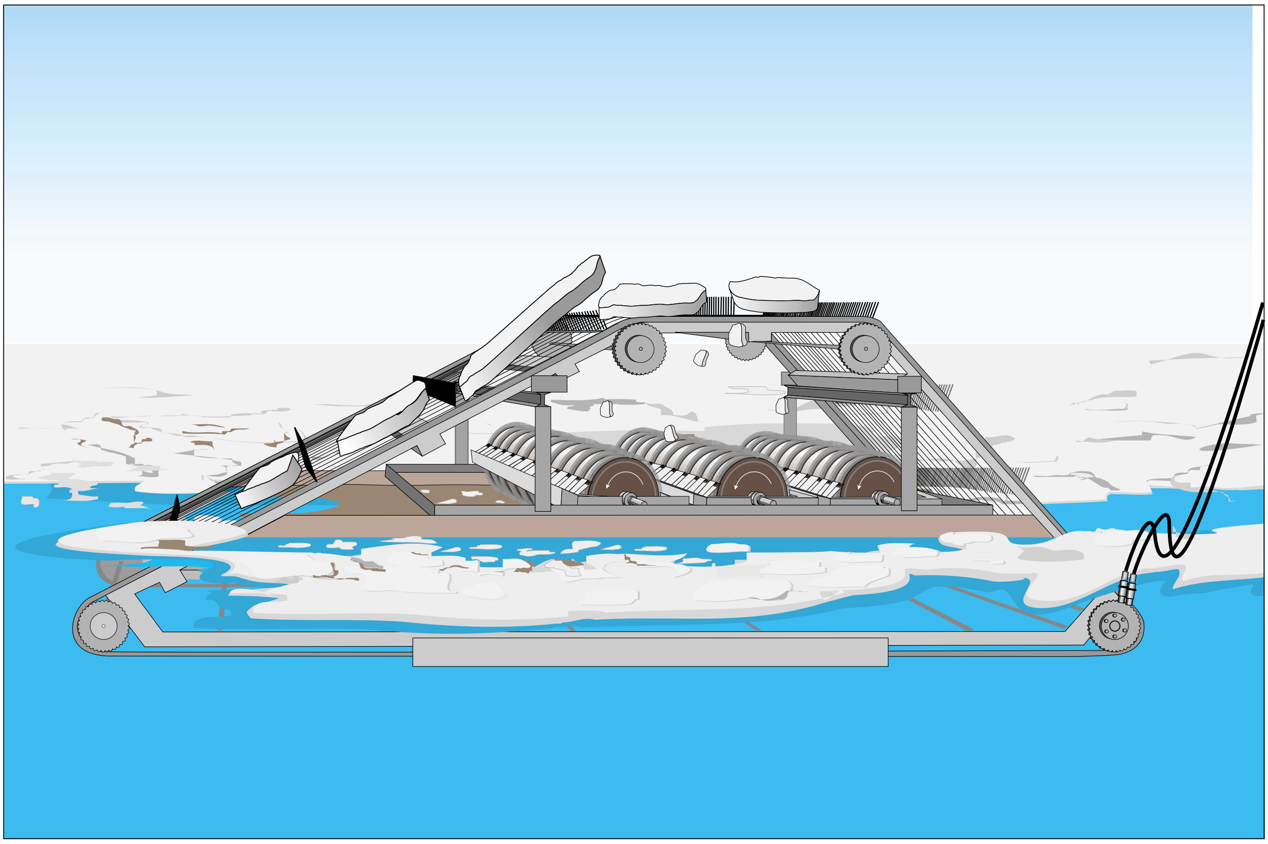

Figure 3.1 Lifting Grated Belt with recovery unit. Flushing tray, water flushing and trough are not shown in this sketch.

3.1.1 Unit Description and Set-up

Figure 3.1 shows a schematic of the Lifting Grated Belt and recovery unit used in Phase 3. Figure D1 in Appendix D provides a detailed illustration of the set-up of the Lifting Grated Belt (LGB) at the Hamburg test facility. The unit was suspended over two I-beams that were fixed to the inside of the LGB frame. These two beams were suspended under two larger I-beams that spanned the main and secondary carriages.

Figure 3.2 shows the Lifting Grated Belt unit with the flushing booms above the front inclined plane and the oil recovery unit within the frame. The unit advances to the right as ice pieces are lifted and deflected over the grated inclined plane by means of the moving rakes. Oil at the water surface is intended to pass through the grating and into the collection area. Some oil that adheres to the large ice pieces may be removed by the flushing operation at the ascending side of the belt when the ice is lifted out of the water. A flushing tray just below the front section of the moving belt prevents the flushing water from interfering with the oil recovery operation below. A trough at the end of this tray was available to contain and pump the flushing product into a separate container for evaluation of oil removal by the flushing system.

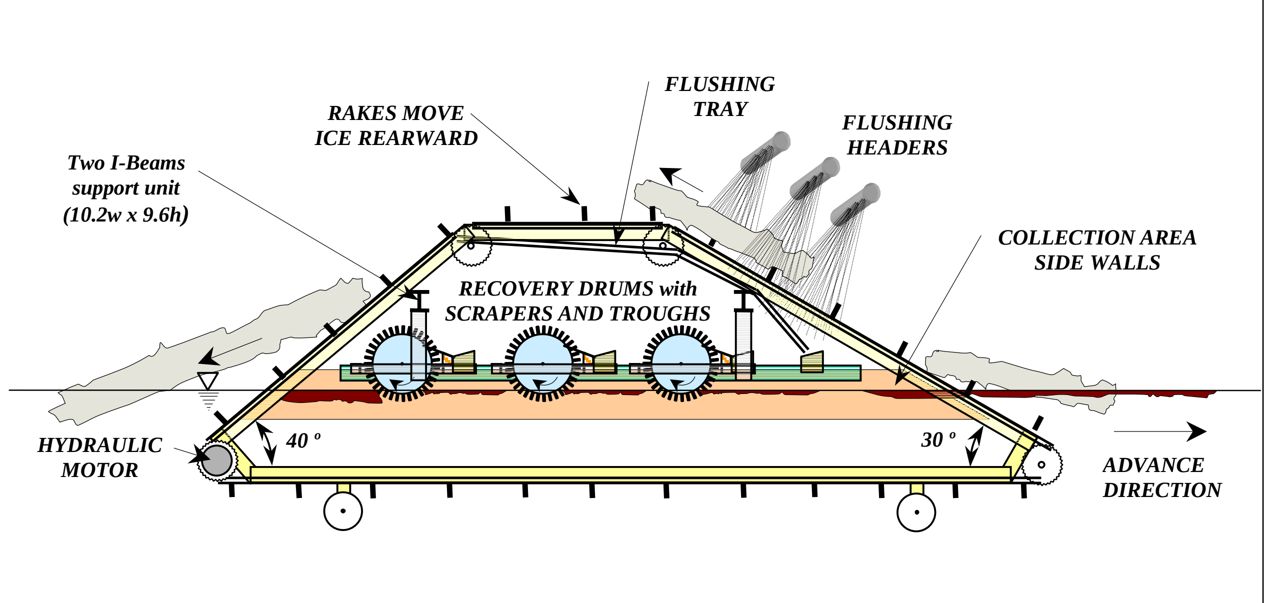

Figure 3.2 Lifting Grated Belt with flushing system and recovery unit.

An oil recovery unit can then recover oil contained in the collection area. In this phase, an oil recovery unit for the LGB collection area consisting of three small brush/drums was evaluated for the first time. Other oil recovery units may be considered for use under the LGB. In this unit, as oil passes from the front to the rear of the collection area due to the action of the rotating brush drums, some of this oil adheres to and is lifted by each drum. The oil is then scraped off, slides into the drum's respective trough and is subsequently removed by an air conveyor and transferred to a separate collection barrel for analysis.

3.1.2 Results and Discussion - Lifting Grated Belt

Overall, the Lifting Grated Belt (LGB) provided an effective means of deflecting ice to facilitate oil recovery operations in ice-infested waters. In Phase 3, a recovery device consisting of three brush drums was evaluated. The following areas are discussed in greater detail:

- Ice Processing
- Flushing
- Oil Recovery Operation

Ice Processing

Functionality The ice processing operation functioned well and the lifting design is mechanically sound, requiring only minor refinements to provide a greater reliability in the prototype unit. The unit lifted and deflected ice pieces nearly 20 cm in thickness and with horizontal dimensions of up to 2 m x 1.5 m. The angles of ascent (30º) and descent (40º) provided effective ice processing. The rear angle provided a smooth return of ice pieces back into the water behind the unit and can also lift ice pieces should the unit have to be operated in reverse. A higher rear angle was chosen both to (i) provide more space for the recovery unit underneath the belt without increasing the overall length of the LGB, and (ii) to investigate whether a higher angle for the inclined planes could be used in general.

Rakes The overall size and shape of the *lifting rakes* worked well to grab and lift the various sizes of ice pieces. The *tines at the ends* of each rake experienced the greatest ice loads and resulted in some of them bending. Subsequently, these end tines were adequately reinforced with pieces of square steel welded to them. Future unit constructions should consider harder rake steel and/or a greater number of reinforced tines (e.g. every 5-10 tine along the length of the rake). The rake tine length also worked well and should not be reduced since this would make it more difficult for large ice pieces to pass over the edge at the top of the ascending side of the belt.

The base of each rake is made of a flat steel profile that is fixed to the chain and slides along the LGB frame. The rakes were often observed to twist back as a result of ice loads. To rectify this problem, the base of one rake was widened to provide a greater support surface and reduce the twisting-back effects. This modification was considered effective and should be included on all the other rakes. Other future refinements may include the addition of Teflon or nylon strips on the LGB frame to reduce friction where the rakes slide. The *spacing between rakes* was appropriate for the purpose of lifting ice pieces. While a reduced spacing (more rakes per unit length of belt) may result in reduced loading and twisting of each rake, it may also result in less effective ice lifting, as was seen in Phase 2 evaluations.

Grating rods The grating rod design worked well to provide a smooth surface on which to push and lift the ice pieces. The spacing of these rods of 6 cm centre-to-centre was adequate to deflect even small ice pieces. Based on these findings, subsequent units may not require the added complexity of the grating rod spacing-adjustment mechanism provided on this unit.

Another complexity of the construction is the spacer underneath the grating rod to prevent ice from getting stuck between the spacer bars and the steel profile keeping it in place. Since no ice was jammed here, there might not be any reason for keeping these spacer bars. By welding the grating bars directly onto a steel tube instead, construction costs can be reduced, and the strength will probably be greater.

Hydraulic power The hydraulic power to the lifting belt operation proved effective. Since a hydraulic power unit was not available at the Hamburg test facility, an electric-hydraulic power pack was provided for these tests. The hydraulic power is supplied by a fixed pump with two chambers and has a maximum flow rate of 60 l/min. The pressure can be varied up to 230 bars. After a cautious start at 50 bars to avoid any damage to equipment, the system pressure was increased to a maximum of 150 bars (2100 psi). There were no difficulties in lifting large ice pieces at this setting.

Hoses leading to the unit must be well protected to avoid snagging and damage from large ice pieces. The chain sprockets should also be protected by means of a metal guard, and the hydraulic motor should be located inside the frame to be protected from collision with large ice.

Flushing

Overall effectiveness The flushing system as designed was not effective. A flushing wand had a greater effect on cleaning the oil from ice pieces and rakes compared to the flushing booms with fixed water nozzles. Test results indicated that flushing could increase oil recovery while reducing oil loss (from oiled ice and over-saturated rakes). The increase in oil recovery resulting from flushing depends on the conditions present, i.e. the amount of oil on ice surfaces, how strongly oil adheres to the ice, oil type and slick thickness. Under these test conditions, an increase in oil recovery efficiency from 15% to 26% was experienced when using flushing. A more powerful flushing system must be designed (by increasing pressure, flow rate and/or temperature) while bearing in mind the negative consequences that could result from using large quantities of water (possibly heated). In general, a modified flushing operation will require some careful designing.

Cleaning oil from lifted ice pieces Ice cleaning seemed most effective with the flushing wand. Higher pressures and flow rates are expected to improve ice cleaning. Ideally, a wand-type flushing head that directs the flushing water only to the oiled areas would reduce the amount of water used. Automating this operation may be difficult and costly, and in most cases it may not be feasible to have an operator outside, directing the flushing. However, having flushing controls remotely located may provide an alternative, allowing the operator to remain in an area protected from the splashing of water and oil.

Cleaning the oiled rakes Oil adheres to or is mechanically lifted by the rakes as they pass through the oil slick at the front of the belt. In this way the rakes may carry a considerable amount of oil up the LGB. As the oiled rakes descend at the rear end of the LGB, much oil still remains on the rakes as they complete their circuit around the unit. If the rakes are "over saturated" with oil, some oil may be released and be lost behind the unit. In some cases it may be important to reduce or eliminate this loss of oil. Cleaning the rakes by flushing or other means should remove the "over-saturated" portion or excess oil so as to eliminate any oil loss behind the unit. Any effort to clean the rakes further may not be necessary, since it will not result in an increase in oil recovery for the LGB unit.

Flushing tray The tray was effective at protecting the recovery area underneath the flushing operation above the belt. The use of a collection trough, placed at the bottom edge of the tray and used to collect the flushing product that descends the tray, eliminated the interference to the oil inflow that otherwise resulted. It remains unclear to what extent this flushing interference affected oil inflow (compare tests LGB6 without trough, with LGB7 and LGB9, both with trough). It is assumed, however, that the more intensive flushing that will be required for the prototype unit will result in more interference and thus warrant the use of a trough.

Clearing flushing tray of oil and slush Some accumulation of oil and slush was observed on the upper sections of the tray where the passage was restricted through the glider rod supports. The flushing tray should be installed below these supports, suspended independently to avoid restricting the movement of oil and slush down the tray. As discussed previously, more effective flushing may also help reduce oil/ice accumulation.

Oil Recovery Operation

Oil recovery In these tests, an oil recovery unit for the LGB collection area consisting of three small brush/drums was evaluated. However, other oil recovery units may be considered for use under the LGB.

In this recovery unit all three drums are rotated in the same direction (clockwise in Figure 3.2), and oil passes from the front to the rear of the collection area due to the action of the rotating brush drums. Some of the oil adheres to each drum and is lifted out of the water as the drum rotates. The oil is then scraped off and slides into the drum trough.

Transfer of recovered product The recovered product was removed from the collection troughs by an air conveyor and transferred to separate collection barrels for analysis, one barrel for each drum. One reason for using an air conveyor is that this is very simple and straightforward to use for such tests. The other reason is that an air conveyor is an interesting method for transferring recovered product from a recovery device in the field to a main vessel at a distance of at least 100 m.

Air conveyors are used for many applications and, in particular, to recover or transfer oil during spills. They are better known as vacuum trucks. Considering that this transfer principle is based on the drag or friction between the air at high speed and the product to be transferred, it is clear that an air conveyor transferring oil, ice and water will suffer from freeze-up of ice at low temperatures. During discussions, a lot of scepticism has been expressed regarding the air conveyor. With a lack of good, alternative lightweight methods for the transfer of recovered product**,** however**,** the question is whether anything can be done to increase the operational window for the use of the air conveyor at lower temperatures. One way of reducing the heat transfer problem would be to supply sufficient heat by injecting hot water into the suction hose to compensate for the heat loss. As much as possible of the heat transfer from the water to the air and hose has to take place in the suction hose. To achieve this, the hot water should be injected as small droplets at the inlet of the hose. A rough estimate shows that such a technique should improve the use of the air conveyor at lower temperatures. For the next phase of the program, further investigations are recommended for carrying out instrumented experiments with a vacuum truck and water from a high-pressure washer with hot water.

To evaluate the concepts during the prototype testing, the duration of the operation is not critical. In this situation it will be sufficient to transfer the recovered product from the troughs to a fairly small, temporary storage device on board the working platform. Under these conditions it is probably a good solution to use a standard type of pump that is known to process high viscosity mixtures like weathered oil and ice.

Recovered product Table 3.1 shows the amount of oil recovered by each of the drums (D1, D2, and D3) as well as the oil recovery efficiency (ORE) of each drum in parentheses. ORE indicates the percentage of oil in the collected product; the difference being water and slush ice.

Table 3.1 Summary of recovery amounts for the Lifting Grated Belt.

Test ID	Description and objectives	Oil Recovery in Litres (Recovery Efficiency in %)					
		D1 (front)	**D2 (middle)**	**D3 (rear)**	**Total**	**Post D3**	**Flush**
LGB 0	First preliminary test without oil. Recovery unit not installed.						
		Smooth/ Turf	**Medium Bristles**	**Stiff Bristles**			
LGB 1	Test without oil. Recovery unit and walls installed under LGB. Flushing used.						
LGB 2	Test without oil. Adjusting belt speed and draft.						
LGB 3	Test without oil.						
LGB 4	First distribution method. Very little oil in water; most cakes on ice.						
LGB 5	New oil distribution method used in this test. Oil distributed between ice floes.	15 (56%)	5 (100%)	13 (56%)	**33**	-	-
		Stiff Bristles	**Smooth/ Turf**	**Medium Bristles**			
LGB 6	Recovery drums rearranged; stiff bristle moved to front, followed by smooth drum and medium stiff bristle. Flushing wand was used.	13 (87%)	15 (48%)	29 (97%)	**57**		
LGB 7	Flushing product now collected in flush trough to avoid disturbing oil inflow.	16 (76%)	16 (38%)	57 (90%)	**89**	19	23
LGB 8	No flushing used to see if recovery increases.	16 (84%)	20 (31%)	39 (91%)	**75**	12	11
LGB 9	Repeat of LGB 7 to assess repeatability. Flushing used and collected.	16 (84%)	21 (26%)	54 (78%)	**91**	-	25

Although the three small drums in the LGB collection area recovered a considerable amount of oil, the throughput efficiency (TE - ratio of amount of oil recovered to amount of oil encountered by the drum) of each drum remained low since a considerable amount of oil did not adhere to the brush drum surfaces. This oil was observed to pass under each of the three drums and was trapped between the third drum and the rear grating rods, as indicated in Figure 3.2. The oil remains trapped here and, if no attempt is made to recover it, is eventually pushed through the rear grating and is lost. In general, drum skimmer operations are carried out where oil is contained in a larger enclosure (like a boom) and is able to pass under the drum (if not recovered) and eventually circulate around the sides to the front of the drum again for multiple passes. In this collection area**,** however**,** the oil remains trapped behind the last drum since there is insufficient space at the sides of the drum for the oil to pass to the front of the drum for repeated passes.

For example, in test LGB 7, the collective TE of all three drums can be estimated as 89 L / (130L - 23L) = 83%, where the 130 L is only an estimate of the oil that might have been available to the LGB unit and 23 L is the amount of oil collected by the flushing operation. This is only an example, since the exact amount of oil encountered by the recovery unit is very difficult to determine (note that while 130 litres of fresh oil were added in the path of the unit for each test, the total amount of oil encountered by the unit may fluctuate due to accumulation and/or spreading of the oil in the basin). Attempts were made to increase the TE by recovering the oil that was seen to pool behind the third drum using a modified operation of the recovery unit; this is discussed in a subsequent section below.

An interesting observation was made related to the operation of the recovery unit in that the last drum (D3) consistently collected more oil than the first and second drums (even before using the modified operation method described below). This is also apparent in the results in Table 3.1. It is likely the result of having a pool of oil form behind D3. Although drum skimmers are not intended to operate by recovering oil on the ascending side of the drum, when oil accumulates in a confined area immediately behind the drum, it is forced to make contact with (or creates a certain pressure on) the rear ascending side of the brush drum. This may lead to: (i) a reduced amount of oil dripping off the rear brush drum surface as it rises through the water/oil surface (as is typically observed on an over-saturated ascending drum surface), and (ii) the natural spreading forces of the pooled oil in the rear causing it to push against and be mechanically lifted by this ascending drum surface (by the brushes in particular).

Modified operation of recovery unit In order to maximise the recovered quantity under the LGB, efforts were made to increase the TE (throughput efficiency) of the recovery unit by recovering the oil that pooled behind the third drum. It was demonstrated that by reversing the direction of rotation of this drum for a brief moment (counter-clockwise in Figure 3.2), the drum gets another opportunity to descend into the oil, allowing the oil adhere to it and collect it. Since the drum now descended into a very concentrated pool of oil, a significant amount adhered to the drum surface. Once the oil adhered to the drum surface**,** its rotation was reversed again (clockwise) in order to scrape the surface with the scraper and comb mechanism. The drum could be operated intermittently in either direction of rotation if it was equipped with a scraper and trough for either direction of rotation. Table 3.1 shows the amount of additional oil that was collected by the third drum, from behind it, using this reversing technique at the end of a test (indicated as “Post D3”). To follow the previous example, an estimated TE using this modified operation might be as follows; (89L collected by normal operation of the three drums + 19 L collected with modified operation)/(130L - 23L) = 100 %.

The above method to improve the brush drum performance resembles more closely a 100% TE operation system where all the oil that enters the LGB collection area is contained and collected. Under different conditions such as higher concentrations of slush ice, the advantages with a reversing drum may be less apparent. With the prototype unit, it is important to test the recovery capability under similar conditions as well as with thicker oil slicks.

The proper operation of this type of recovery unit was observed to be highly sensitive to draft fluctuation. For the prototype, the motion of the LGB relative to the water surface probably could have significant adverse effects on the operation of the recovery unit in the collection area (e.g., fluctuating draft of small drums). If so, the recovery unit may have to be incorporated within the LGB in such a way that it can move freely with the water surface and maintain a more constant draft.

3.2 Brush/Drum System

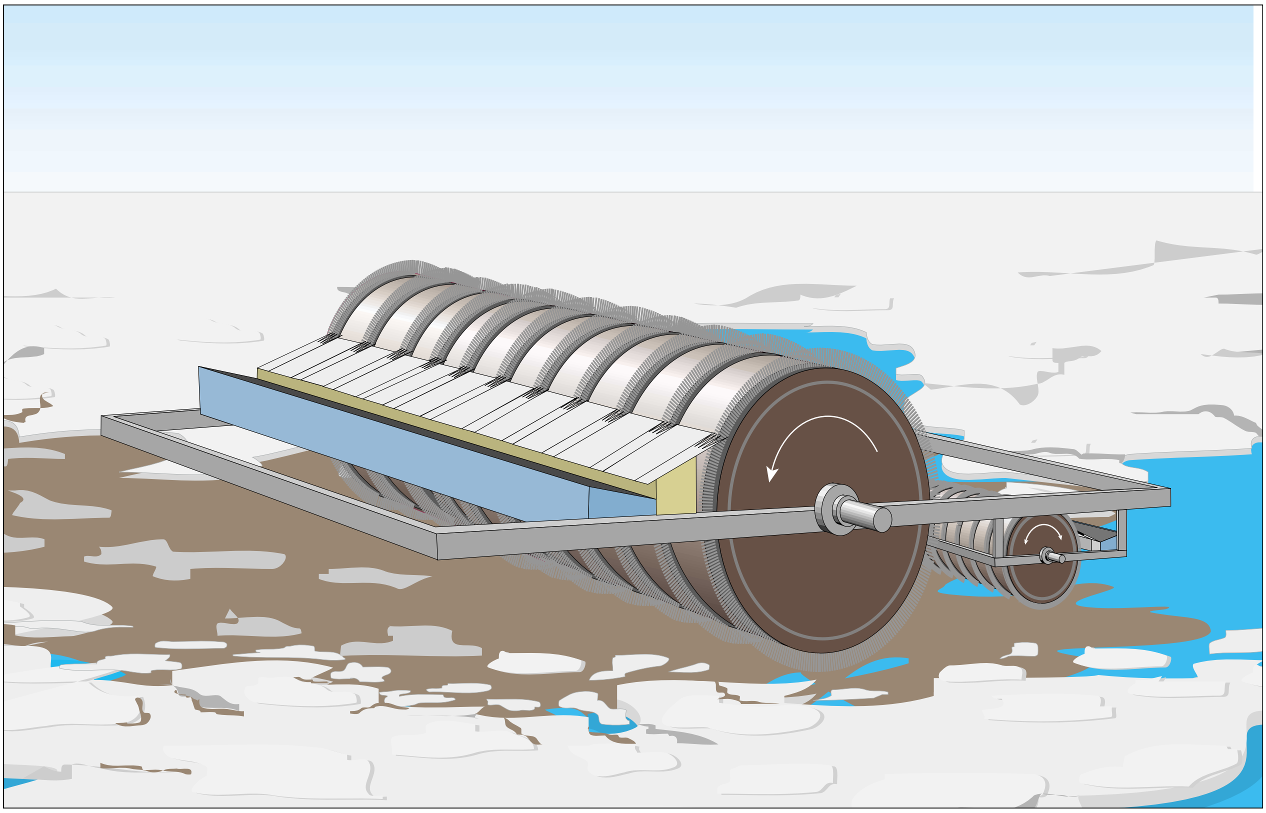

Figure 3.3 Brush/Drum system after modification.

3.2.1 Unit Description and Set-up

The Brush Drum System underwent important modifications during the testing period in Hamburg. At the test temperature, the oil that was supplied for these tests had a viscosity that was significantly higher than the oil used in Phase 2 evaluations and in Phase 3 shakedown tests. As a consequence of high viscosity, this resulted in unexpected difficulties in the oil adhering to the drum surfaces. The Technical Committee was aware of the potential difficulties that may result when operating in oils that are close to or below their pour point, but it was not intended to use such type of oil at this point.

It initially was intended to use the oil types used previously. However, in light of the situation that presented itself during these tests, it was decided to attempt to tackle the issues of reduced adhesion and high viscosity. Consequently, after a few tests the brush/drum configuration was altered significantly as described below to enhance recovery of this new oil type.

The set-up arrangement of the original Brush/Drum system at the Hamburg test facility is described in Figure D2 (Appendix D). The set-up for the second Brush Drum configuration was similar to this. Four tether lines fastened to a support frame supported the unit. This support frame was fixed to the two I-beams that spanned the main and secondary carriages. The lengths of the tether lines were adjusted to obtain the desired operating draft and to provide an effective angle of incidence between the drum and the water surface.

Figures 3.4a and 3.4b present details of the two Brush/Drum systems tested. Both configurations use the first drum to deflect oncoming ice pieces.

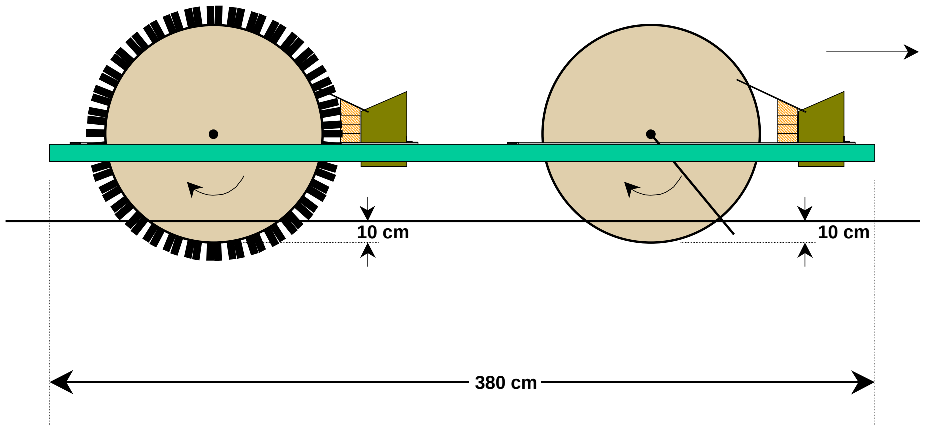

Figure 3.4a Brush Drum with two large drums (Configuration 1).

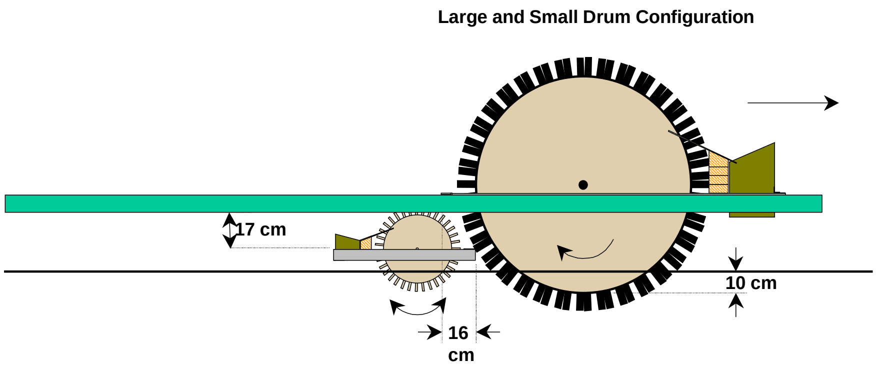

Figure 3.4b Brush Drum with one large and one small drum (Configuration 2).

In the first configuration, lighter oils adhere to the drum surfaces and are scraped off and collected in the recovery troughs. This system does not perform effectively when operated in high viscosity, low adhesion oils.

The second configuration uses a smaller drum placed just behind the larger first drum and rotated in the reverse direction to contain and pool oil in the area between the two drums. The direction of rotation for this small drum is periodically reversed briefly so that the pooled oil adheres to it, but not long enough to have oil deflected under and lost out the back of the unit. This is explained in more detail later in the report.

3.2.2 Results and Discussion - Brush/Drum

The following areas are discussed in greater detail:

- Ice Processing
- Oil Recovery Operation

Ice Processing

Functionality Both of the two Brush Drum configurations use the first drum as an ice-deflecting device by submerging the ice below the water surface. At the same time the free-floating oil remains in contact with the drum surface and is moved backward for subsequent oil recovery through adhesion to the first or second drum; this is discussed in detail in the following oil recovery section. In essence, this ice processing method is effective and simple. However, for proper ice deflection, certain parameters were carefully chosen and incorporated into the designs. These parameters include the angle of incidence and the brush characteristics.

Angle of Incidence and Draft of Deflecting Drum Tests have shown that the angle of incidence at which the drum meets the ice pieces is critical for effective ice deflection. In the case of the drums used in these tests, the maximum angle of incidence that permitted effective ice deflection was approximately 37 degrees. This corresponds to a draft of 10 cm for the 1.0 m-diameter drums used. An angle of incidence greater than this may not provide sufficient ice grabbing and deflection, and may result in ice being pushed forward instead of being deflected. It should be noted that the critical parameter in ensuring effective ice deflection is the angle of incidence and not the draft. The resulting draft for a particular angle of incidence will depend on the dimensions of the drums used.

To achieve the required angle of incidence (corresponding to a draft of 10 cm), the unit tested had to be partially lifted by means of the tether lines attached to the support frame (shown in Figure D.2, Appendix D). At the required draft, the buoyancy forces provided by the drums were equivalent to about 60 kg per drum, or 120 kg for the two drums in the original configuration. Since the tested unit including full troughs has a total weight of approximately 450 kg, it is apparent that a prototype will require some additional buoyancy, likely in the form of vessel floatation. An alternative concept was discussed that would provide similar ice deflection and oil processing characteristics as the drums but would result in a geometry that would have a much greater buoyancy-to-weight ratio.

Brush Bristle A variety of bristle types were used on the large drums without any obvious difference in ice-processing effectiveness. Based on previous evaluations of this system, the bristles were selected to provide sufficient strength for ice deflection for the ice sizes encountered.

Rotational Speed/Hydraulic Power The rotational speed of the first drum had a clear effect on ice deflection performance. In most cases, the first drum in both configurations evaluated was rotated at speeds between 4 and 8 rpm. Operating at higher speeds did not provide sufficient time for the bristles to 'grab' the ice and transfer momentum to the large ice pieces in order to deflect them. High rotational speeds also will result in strong surface currents induced below and behind the drums. Such currents usually lead to greater oil loss.

A hydraulic motor, without any reduction gear, was used to rotate the large drums. At the low rotational speeds used in these tests, the large drums occasionally experienced an uneven, pulsating rotation. Despite attempts by qualified personnel to correct this, the problem could not be properly solved.

To ensure a smoother rotation at low rpm, it is recommended that the prototype unit uses a hydraulic motor with a reduction gear, similar to what was used for the first large drum tested in Phase 2. This set-up consisted of a small hydraulic motor (Danfoss OMM 12.5) and a reduction gear (38,6:1 ratio).

Oil Recovery

Table 3.2 Summary of Recovery Amounts for Brush Drum.

Test ID	Configuration	Description and objectives	Oil added (l)	Oil Recovery in Litres (Recovery Efficiency in %)		
				D1	**D2**	**Total**
				Smooth	**Spiked**	
LDS 1	1	Preliminary test, 2 composite drums; D1 Smooth drum, D2 Spiked drum. No oil	0	-	-	-
LDS 2	1	First test with oil. for the Brush-drum system	130	31 (84%)	17 (63%)	**48**
LDS 3	1	Vary draft and rpm of rear drum to attempt to improve recovery.	130	19 (70%)	13 (59%)	**32**
LDS 4	1	Spiked drum operated as first drum. Smooth D1 lifted out of water.	0	removed	similar above	
				Spiked	**Small brush**	
LDS 5	2	Modified configuration; D1 spiked drum, D2 small brush drum. No oil added.	0	27 (61%)	49 (91%)	**76**
LDS 6	2	Same set up. Oil added.	130	54 (79%)	83 (95%)	**137**
LDS 7	2	Repeat of above.	130	70 (72%)	84 (94%)	**154**
LDS 8	2	New less viscous oil now used. Same drum configuration as above.	130	61 (85%)	53 (91%)	**114**
LDS 9	2	Spiked drum D1 replaced by the Ringed Brush-Drum.	130	41 (41%)	85 (96%)	**126**

Figure 3.4 shows the two configurations that were evaluated in Hamburg. Although the first configuration worked well in the lighter oils used during the shakedown testing and in the previous Phase 2 testing, this was not the case when operated in the much more viscous and less adhesive oil during the Hamburg tests. Table 3.2 gives the recovered oil amount for each drum for the first configuration as LDS2 to LDS4. Numbers in parentheses indicate oil recovery efficiency (ORE) of each drum (percentage of oil in collected product; the difference being water and slush ice).

The modified configuration (Configuration 2) of the Brush Drum, however, proved to be very effective in oil with these characteristics, as can be seen from the results of tests LDS6 through LDS9 in Table 3.2. Whether this second configuration also works well with lighter oils has yet to be determined. Following is a brief explanation of the mechanisms involved in each of the configurations.

In the first configuration, the two large drums operate independently of each other as 'one-pass' systems in that the drum relies on the brief moment of a single pass over the oil slick to have the oil adhere to its surface. Any oil that does not adhere to the drum surface passes under it and is lost. Each drum relies on the adhesion characteristics between the oil and the drum or brush surfaces. In open water conditions, the throughput efficiency for this type of system is often low. Throughput efficiency (TE) for each drum is defined as follows:

$$\text{TE for drum} = \frac{\text{quantity of oil that adheres, is lifted and collected by the unit during a single pass}}{\text{amount of oil encountered by the drum}} \times 100$$

The drum TE will vary with changes in parameters such as oil viscosity and adhesion, drum and brush surface characteristics as well as drum draft. Where oil adhesion is very low, the unit's TE can drop dramatically. This was the case in these tests. By increasing the number of drums that pass over a given path, a 'multi-drum' system as in Configuration 1 (Figure 3.4a) can provide a higher overall system TE. Alternatively, a 'multi-pass' operation can also increase the recovered amount over a given area by operating the unit repeatedly over the same area.

The second configuration shown in Figure 3.4b is an attempt to control, reduce or even eliminate the oil loss under the drum and behind the unit. The primary function of the larger drum in the front is to deflect ice, but it may also recover some oil. The smaller drum behind is normally operated in the opposite direction to the large drum, and the scraper and trough for this drum face the back of the unit. The intention is to catch and contain the oil that is released by the first drum that would otherwise be lost out the back. In this way, a pool of oil is formed in the confined area between the two drums. Continuing to operate the drums in this direction (in Figure 3.4b, the large drum rotating clockwise and the small drum rotating counterclockwise) increases the recovery rate of the large drum slightly since (as also explained in the LGB oil recovery section) the pooling immediately behind the large drum results in less oil dripping off the back side of the drum and may even force additional oil to adhere to its surfaces. This can be seen in Table 3.2 that indicates the oil recovery of the Spiked drum, D1, in the second configurations (test LDS 6 through LDS9) was greater than that of either of the two drums in the first configuration (LDS1-LDS4).

A further increase in oil recovery was achieved with the second configuration by briefly reversing the direction of rotation of the small drum (clockwise in Figure 3.4 b) in order to have its descending side make contact with the oil (similar to the technique used in the 'modified operation of recovery unit' in the LGB). This resulted in a significant amount of oil adhering to the drum. The rotation is quickly reversed again (to counterclockwise) in order to scrape the oil into the trough. Rotating for too long in the clockwise direction would result in much of the pooled oil being pulled under the small drum and being lost behind the unit. These results are indicated in Table 3.2 as D2 in tests LDS 6 to LDS 9.

4. CONCLUSIONS AND RECOMMENDATIONS

The Lifting Grated Belt and the Brush Drum concepts have both been further developed and evaluated on a larger scale than in Phase 2. Quantitative results have been obtained through tests carried out in the cold test facility at the Hamburg Ship Model Basin. The oil provided for these tests had other physical properties, presenting new challenges that were solved in a satisfactory way. Throughout this extensive testing period, both concepts underwent refinements and modifications. Under the given conditions, both concepts are considered to provide effective methods to deal with oil spills in ice. Reasonable recovery rates were observed for the conditions and the amount of oil present. Recovery rates can be expected to increase in conditions where a greater amount of oil is present.

The following specific conclusions and recommendations apply to each of the concepts studied, as indicated:

Lifting Grated Belt

Ice Processing

- The ice deflection approach is considered an effective method for a wide range of ice sizes. Phase 3 proved this operation is effective also for larger ice than used in previous evaluations.

- The rake tines should be strengthened or reinforced. Rake bases should be widened and, if considered necessary, friction can be reduced along the sliding areas to reduce twisting of the rakes.

- Hydraulic hoses leading to the unit must be well protected to avoid snagging and damage from large ice pieces.

- Chain sprockets should be protected by means of a metal guard.

- The hydraulic motor should be located inside the LGB frame to protect it from impact with large ice.

- The hydraulic hose arrangement presently in use is cumbersome and difficult to use. The prototype will require a rearrangement of hydraulic hoses and controls, both to facilitate its operation and to make the control panel more compact.

- A means of adjusting the tension of the belt chain is required.

Flushing

- Although the fixed flushing nozzles were ineffective, the more direct wand proved that some forms of flushing can provide more effective cleaning of deflected ice pieces and at the same time increase the amount of recovered oil.

- Additional evaluations of a flushing system are required to determine the effects of variations in pressure, flow rate and/or heat input to clean oil from the ice and rakes. Such an evaluation is necessary at the initial stages of the next phase, before finalisation of the prototype design.

Oil Recovery

- The oil recovery unit used in the collection area of the LGB proved promising to separate and collect the oil from the slush and water in this enclosed area. However, several modifications have to be made to the design to incorporate the techniques used to create and contain a pool of oil between drums, and subsequently collect this oil through periodic controlled reversal of drum rotation. Designing a dual direction scraper/comb mechanism on one of these drums may permit oil recovery in both directions of rotation.

- The oil recovered may often be mixed with slush or ice pieces that make offloading difficult. The use of auger conveyors together with added heat in the collection troughs should be considered to help move the collected product to the offloading hose.

- The prototype unit should include an air conveyor or off-loading pump with higher capacity than that used in these tests.

- It is recommended that a hot water injection system be introduced at the inlet of the suction hose to improve the operation of the air conveyor in low temperatures.

- For the prototype, the recovery unit probably should be incorporated within the LGB in such a way that it can move freely with the water surface and maintain a constant draft, separate from the vertical movement of the LGB and the operating platform.

Brush/Drum

Ice Processing

- The ice deflection operation of the Brush Drum system was effective with the 1.0 m diameter drums as long as the forward drum was operated at an angle of incidence less than 37 degrees and at a low rpm. The bristle bundles provided sufficient overall stiffness to be able to deflect the ice pieces processed in these tests. Bristles should not be overly thick as this makes combing-out oil more difficult and less effective.

- For smoother drum rotation, hydraulic motors with a high-ratio reduction gear should be used to eliminate pulsation in drum rotation.

Oil Recovery

- The first configuration, consisting of two large drums operated in series and relying strictly on a one-pass oleophilic process, was not very effective at recovering the highly viscous oil used in these tests.

- The second Brush Drum configuration using one large and one small drum was very effective at recovering both the high and low viscosity oils and thus should be used in the prototype unit of Phase 4. This design will provide the greatest recovery performance in very viscous and less adhesive oils since the process does not rely strictly on an oleophilic recovery process, as does the first configuration.

- The second configuration should be tested with oils of different viscosity and slick thickness to evaluate its performance limitations in these varying conditions.

- To reduce or eliminate the oil loss that was observed, walls must be incorporated at the sides of the second configuration where the oil pool is formed.

5. REFERENCES

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Appendix A – Overview of results from Hamburg tests

PHASE 3 TEST MATRIX OF RESULTS OF QUANTITATIVE TESTING

Test ID	Description and objectives	Oil Recovery (Litres) and Recovery Efficiency					
		D1	D2	D3	Total	Post D3	Flush
LGB 0	First preliminary test without oil. Recovery unit not installed.						
		Smooth/Turf	Medium	Stiff			
LGB 1	Test without oil. Recovery unit and walls installed under LGB. Flushing used.						
LGB 2	Test without oil. Adjusting belt speed and draft.						
LGB 3	Test without oil.						
LGB 4	First distribution method. Very little oil in water; most cakes on ice.						
LGB 5	New oil distribution method used in this test. Oil distributed between ice floes.	15 (56%)	5 (100%)	13 (56%)	**33**	-	-
		Stiff	Smooth/Turf	Medium			
LGB 6	Recovery drums rearranged; stiff bristle moved to front, followed by smooth drum and medium stiff bristle. Flushing wand was used.	13 (87%)	15 (48%)	29 (97%)	**57**		
LGB 7	Flushing product now collected in flush trough to avoid disturbing oil inflow.	16 (76%)	16 (38%)	57 (90%)	**89**	19	23
LGB 8	No flushing used to see if recovery increases.	16 (84%)	20 (31%)	39 (91%)	**75**	12	11
LGB 9	Repeat of LGB 7 to assess repeatability. Flushing used and collected.	16 (84%)	21 (26%)	54 (78%)	**91**	-	25

Test ID	Description and objectives	Oil Recovery (L) and Recovery Efficiency		
		D1	D2	Total
		Smooth	Spiked	
LDS 1	Preliminary test, 2 composite drums; D1 Smooth drum, D2 Spiked drum. No oil			
LDS 2	First test with oil. for the Brush-drum system	31 (84%)	17 (63%)	
LDS 3	Vary draft and rpm of rear drum to attempt to improve recovery.	19 (70%)	13 (59%)	
LDS 4	Spiked drum operated as first drum. Smooth D1 lifted out of water.	removed	similar above	
		Spiked	Small brush	
LDS 5	Modified configuration; D1 spiked drum, D2 small brush drum. No oil added.	27 (61%)	49 (91%)	76
LDS 6	Same set up. Oil added.	54 (79%)	83 (95%)	137
LDS 7	Repeat of above.	70 (72%)	84 (94%)	154
LDS 8	New less viscous oil now used. Same drum configuration as above.	61 (85%)	53 (91%)	114
LDS 9	Spiked drum D1 replaced by the Ringed Brush-Drum.	41 (41%)	85 (96%)	126

Appendix B – Information and Observations from Hamburg tests

LGB-0 **Sept. 28, 1998**

Objectives First preliminary test w/o oil, to ensure proper operation of unit, to select appropriate belt speed and advance speed. Recovery drums and walls not installed under belt.
To evaluate ice processing capabilities for the first time of this larger LGB unit.

Test Setup/Conditions

Belt Speed very low belt speed, not recorded but estimated at 10 mm/s from video
Belt Freeboard 88.5 cm (top of frame to water surface)
Drum 1 not installed
Drum 2 not installed
Drum 3 not installed

Air temperature (°C) -2
Water temperature (°C) -0.5

Speed of advance not recorded
Duration of test not recorded 15:11-
Length of test run not recorded
Ice mostly 1 – 2 m x 20 cm thick; some brash and slush
Oil added none
Water flushing Flushing not used.

Observations Ice catching on hydraulic hoses, to be strapped to the LGB frame.
Very low belt speed. Belt stops when large ice pieces are lifted by the belt. Hydraulic pressure was increased in subsequent tests to overcome this.
Rake tines are bending, especially at the ends. Rake material may be too soft.

Test Results LGB 0
No numerical data collected

Comments Several minor problems were identified during the operation of this unit (see observations section) and were corrected for subsequent tests. Additional preliminary tests required to evaluate ice processing of unit.

LGB-1 **Sept. 28, 1998**

Objectives Preliminary test without oil. Small recover drums and walls are now in place under belt. Flushing used. Half the rake end-tines have been reinforced with a welded piece of flat iron.
Ensure proper operation of unit; select appropriate belt speed and advance speed.
Evaluate ice processing capabilities of this new unit.

Test Setup/Conditions

Belt Speed varied during tests; not recorded
Belt Freeboard 88.5 cm
Drum 1 smooth/sorbent turf (ratio of length:91.2/48.5 cm) diameter (31.5+2 cm) x 140cm
Drum 2 8 soft/7 medium-bristle strips + 8 cm
Drum 3 14 stiff-bristle strips + 9 cm
Draft 1 - 2 cm
Rotational speed varied throughout test

Air temperature (^oC)	-1.1	-2.0	-2.2	-1.8
Water temperature (^oC)	-1.4	-0.2	-0.3	

Speed of advance 15 mm/s
Duration of test approximately 1 3/4 hours(several tests) 17:30 – 19:15 hrs
Length of test run 14 m
Ice mostly 1 – 2 m x 20 cm thick; some brash and slush
Oil added none
Water flushing Unspecified amount in flush container @ 33.5^{o}C
Not used for entire test duration.

Observations A lot of condensed steam in air from flushing with warm water; reduces visibility.
Hose came off water pump. Flushing operation discontinued.
Electrical breakers tripped, halting carriage. Repeated attempts (4) involved in running length of tank. This electrical problem was corrected for subsequent tests.
Large ice pieces required manual lifting assistance to prevent belt from stopping. Hydraulic pressure was still insufficient at this setting of 50-60 bars.
Ice pieces may be very large for these confined test conditions (1.5-2. m^2). Most of the ice pieces are rectangular, resulting in very little room for ice to move in basin.
Reinforcement pieces were welded to half the rake end tines to prevent bending. This reinforcement worked well.
Hydraulic hoses to LGB tied off close to frame to avoid ice pieces from catching
Ice conditions remain basically same after test
Small drum assemblies were lifted out and stored in boxes at end of day

Test Results LGB 1
No numerical data collected
Stiff-bristle drum in the back (Drum 3) picked up a good deal of slush. Not the case with Drum 2 (softer bristles) and Drum 1 (smooth drum in the front).

Comments Several problems were identified during this test (see observations section) and were corrected for subsequent tests.
Another preliminary test was required.

LGB-2 **Sept. 29, 1998**

Objectives Preliminary test w/o oil, to ensure proper operation of unit, to select appropriate belt speed and advance speed.
Electrical problems resolved. Hydraulic pressure for belt was increased.
To evaluate ice processing capabilities of this new unit.

Test Setup/Conditions

Belt Speed 40 cm/s (or 2.5s/m)
Belt Freeboard 88.5 cm
Drum 1 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 2 8 soft/7 medium-bristle strips + 8 cm
Drum 3 14 stiff-bristle strips + 9 cm
Draft 1.5 - 2 cm
Rotational speed 7 rpm

Air temperature (^{o}C) -2.1 -2.0 -2.2 -1.7
Water temperature (^{o}C) -1.0 -0.2 -0.2

Speed of advance 3.6 cm/s
Duration of test 8 minutes 14:01:30 – 14:09:30
Length of test run 17.5 m
Ice mostly 1 – 2 m x 20 cm thick; very little slush
Oil added none
Water flushing 150 L water used to lightly spray ice. Lower flushing water temp. used.

Observations Large ice makes rakes heel, or twist backwards because of the force at the rake tips. Although this wasn't a serious problem, the base of one rake, where it slides up the frame, was widened by welding flat steel pieces. This rake twisted significantly less than the others.
New turf glued in place (with contact cement) on Drum 1 before test
Bristle strips tightened on Drum 2
Electrical breaker not tripping during this test
Belt stops due to weight of large pieces of ice. Hydraulic pressure for the belt had intentionally been left lower than maximum. Now it was increased and this improved its lifting capacity of large ice. Highest required pressure was 160 Bars.
Some large ice pieces break easily when lifted by belt.
When backing up belt, we can observe an outward current due to the belt speed.
All tines are reinforced have a positive effect.

Test Results LGB 2
No numerical data collected
Water collected by three drums = 10 , 4 and 10 litres.
Slush and brash ice accumulates under belt between Drum 3 and the descending portion of the rear grating.
Turf drum sector picks up some slush

Comments

Belt speed maybe slightly too high.
Ice processing works well.
A last preliminary test will be carried out to make sure everything is ok before adding oil.

LGB-3 **Sept. 29, 1998**

Objectives Third and last test before adding oil, to check everything is operating as it should.

Test Setup/Conditions

Belt Speed 38 cm/s (approx. same as previous test)
Belt Freeboard 88.5 cm
Drum 1 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 2 8 soft/7 medium-bristle strips + 8 cm
Drum 3 14 stiff-bristle strips + 9 cm
Draft 1.5 - 2 cm
Rotational speed 7 rpm

Air temperature (^{o}C) -2
Water temperature (^{o}C) -0.2

Speed of advance 2.2 cm/s (unchanged)
Duration of test 10 minutes 15:47:40 – 15:57:40
Length of test run 13 m
Ice mostly 1 – 2 m x 20 cm thick. Still very many large ice pieces in the path, some slush and brash.
Oil added none
Water flushing Unspecified amount of water used to spray ice.
Little slush in tray except where there is no flushing (at top)

Observations Large pieces of ice lifted by the belt. Metal protection bar damaged by a large ice piece.
Large ice pieces are a problem only when a lot of the ice is passing between the LGB and the fast ice in the tank.
Ice floes are pushed forward at the front edges of the belt (too little space on the sides of the belt.
Still some fog from the flushing water.
Turf is processing slush better than smooth drum, but also picks up more slush.
Slush and brash ice accumulates under belt between Drum 3 and the descending portion of the rear grating.
Chain came off sprocket (left then right side) when ice piece was jammed between the fast ice and the rear belt sprocket. Testing had to be halted.
Technician enters water in dry suit to facilitate the repair. The master links had to be disconnected for this repair.

Test Results LGB 3
No numerical data collected

Comments Unit operated well until chain came off sprocket.

The chain was reinstalled and prepared for next test, with oil.

Careful attention was used in subsequent tests to ensure large ice pieces did not jam into sprocket again. A sprocket guard should be designed into future units.

It has been shown that this LGB unit can lift and process very large pieces of ice. Therefore, the very large ice pieces will be broken somewhat to make it easier for subsequent tests to be carried out in such limited space.

Decided to go with lower belt speed in subsequent tests.

This advance speed may seem appropriate for a full scale unit; may not require to be higher during field operation. This speed to be maintained during subsequent tests.

LGB-4 **Sept. 30, 1998**

Objectives First test with oil. To evaluate oil distribution method using oil distributor. To evaluate oil recovery and ice processing capabilities of unit.

Test Setup/Conditions

Belt Speed 33 cm/s (slightly slower than previous test)
Belt Freeboard 88.5 cm
Drum 1 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 2 8 soft/7 medium-bristle strips + 8 cm
Drum 3 14 stiff-bristle strips + 9 cm
Draft 1.5 - 2 cm
Rotational speed 7 rpm

Air temperature (°C) -0.6 -0.9 +0.1 -0.5
Water temperature (°C) -0.1 -0.2 -0.3

Speed of advance 3.9 cm/s
Duration of test 7 minutes 25 sec 12:05:35 – 12:13:00
Length of test run 17.5 m
Ice mostly (70%) 0.5 – 1 m x 20 cm thick, some slush and brash ice (large ice had been broken up since last test)
Oil added 130 litres IFO 30 oil added ON and BETWEEN ice using distributor, in a path as wide as the belt, covering about 15 m in length
Water flushing 650 litres water used to spray ice.
Little slush in tray except where there is no flushing (at top)
Flushing not effective; oil is caked-on to tops of ice pieces since oil distribution method pours most oil (warm) on top of ice.

Observations Most oil appears to be on ice (because of distribution method) and adheres to it since oil is below its pour point.
Middle drum recovers least amount of material
Astroturf segment of smooth drum picks up slush, otherwise similar to smooth portion in terms of oil pickup.
Some oil also sticking to rakes.
Still little room for ice to pass at left side of LGB (potential for jamming at rear sprocket again).
Some slush and brash ice staying on flushing tray, not sliding down.
Slush and brash ice accumulates under belt between Drum 3 and the descending portion of the rear grating.

Test Results LGB 4
No numerical data collected

Comments Oil distribution method resulted in an unrealistically high percentage of oil on top surface of ice pieces and very little on the water surface.
Also, since oil is warm when distributed, it adheres greatly to ice surfaces upon cooling, making flush-cleaning very difficult. This resulted in poor flush-cleaning with most oil passing over unit on ice pieces, and therefore little oil entering into unit for recovery.
A new oil distribution method is used during subsequent tests.

LGB-5 **Sept. 30, 1998**

Objectives Evaluate oil recovery and ice processing performance of unit
Evaluate new oil distribution method

Test Setup/Conditions

Belt Speed 20 - 32 cm/s (varied during test)
Belt Freeboard 88.5 cm (unchanged)
Drum 1 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 2 8 soft/7 medium-bristle strips + 8 cm
Drum 3 14 stiff-bristle strips + 9 cm
Draft 3 cm (increased from previous test)
Rotational speed 7 rpm (unchanged)
Air temperature (^{o}C) +0.7 -0.5 +0.4 +0.3
Water temperature (^{o}C) -0.2 -0.2 -0.2

Speed of advance 3.6 cm/s .
Duration of test 9 minutes 15:43:40 – 15:52:40
Length of test run 19.5 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush (same)
Oil added 130 litres IFO 30 oil added primarily BETWEEN ice pieces directly from hose
Water flushing 550 litres water @ 30^{o}C used to spray ice but with little effect on oil
Slush is washed off and drops into tray along with oil

Observations Flushing nozzles tilted towards the incoming ice for a more aggressive spray angle. Flushing operation not very effective.
Slush on tray is not being removed much due to lack of flushing.
Flushing not very effective on oil that was "caked-on" ice from previous distribution method.
Some pileup of slush &oil in front of Drum 1. Ice processing of this drum slower than others.
Slush, brash ice and oil accumulate under belt between Drum 3 and descending portion of rear grating.
Some brash ice falls through grating when floes flip over to the rear slope of the belt.
Drum 3 broke at the ends and test had to be halted.

Test Results LGB 5

		Drum 1 Smooth	Drum2 White Brush	Drum 3 Black Brush
Volume of total recovered product		27	5	23
Water collected		12	0	2.5
Oil recovered	Total= 33 L	15	5	13
Slush collected		0	0	7.5
Oil recovery efficiency		56%	100%	56%
Slush recovery percentage		0	0	20%

Comments This distribution method results in less oil on the ice tops and more on the water surface between the ice pieces.

Recovery of the smooth drum in position D1 is highest, with a recovery efficiency of 56%. Most of the water recovered from this drum resulted from the absorbent turf surface.

Second drum with medium bristle stiffness has lowest recovery for unknown reasons.

Last drum has good recovery, although a higher slush collection also.

Overall recovery is low, but better than previous test. Low recovery may be due to lower encounter rate during these initial tests, until oil in basin reaches an equilibrium pre-load.

Considerable amount of oil is passing under the drums and being trapped between the last drum and the descending side of the LGB. In subsequent tests, efforts will be made to recover oil at this point also (e.g. LGB7).

Ice processing by Drum 1 (smooth) was slow at times with some pile-up in-front.

Flushing has limited effect on oil which adheres tenaciously to ice.

SINTEF

LGB-6 **Oct. 1, 1998**

Objectives Stiff-bristle brush was repaired and moved to front position to attempt to increase its recovery and to increase ice processing in front of Drum 1.
Evaluate oil recovery and ice processing performance of unit.
Evaluate flushing with more direct flushing wand.

Test Setup/Conditions

Belt Speed 28 cm/s
Belt Freeboard 88.5 cm
Drum 1 14 stiff-bristle strips diameter 31.5 cm + 9 cm x 140 cm
Drum 2 smooth/sorbent turf (91.2/48.5 cm) + 2 cm
Drum 3 8 soft/7 medium-bristle strips + 8 cm
Draft 3 cm (possibly slightly greater due to increase in water level)
Rotational speed 7 rpm (unchanged)

Air temperature (^oC) +0.5 +0.3 +1.2 +0.6
Water temperature (^oC) 0.0 -0.2 -0.5

Speed of advance 3.8 cm/s
Duration of test 9 minutes 15 seconds 15:53:25 – 16:02:40
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres IFO 30 oil added between ice directly from hose
Water flushing 150 litres water @ 30 ^oC used to spray ice FROM WAND only.

Observations Flushing with more direct wand method is more effective (where applied). Would need more of these wands for thorough cleaning of ice.
Much oil adheres to rakes. Most of this oil remains adhered to rakes as they travel around the unit. Some oil falls into flush tray area and some may fall and be lost behind the unit.
Ice pieces hit hydraulic and electrical lines. These should be tied off.
Slush, brash ice and oil accumulate under belt between Drum 3 and descending portion of rear grating.
A lot of oil and slush in flush tray.

Test Results LGB 6

		Drum 1 Black Brush	Drum2 Smooth	Drum 3 White Brush
Volume of total recovered product		15	33	32
Water collected		2	18	2
Oil recovered	Total= 57 L	13	15	29
Slush collected		0	0	1
Oil recovery efficiency		87%	48%	97%
Slush recovery percentage		0%	0%	3%

Comments Overall oil recovery considerably higher than previous test. However, Drum 1 (stiff bristles) recovery is slightly lower. Higher recovery rate may be due to an increase in encounter rate during these several first tests with oil, while oil in test basin reaches an equilibrium pre-load.

Although the three drums recover some of the oil they encounter, they do not have, and may never have, a 100% oil-encounter-efficiency (recover all the oil that is encountered) in oil-in-ice conditions. Therefore, many drums would have to be used (not always feasible in reality) or a unit with a higher throughput efficiency must be conceived.

LGB-7 **Oct. 2, 1998**

Objectives Configuration of unit was same as in previous test. In previous tests, the flushing product (water, oil and slush ice) was allowed to run down the tray into the area in front of first drum, possibly disturbing the incoming oil. In this test the flushing product was collected (in a trough added at the bottom end of the tray) and pumped into a container in order to observe if this reduces the disturbance and improves oil inflow.

Evaluate oil recovery and ice processing performance of unit

Test Setup/Conditions

Belt Speed 27 cm/s
Belt Freeboard 88.5 cm
Drum 1 14 stiff-bristle strips + 9 cm
Drum 2 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 3 8 soft/7 medium-bristle strips + 8 cm
Draft 3 cm
Rotational speed 7 rpm

Air temperature (^{o}C) +0.5 +0.6 +1.6 +0.8
Water temperature (^{o}C) -0.1 -0.1 -0.4

Speed of advance 2.8 cm/s
Duration of test 12 minutes 37 sec 10:40:45 – 10:48:42 + 11:06:40 – 11:11:20
+ 5 minutes 11:16:00 drums are stopped
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres IFO 30 oil added between ice directly from hose
Water flushing 175 litres water @ 15 ^{o}C used to spray ice with wand

Observations Rakes appear to hold significant amount of oil.
Again, the more direct flushing wand works well where applied.
Flushing product collected and continuously removed from trough with air conveyor.

Less slush/oil left on tray after test since greater amount of flushing water directed to tray.
Stopped run momentarily to empty drum troughs to avoid overflowing.
Some recurring problems with jamming of ice pieces in air conveyor hose.
Slush, brash ice and oil accumulate under belt in area between Drum 3 and descending portion of rear grating. After test run, once LGB stopped, this area under belt was cleared by rotating Drum 3 backwards and forwards, attempting to have oil adhere to drum for recovery. Worked well. Recovery product recorded for this operation as Post Drum3.

Test Results LGB 7

	Drum 1 Black Brush	Drum2 Smooth	Drum 3 White Brush	Post Drum3	Flushin g
Volume of total recovered product	21	42	63	21	199
Water collected	2	24	0	n/m	n/m
Oil recovered Total= 89L + 19post +23 Flush	16	16	57	19	23
Slush collected	3	2	6		

Oil recovery efficiency	76%	38%	90%	90%	
Slush recovery percentage	14%	5%	10%		

Comments This test resulted in considerable increase in recovered oil from the previous test (from 57 to 89 litres, or 56%), excluding the oil collected by Post Drum3 and in the flushing trough. This may be attributed to the flushing product being collected and not allowed to disrupt oil inflow. Contrary to what might be expected, however, the Drum1 recovery did not increase much as a result of this change (from 13 to 16 litres).

This test gives an idea of how much oil is being collected by the flushing and tray assembly.

Reversing Drum 3 proved to be a good method to improve oil recovery of this unit.

LGB-8 **Oct. 2, 1998**

Objectives Configuration of unit was same as in previous test. This test is a repeat of previous test in order to confirm the repeatability of test. However, the flushing system was not operated during this test (to see if this would improve recovery). Look for whether third drum will pick up a similar amount of oil without the help of flushing[15].

Evaluate oil recovery and ice processing performance of unit

Test Setup/Conditions

Belt Speed 23 cm/s
Belt Freeboard 88.5 cm
Drum 1 14 stiff-bristle strips + 9 cm
Drum 2 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 3 8 soft/7 medium-bristle strips + 8 cm
Draft 3 cm
Rotational speed 7 rpm

Air temperature (^{o}C) -0.5 -0.7 0.0 -0.5
Water temperature (^{o}C) 0.0 0.0 -0.1

Speed of advance 3.1 cm/s
Duration of test 11minutes 40 s 15:42:50 – 15:54:30
Length of test run 22 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres IFO 30 oil added between ice directly from hose
Water flushing no flushing; collection trough is emptied only after test

Observations Tray has slush and oil caught in it.

Slush, brash ice and oil accumulate under belt in area between Drum 3 and descending portion of rear grating.. After test run, once LGB stopped, this area under belt cleared by rotating Drum 3 backwards and forwards, attempting to have oil adhere to drum for recovery. Worked well. Recovery product recorded for this operation as Post Drum3.

Although no flushing was used for this test, at the end of the test, the flushing trough was emptied of the oiled slush that had fallen and accumulated into it.

Test Results LGB 8

	Drum 1 Black Brush	Drum2 Smooth	Drum 3 White Brush	Post Drum3	Flushin g
Volume of total recovered product	19	65	43	14	14
Water collected	2	43	0	n/m	n/m
Oil recovered Total= 75L + 12postD3 +11 Flush	16	20	39	12	11
Slush collected	1	2	4	n/m	n/m
Oil recovery efficiency	84%	31%	91%	86%	-
Slush recovery percentage	5%	3%	9%	n/m	-

Comments Recovery rates are within the same range as the previous two tests, which confirms repeatability of testing method and results.

However, the recovery rate of D3 was lower in this test than the previous test (39 from 57 l) although there doesn't appear to be any reason to think that the flushing would improve D3 recovery.

Not using flushing resulted in less oil being collected in the trough, probably remaining on the tray.

LGB-9 **Oct. 3, 1998**

Objectives This test is similar to LGB7 where the flushing product was collected and pumped off during the test. However, flushing nozzles were not used; only the hand-held flushing wand was used to see if more oil could be removed and collected from the rakes and flush tray. A lower belt speed is used to allow more time for this flushing process.
Evaluate oil recovery and ice processing performance of unit.

Test Setup/Conditions

Belt Speed 17 cm/s (slower than previous test)
Belt Freeboard 88.5 cm
Drum 1 14 stiff-bristle strips + 9 cm
Drum 2 smooth/sorbent turf (91.2/48.5 cm) diameter 31.5 cm + 2 cm x 140 cm
Drum 3 8 soft/7 medium-bristle strips + 8 cm
Draft 2 cm
Rotational speed 7 rpm
Air temperature (^oC) -0.5 -0.6 +0.5 -0.2
Water temperature (^oC) 0.0 0.0 -0.1
Speed of advance 20 mm/s
Duration of test 14minutes 35 sec 11:55:40 – 12:10:15
+ 8 minutes 5 sec 12:18:20 drum rotation stopped
Length of test run 22 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush.
Oil added 130 litres IFO 30 oil added between ice directly from hose
Water flushing only wand used to direct spray at rakes and tray

Observations Ice conditions have not changed significantly.
Slush, brash ice and oil accumulate under belt in area between Drum 3 and descending portion of rear grating.. This area was not cleared with Drum 3 after this test.
Ice was not broken up and oil was in small sheets toward end of test.
A significant amount of oil appears to adhere and hold onto rakes.
Flushing with more direct wand method is more effective (where applied). However, would need more of these wands for thorough cleaning of ice. Flushing trough overflows a little.
Flushing in general melts and reduces the amount of slush accumulation in tray.

Test Results LGB-9

	Drum 1 Black Brush	Drum2 Smooth	Drum 3 White Brush	Post Drum3	Flushing
Volume of total recovered product	19	81	69		202+12
Water collected	2	56	8		n/m
Oil recovered Total= 91L + 25 Flush	16	21	54	n/m	15+10
Slush collected	1	4	7		n/m
Oil recovery efficiency	84%	26%	78%		-
Slush recovery percentage	5%	5%	10%		-

Comments Recovery rate is 11% lower than LGB 7, which is within the margin of error for these tests. It was observed, as in previous tests, that the manual flushing hose method resulted in more oil being removed from the ice pieces, rakes and the flush tray where the water stream was directed. Although the overall recovery rate did not increase, and the amount of oil collected in the flushing trough remained very similar to LGB7 (25L compared to 23L), it should be noted that only one flushing wand was being evaluated at this time. While several of these rods could be used to increase this oil flushing, one must keep in mind the large volumes of water that are required for this operation.

As with the previous test, these test results also demonstrate repeatability of results since recovery rate is in the same range as previous test with similar configurations.

LDS-1 **Oct. 6, 1998**

Objectives
First preliminary test with this Large Drum System to ensure proper operation of unit and to select appropriate drum rpm, drafts and unit advance speed.
No oil was added to test basin.
Evaluate ice processing performance of unit.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	0-smooth	6-9	14/15 cm
Drum 2	composite	5 stiff/5 medium	5-9	17/12 cm

Air temperature (^oC)	+0.6	-0.2	-0.4	+0.7
Water temperature (^oC)	+0.3	-0.2	-0.2	

Speed of advance	20 mm/s	
Duration of test	5 minutes 0 sec	15:06:40 - 15:11:40
	6 minutes 17 sec	15:33:43 - 15:40:00
Length of test run	11 ½ m and 10 m	
Ice	mostly 0.5 – 1 m x 20 cm thick, some smaller pieces and slush	
Oil added	none	

Observations
Ice was pushed ahead by Drum 1 during 2 runs within the test.
Run was stopped momentarily to lift unit and reduce draft of rear drum to improve ice processing.
Unit was supported upwards by flexible cords at all four corners.
Very little ice between two drums.
High rpm resulted in considerable current behind Drum 2 (bristles), but less behind Drum 1 (smooth).
High rotational speed also resulted in high water pickup by both drums.

Test Results LDS-1
No numerical data collected during this preliminary test.
High rpm resulted in some water pick up.

Comments
The draft of the unit was too great (unit too deep) and resulted in difficulties with ice processing and will have to be reduce in next test.
A slightly lower rpm for both drums will also be used to improve ice processing.
The advance speed of unit seems appropriate and was controlled by the main bridge. This to be used in subsequent tests also. Because the unit had to be supported by the bridge frame, it was not possible to evaluate the unit's ability to advance itself.

LDS-2 **Oct. 6, 1998**

Objectives First test with oil with the Large Drum System.
Using lower draft to improve ice processing.
Evaluate oil recovery and ice processing performance of both drums.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	0 (smooth)	4	9 cm
Drum 2	composite	5 stiff/5 medium	6/5	10cm

Air temperature (^oC) +1.2 +1.0 +1.1 +1.7
Water temperature (^oC) +0.3 +0.2 0.0

Speed of advance 20 mm/s
Duration of test 8 minutes 32 sec 17:08:12 - 17:16:44
Length of test run 18 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres of IFO 30 oil added

Observations Flexible cords to support unit at four points were replaced by rope to facilitate draft adjustment.
Second drum had slight problems rotating smoothly at this rpm with these hydraulic motors.
Ice processing improved at this draft.
Fair oil adhesion to smooth drum D1. Some oil recovery in the form of long and thick patches of oil adhering to this drum.
Most oil drips off without adhering to bristles of second drum.
Considerable amount of oil could be seen passing both drums without adhering and being recovered.
Plenty of open water behind Drum 1 and behind Drum 2 as both drums appear to create a slight outflow current behind them.

Test Results LDS-2

	Drum 1 Smooth	Drum2 Spiked Brush		Total
Volume of total recovered product	37	27		
Water collected	6	10		
Oil recovered	31	17		48
Slush collected	n/m	n/m		
Oil recovery efficiency	84%	63%		
Slush recovery percentage	-	-		

Comments The drafts used in this test, approximately 10 cm for both drums (or angle of incidence of 37^o) seemed to be appropriate for proper ice processing. This draft will be maintained in most subsequent tests.
Oil recovery was comparatively lower than that of units tested in Phase 2, as should be expected, due to the high viscosity and low adhesion of this oil type. Subsequent tests will look into improving the performance with this oil, as opposed to changing to a less viscous oil.

Although Drum2 recovered less oil, it must be noted that this drum experiences a lower encounter rate, since Drum1 has recovered some oil, and is also working with a wetted oil that has passed under Drum1.

LDS-3 **Oct. 7, 1998**

Objectives To vary the draft of the rear drum and the rpm of both drums to order to attempt to improve recovery performance.
Evaluate oil recovery and ice processing performance of both drums.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	0 (smooth)	changed during run	9 cm
Drum 2	composite	5 stiff/5 medium	changed during run	10cm

Air temperature (°C)	+0.4	+0.4	+1.2	+0.5
Water temperature (°C)	+0.4	+0.2	-0.2	

Speed of advance 20 mm/s
Duration of test 7 minutes 43 sec 09:56:10 – 10:03:53
Length of test run 20 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres of IFO 30 oil added

Observations Ice processing works well.
Drum 2 bristles deflect quickly, but do not have any 'scrubbing' effect on oiled ice floes.
Some (low) oil adhesion to smooth Drum 1. This drum appears to have a lower recovery than during the previous test.
Most oil drips off at rear of second drum without adhering to bristles.
A considerable amount of oil passes under both drums without being recovered. Some patches of free floating oil do not adhere to either smooth or bristle drums and are rejected out back with considerable momentum, as ice is.
Air conveyor has less jamming problems when water is occasionally sucked in with brash ice and oil.

Test Results LDS-3

	Drum 1 Smooth	Drum2 Spiked Brush		Total
Volume of total recovered product	27	22		
Water collected	8	9		
Oil recovered	19	13		32
Slush collected	n/m	n/m		
Oil recovery efficiency	70%	59%		
Slush recovery percentage	-	-		

Comments This test resulted in a lower recovery rate than the previous and may be due to greater draft used..
Variations in drum rpm and draft did not appear to result in a significant improvement in adhesion of this oil to either drum.
Again, this oil has a very high viscosity and low adhesion. Subsequent tests will continue to look into improving the recovery performance with this oil, as opposed to changing to a less viscous oil.

LDS-4 **Oct. 7, 1998**

Objectives To observe whether oil adhesion will improve for the spiked drum, Drum 2, when encountering the oil firsthand, without the possible disturbance or wetting effect of Drum 1. In effect, to lift Drum 1 out of water and allow Drum 2 to operate alone.
No additional oil added.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	(not used; lifted out of water and not included in this test)			
Drum 2	composite	5 stiff/5 medium	changed during run	varied

Air temperature (°C)	+0.4	+0.4	+1.2	+0.5
Water temperature (°C)	+0.4	+0.2	-0.2	

Speed of advance	20 mm/s (31 mm/s)	
Duration of test	7 minutes 43 sec	11:43:45 – 11:50:45
Length of test run	14.5 m	
Ice	mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush	
Oil added	no oil added	

Observations Draft and rpm varied; ice processing ok. at shallow draft
Still very little oil adhesion onto drum or bristles. Oil continues to drip from back of drum.

Test Results LDS-4
No numerical data collected during this preliminary test.

Comments Although no oil was added into test basin for this test, it was evident that oil adhesion on the Drum 2 continued to be low, even when encountering the oil firsthand.

LDS-5 **Oct. 7, 1998**

Objectives Evaluate a modified configuration. In an effort to improve oil recovery in this high viscosity, low adhesion oil, the unit was modified. The smooth drum, previously Drum 1, was removed and the Spiked Drum, previously Drum 2, was moved into position of Drum 1. A smaller brush-drum unit (from the LGB) was installed immediately behind the now Drum 1 and was operated in the reverse rotational direction to accumulate the oil between the two drums and assist in recovering this oil through forced adhesion or mechanical lifting.

Also, evaluate whether ice may pile up between drums because of the reversed rotation of Drum 2.

Evaluate oil recovery and ice processing performance of this modified unit. No oil added.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	5 stiff/5 medium	7	10 cm
Drum 2	plastic (small)	14 stiff-bristle strips	8 contra-rotating	2 –3 cm

Air temperature (^oC)	+0.3	-0.3	-0.7	-0.1
Water temperature (^oC)	+0.4	+0.2	-0.1	

Speed of advance 20 mm/s
Duration of test 9 minutes 40 sec 16:35:40 – 16:45:20
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added no oil added

Observations Small drum appears to have good recovery.

Oil seems to be picked up by mechanical action and adhesion; the former is necessary to achieve the latter.

Drum 2, small drum, was intermittently rotated forward (therefore operating in same direction as Drum 1 and direction of travel) for approximately 1 rotation in order to have the oil that was trapped between the two drums adhere to it, and then reversed again to be scraped off. This action (rotate small drum forward briefly) also assists ice processing during this moment.

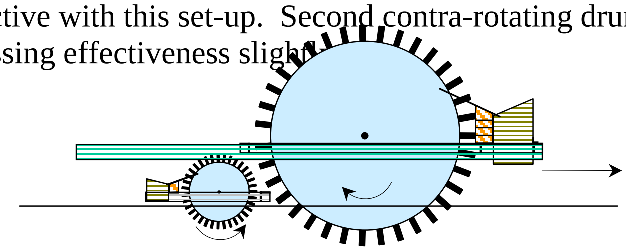
Some oil escapes from between the two drums at sides.

Test Results LDS-5

	Drum 1 Spiked Brush	Drum2 Small Brush		Total
Volume of total recovered product	44	54		
Water collected	17	5		
Oil recovered	27	49		76
Slush collected	n/m	n/m		
Oil recovery efficiency	61%	91%		
Slush recovery percentage				

Comments This unit configuration resulted in visible improvement in oil recovery performance. Quantities recovered also indicate this. Oil recovery rate is good even considering new oil had not been added for this test.

Ice processing was still effective with this set-up. Second contra-rotating drum may be reducing ice processing effectiveness slight



LDS-6 **Oct. 8, 1998**

Objectives This test was similar to the previous, with the addition of 130 litres of oil. Evaluate oil recovery and ice processing performance of this modified unit.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	5 stiff/5 medium	5	10 cm
Drum 2	plastic (small)	14 stiff-bristle strips	8 contra-rotating	2 –3 cm

Air temperature (°C)	+0.3	-0.3	-0.7	-0.1
Water temperature (°C)	+0.4	+0.2	-0.1	

Speed of advance 20 mm/s
Duration of test 9 minutes 45sec 10:29:57 – 10:40:42
+ 2 minutes 40 sec 10:43:22 stopped operation
- 30 sec (stopped operation)
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres of ISO 30 oil added

Observations Drum 2, small drum, was rotated in reverse and intermittently rotated forward (therefore operating in same direction as Drum 1 and direction of travel) for approximately ¾ rotation and then reversed again in order to have the oil that was trapped between the two drums adhere to it and be scraped off. Recovery of small drum is very good due to this reversing action.

Oil seems to be picked up by mechanical action and adhesion; the former is necessary to achieve the latter. Most oil adheres during the first ¼ of forward rotation (bristles penetrating unwetted oil/air interface from above).

Some oil was observed to escape from between the two drums out the sides and under Drum2.

Ice processing continued to be effective even with small Drum2 operating in reverse. When required, Drum 2 is operated in forward direction for several rotations to clear any ice that might be trapped between two drums. The latter operation was not required often.

Test Results LDS-6

	Drum 1 Spiked Brush	Drum2 Small Brush		Total
Volume of total recovered product	68	87		
Water collected	11	0		
Oil recovered	54	83		137
Slush collected	3	4		
Oil recovery efficiency	79%	95%		
Slush recovery percentage	4%	5%		

Comments This unit configuration resulted in visible improvement in oil recovery performance. Much less oil escaped in the back together with the ice. Quantities recovered also indicate this.

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This reciprocating action is what results in the greatest adhesion and thus recovery. The small drum should be rotated forward only for a very brief moment (1/4 turn) in order to avoid losing oil behind this drum. Due to frequency controller settings for this drum, this was not always possible and may have been the reason for some minor oil loss from behind this drum. The frequency controller for this drum was adjusted to improve this action in subsequent tests.

LDS-7 **Oct. 8, 1998**

Objectives This test was similar to the previous, to confirm the repeatability of results before changing oil type in LDS8.
Evaluate oil recovery and ice processing performance.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	5 stiff/5 medium	4 - 8	10 cm and raised during run
Drum 2	plastic (small)	14 stiff-bristle strips	8 contra-rotating	2 –3 cm

Air temperature (^oC) +1.1 +0.3 +1.2 -0.7
Water temperature (^oC) +0.5 0.0 -0.2
Speed of advance 20 mm/s
Duration of test 12 minutes 0sec 12:50:40 – 13:03:20
Several minutes unspecified, for continued operation
\+ 30 sec (stopped operation)
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres of ISO 30 oil added

Observations Drum 2, small drum, was rotated in reverse and intermittently rotated forward (therefore operating in same direction as Drum 1 and direction of travel) for approximately **1/4** revolution (reduced from previous test) and then reversed again in order to have the oil that was trapped between the two drums adhere to it and be scraped off.
Oil pickup by small drum is good. Oil seems to be picked up by mechanical action and adhesion; the former is necessary to achieve the latter.
Less oil escaped from behind the unit - probably due to the faster change in rotational direction of Drum 2 (due to adjustments in controller box) and thus shorter forward rotations (1/4 revolution) and less oil loss. However, oil losses continued on side away from stationary ice.
Initially, some ice was being pushed and not processed by D1 composite drum so it was raised. Afterwards, ice processing continued to be effective even with small Drum2 operating in reverse. When required, Drum 2 was operated in forward direction for several rotations to clear any ice that might be trapped between the two drums. The latter operation was not required often.

The air conveyor capacity was not enough for the higher recovery rate being experienced.

At end of test, when advance stops, the Drum 1 is also rotated in reverse intermittently and an increased recovery is observed during this moments.

Test Results LDS-7

	Drum 1 Spiked Brush	Drum2 Small Brush		Total
Volume of total recovered product	97	89		
Water collected	27	0		
Oil recovered	70	84		154
Slush collected	0	5		
Oil recovery efficiency	72%	94%		

Slush recovery percentage	0%	6%		

Comments As in previous test, this unit configuration resulted in visible improvement in oil recovery performance. Quantities recovered also indicate this.

The reciprocating action is what results in the greatest adhesion and thus recovery.

A slightly higher recovery rate resulted in this test, probably due to the improved reserving action of only ¼ rotation (visibly less oil loss) and also that D1 was also reversed at the end of test..

These recovery quantities are comparable to the previous test, hence tests are repeatable.

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LDS-8 **Oct. 8, 1998**

Objectives First test with new, lower viscosity oil blend. Most viscous oil had been removed from basin.
Same drum setup as previous test.
Evaluate oil recovery of this unit with a lower viscosity oil.

Test Setup/Conditions

	Material	Bristles	Rotational Speed	Draft
Drum 1	composite	5 stiff/5 medium	4 - 8	10 cm and raised during run
Drum 2	plastic (small)	14 stiff bristles	8 contra-rotating	2 –3 cm

Air temperature (^{o}C)	+1.1	+0.3	+1.2	-0.7
Water temperature (^{o}C)	+0.5	0.0	-0.2	

Speed of advance	20 mm/s	
Duration of test	11 minutes 44 sec	17:14:56 – 15:26:40
	Several minutes	unspecified, for continued operation
Length of test run	22 m	
Ice	mostly 0.5 – 1 m x 15 - 20 cm thick, some smaller pieces, little slush	
Oil added	130 litres of blend of ISO 30 oil and diesel (30%) added	

Observations Oil is visibly less viscous than previous, and remained fluid when cooled on the water and ice surfaces, unlike the previous oil blend.
Drum 2, small drum, was rotated in reverse and intermittently rotated forward, as in previous tests.
Oil pickup by both drums is good.
A greater amount of oil reached and adheres to the smooth portion of the large drum, (between the bristle strips) as compared to the previous oil. However, the bristles recover more oil than the smooth surface (a lighter oil would likely reach more of the smooth surface). Oil recovery on either brush-drums with this oil appears to be more a result of adhesion than in the case of "forced adhesion" observed in the previous tests with the more viscous oil.
Oil losses appear from side of unit away from stationary ice. Not much lost from back.
As in previous test, initially some ice was being pushed and not processed so composite drum was raised.

Oil flows much easier into troughs from scrapers.

Large drum pushes ice slightly.

Test Results LDS-8

	Drum 1 Spiked Brush	Drum2 Small Brush		Total
Volume of total recovered product	72	58		
Water collected	8	0		
Oil recovered	61	53		114
Slush collected	3	5		
Oil recovery efficiency	85%	91%		

Slush recovery percentage	4%	9%		

Comments The reciprocating action of this drum configuration appears to provide a good oil recovery even for this oil type.

The oil recovery is somewhat lower than that of the previous tests with viscous oil .

LDS-9 **Oct. 9, 1998**

Objectives Similar test to previous, but the Spiked drum was replaced by the Ringed brush drum. Small drum was left in same configuration as previous.
Evaluate oil recovery and ice processing for the Ringed Drum with this lower viscosity oil.

Test Setup/Conditions

6.	Material	Bristles	Rotational Speed	Draft
Drum 1	stainless	15 med.-bristle strips	4	10 cm
Drum 2	plastic (small)	14 stiff bristles	8 contra-rotating	2 –3 cm

Air temperature (^{o}C) +1.6 +1.6 +2.4 +2.0
Water temperature (^{o}C) +0.8 +0.1 -0.2

Speed of advance 20 mm/s
Duration of test 13minutes 2 sec 15:17:18 – 15:30:20
2 minutes 40 sec 15:33 (stopped operation)
Length of test run 21 m
Ice mostly 0.5 – 1 m x 20 cm thick, some smaller pieces, little slush
Oil added 130 litres of blend of ISO 30 oil and diesel (30%) added

Observations Drum 2, small drum, was rotated in reverse and intermittently rotated forward, as in previous tests.
Rpm of Drum 1, large drum, steadily increases (inadvertently) throughout test duration. This visibly increases water collection on large drum.

Good oil adhesion to bristles of ringed brush. Very little oil reaches the smooth drum surface between the closely-spaced brushes on this ringed brush drum.
Oil recovery on either brush-drums with this oil appears to be more a result of adhesion than in the case of "forced adhesion' observed in the previous tests with the more viscous oil.
Oil losses appear from side (along with ice pieces) of unit away from stationary ice but very little oil is lost from the rear of the unit.
Ice processing of large ice pieces not too impressive. A smaller draft may help. Medium ice pieces, however, are deflected by Drum 1 and remain between drums a while, tumbling around before they are deflected out back.

Test Results LDS-9

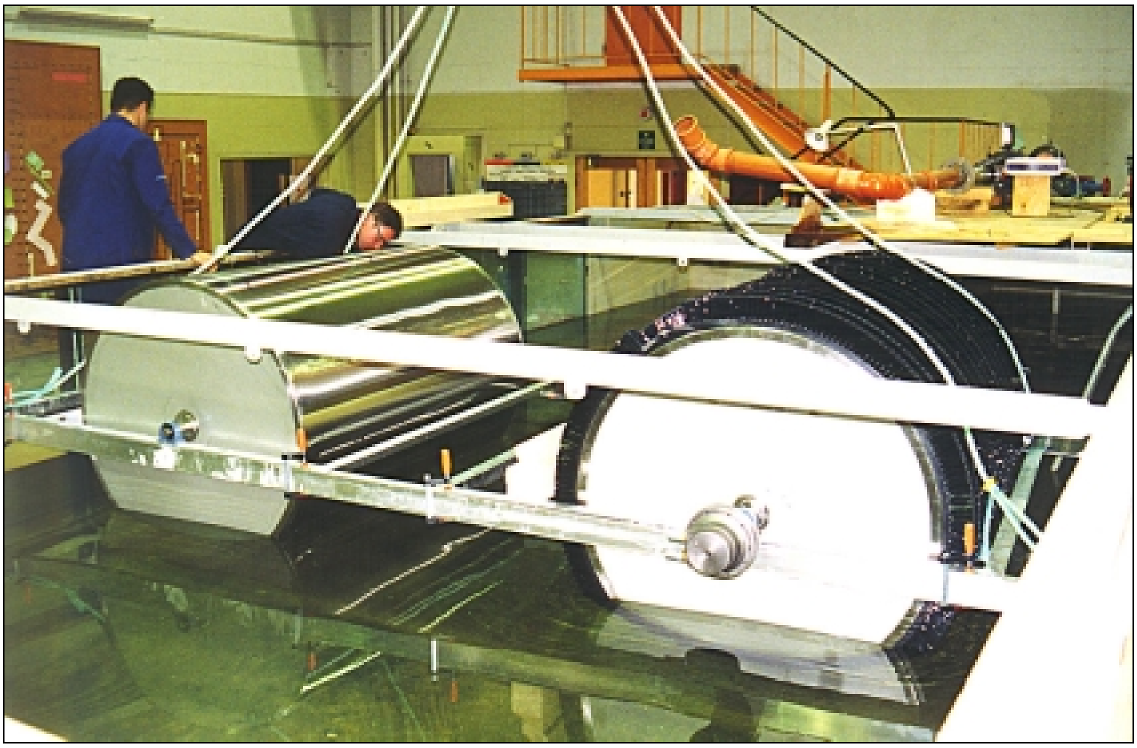
	Drum 1 Ringed Brush	Drum2 Small Brush		Total
Volume of total recovered product	100	89		
Water collected	50	0		
Oil recovered	41	85		126
Slush collected	9	4		
Oil recovery efficiency	41%	96%		
Slush recovery percentage	9%	4%		

Comments The reciprocating action of this drum configuration appears to provide a good oil recovery even for this oil type.

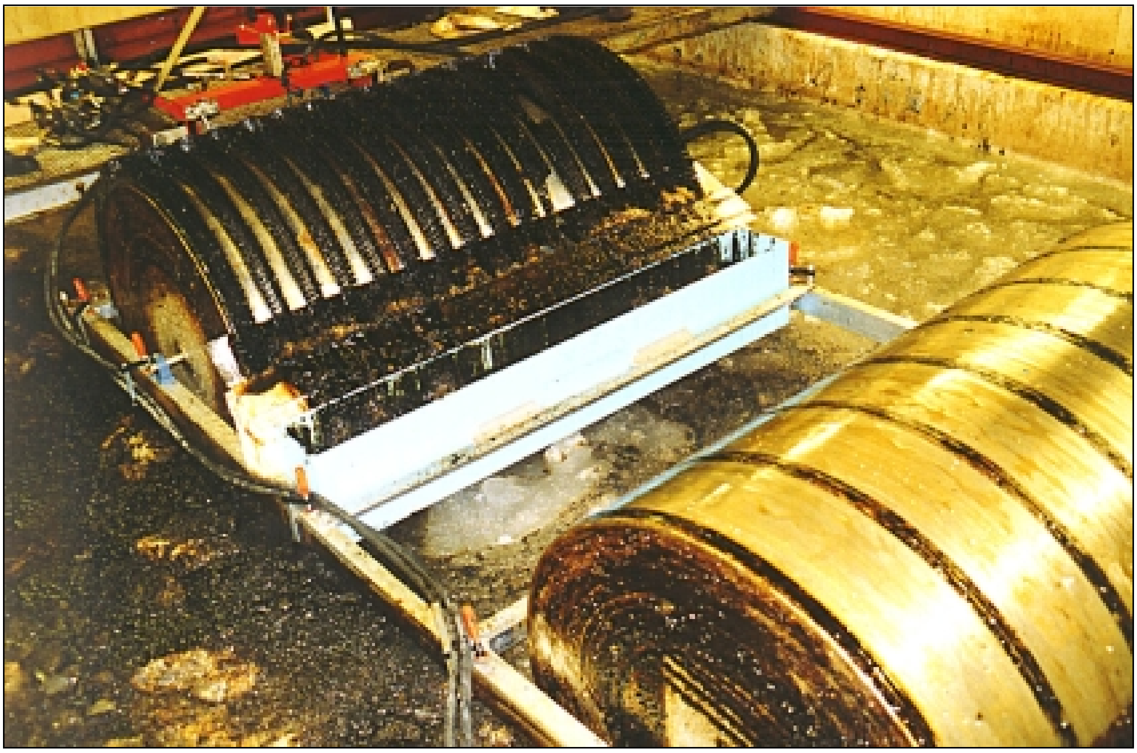
The oil recovery for ringed brush-drum was lower than that of the Spiked drum. This is likely a result of the unintentional increase in rpm of the ringed brush-drum, which reduced adhesion of oil to its surfaces. This also resulted in a higher water pickup (lower recovery efficiency).

However, note that the overall unit recovery is very similar to the previous test and we may suggest that any oil not recovered by the first drum is trapped and recovered by the second drum.

Appendix C – Photos

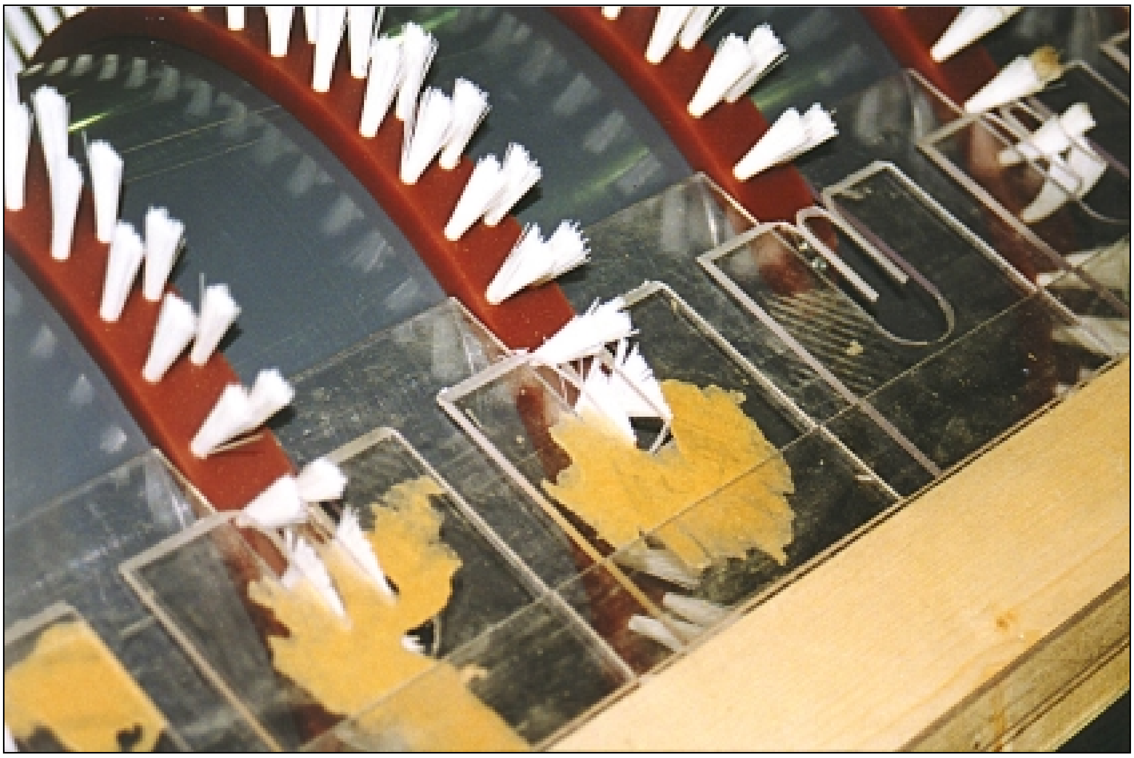


Buoyancy test of large stainless steel brush/drums, Configuration 1.

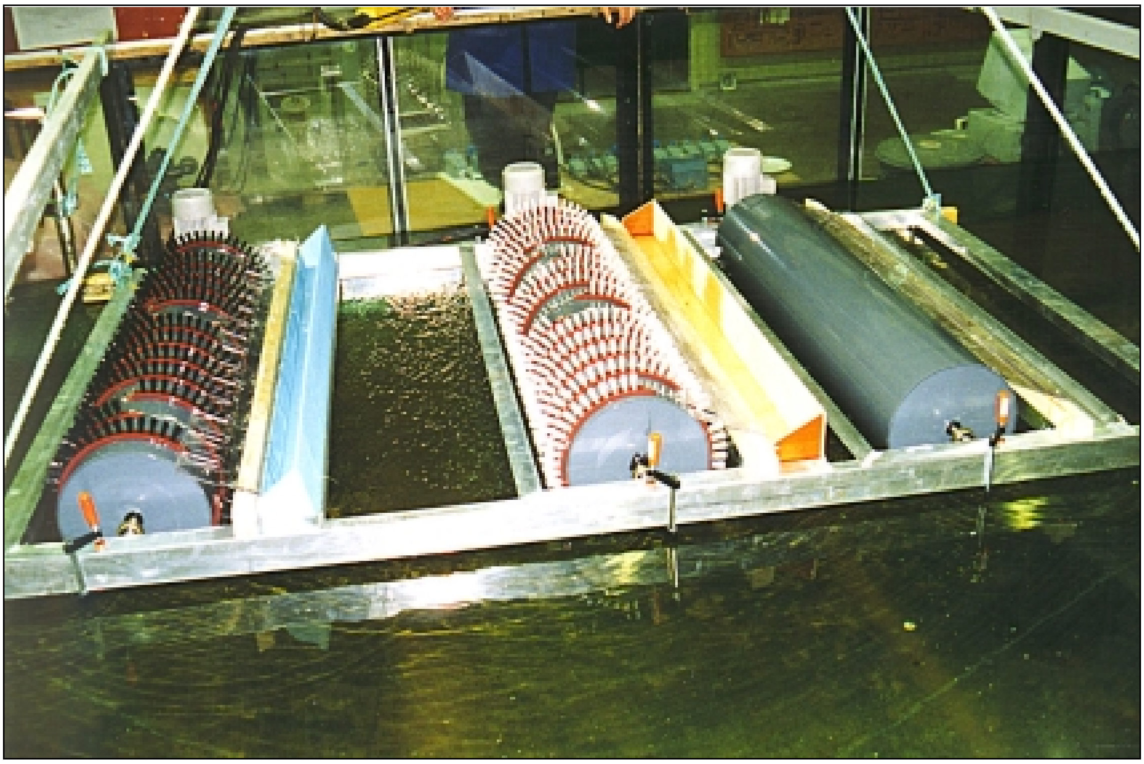


Stainless steel brush/drums in wet test with oil and ice.

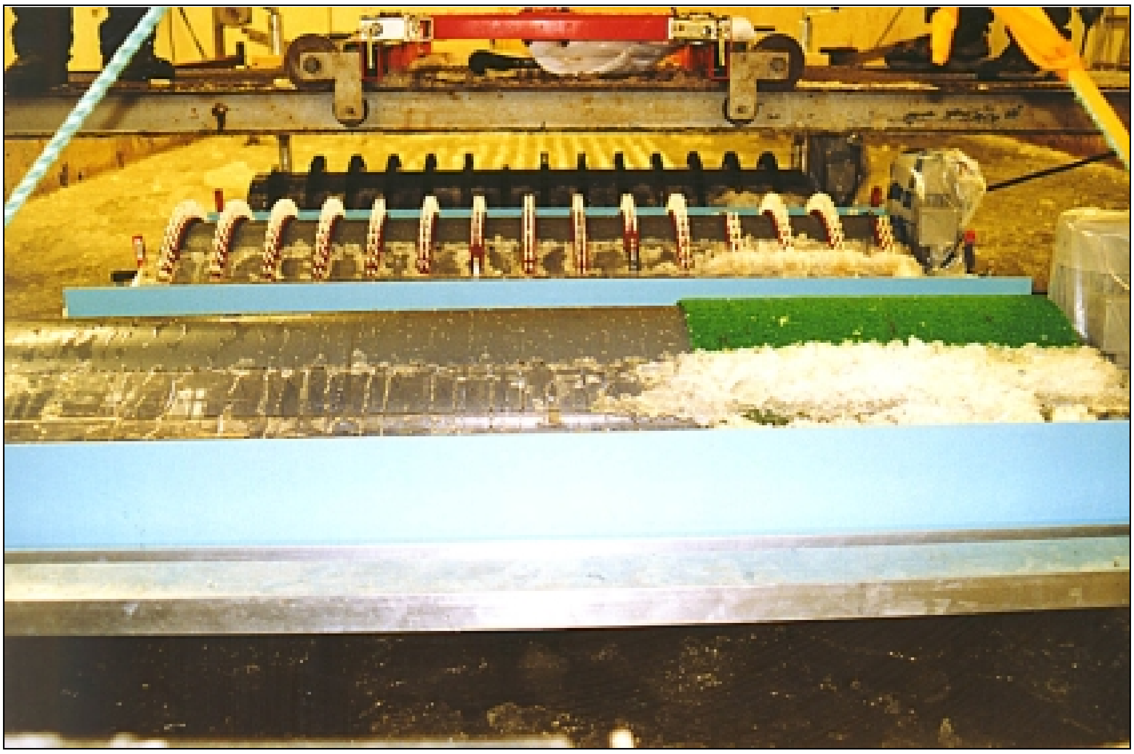
Fixing bristles to small brush/drum recovery unit for Lifting Grated Belt.



Bristles and scraper/comb arrangement for small drums.



Wet test with small drums mounted on one common frame.



Front view of small drums in cold lab with ice.

Tanks for prepared oil and waste oil are offloaded outside the HSVA Ice Tank.

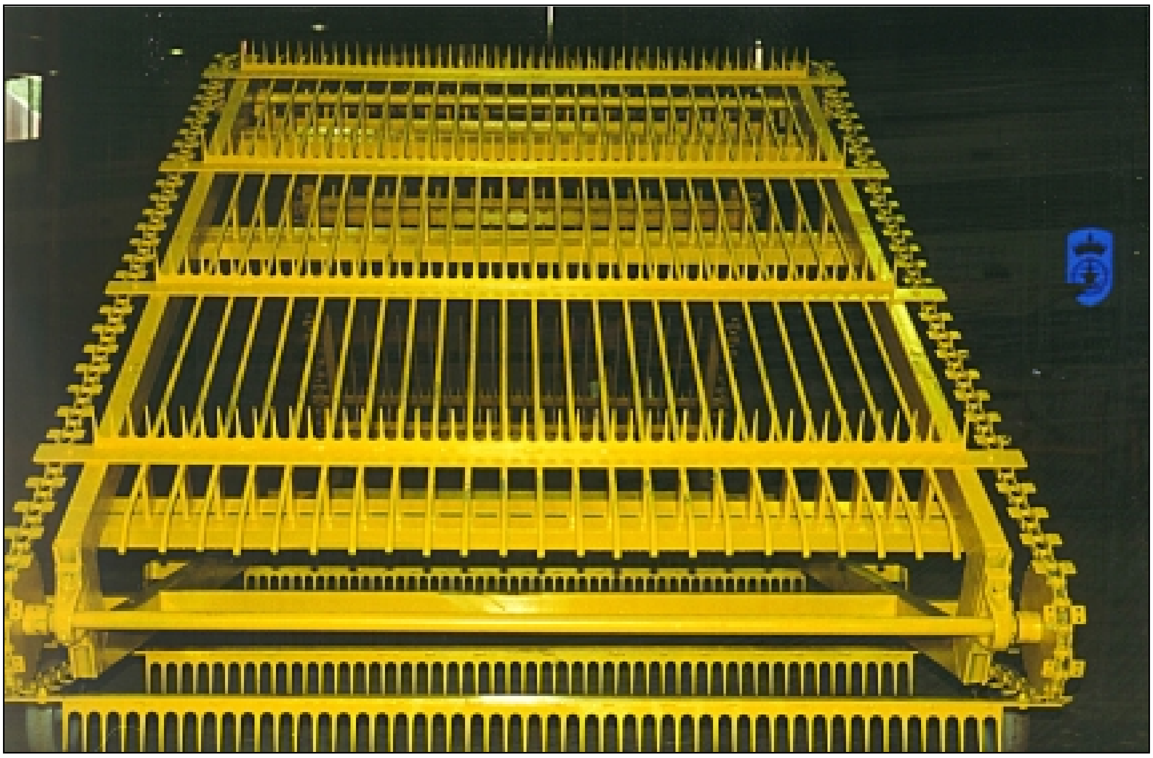
Cutting the ice in the HSVA test tank with a chain saw before starting the testing.

The Steering Committee visiting the test tank. Part of the LGB in the foreground.

Preparation of barrels for storage of recovered product.

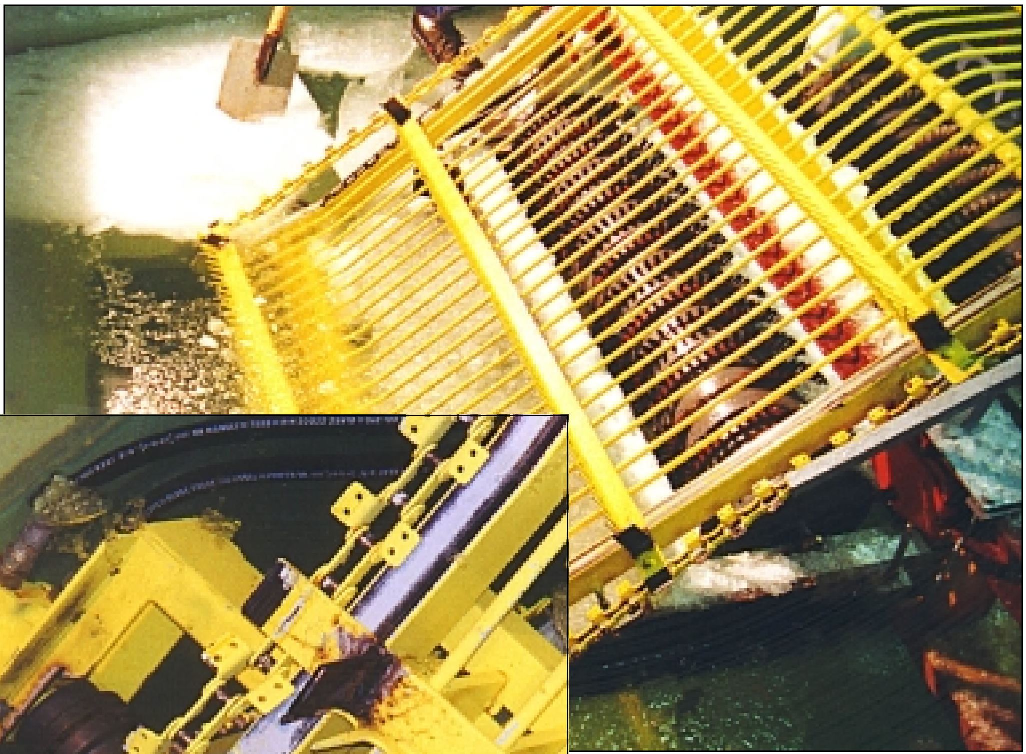
LGB installed in the test tank, supported by I-beams. Small brush drums underneath the belt, green barrels for recovered product to the left. In the background the main carriage with crane (green beam with winch) and flushing water tank (white).

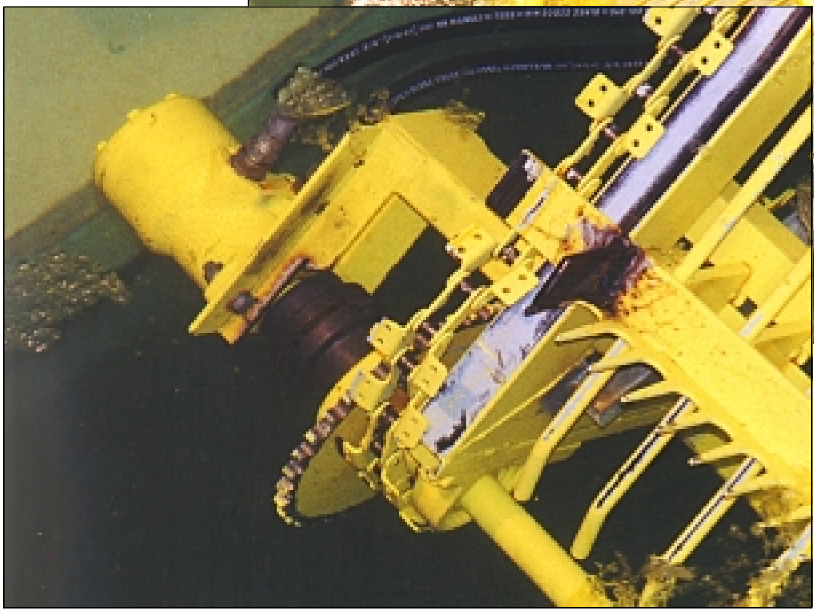
LGB seen from the other side. Secondary carriage with crane and air conveyor in the background.



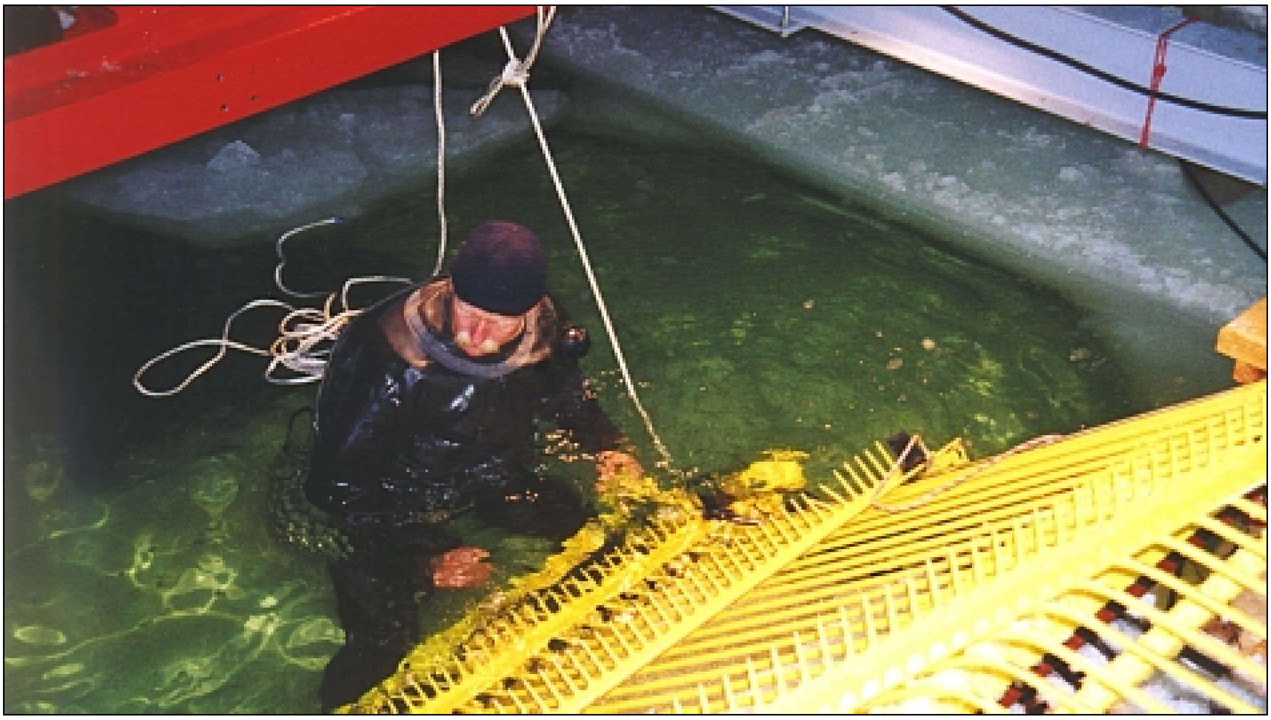
LGB before use. Attachment of rakes and grating rods can be seen.

Reinforced rake tine (left), rake tines before reinforcement (right).





An ice piece was jammed between the chain and the sprocket.



The dry suit made it fairly simple to correct the problem.

Initial method to distribute the oil in the tank.

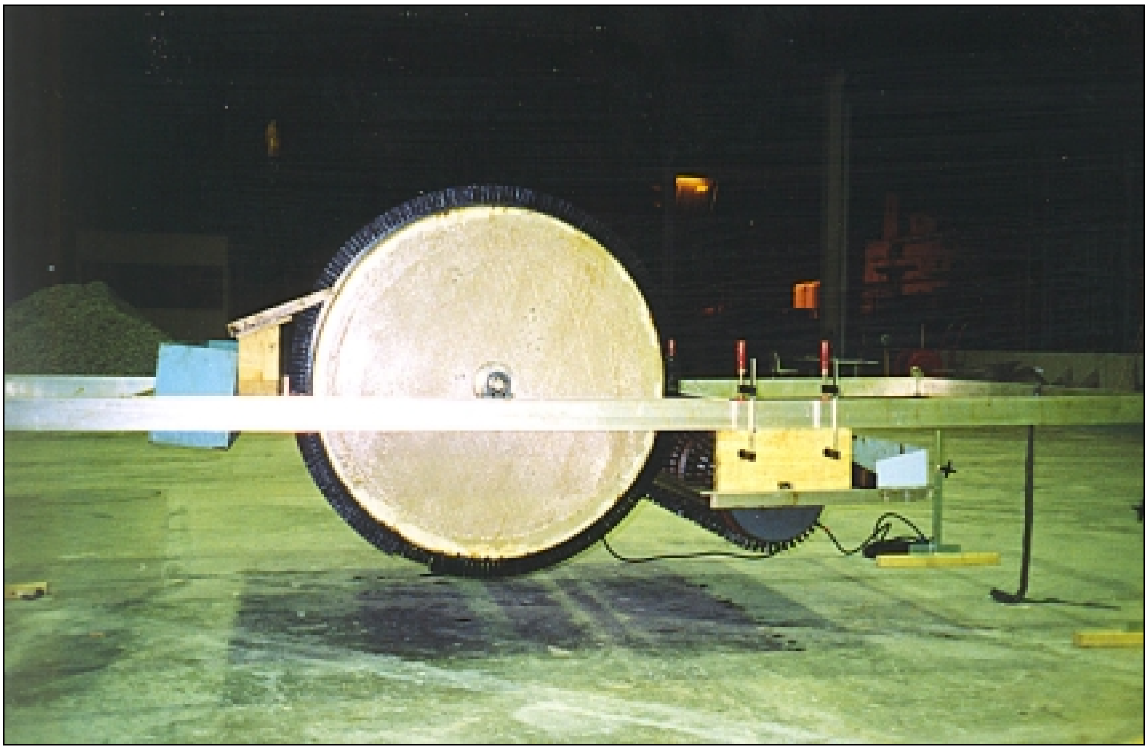
Close-up of spray boom for deployment of oil in test tank.

First test after initial deployment of oil.

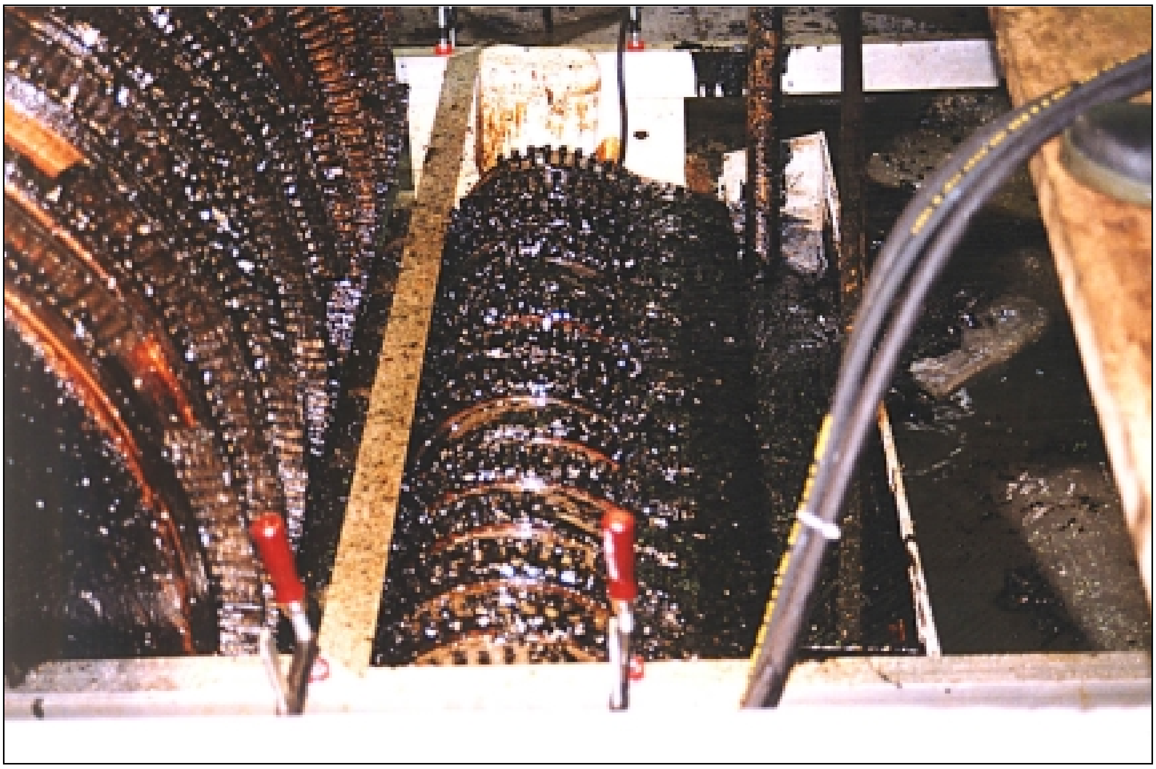
Applying warm water spray on the LGB.

Large brush drum system installed in the test tank, Configuration 1 with two large drums. Smooth drum to the left, brush drum with two different materials to the right, both drums of composite material.

Secondary carriage with air conveyor and two barrels for recovered product, one for each of the two large drums.



Large brush drum with scraper/combs and troughs, Configuration 2 with large and small drums in combination.



Large brush drum in front of small brush drum, gave the best results.

Appendix D – Figures

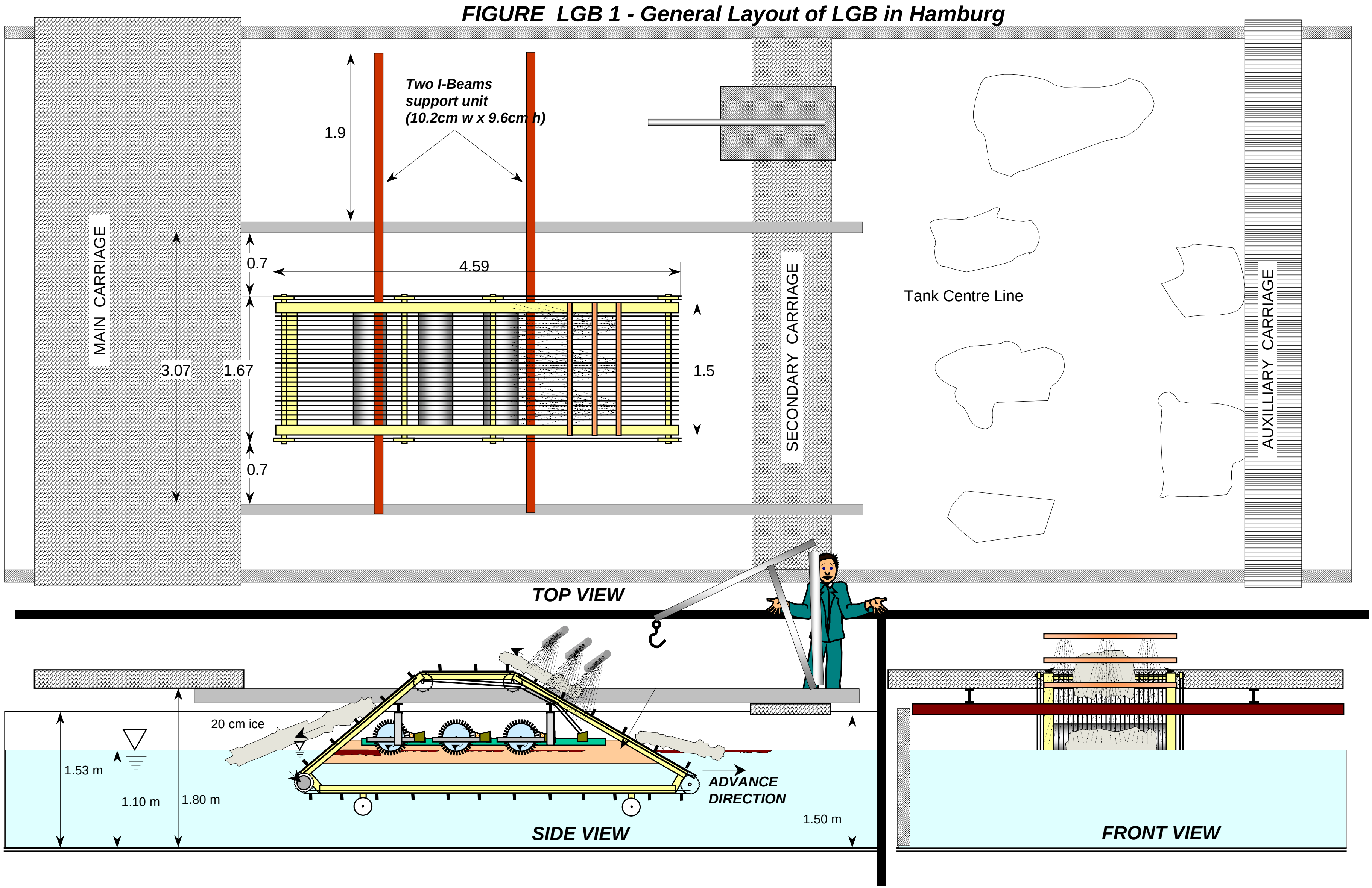


Figure D.1 Layout of the Lifting Grated Belt in the HSVA test tank.

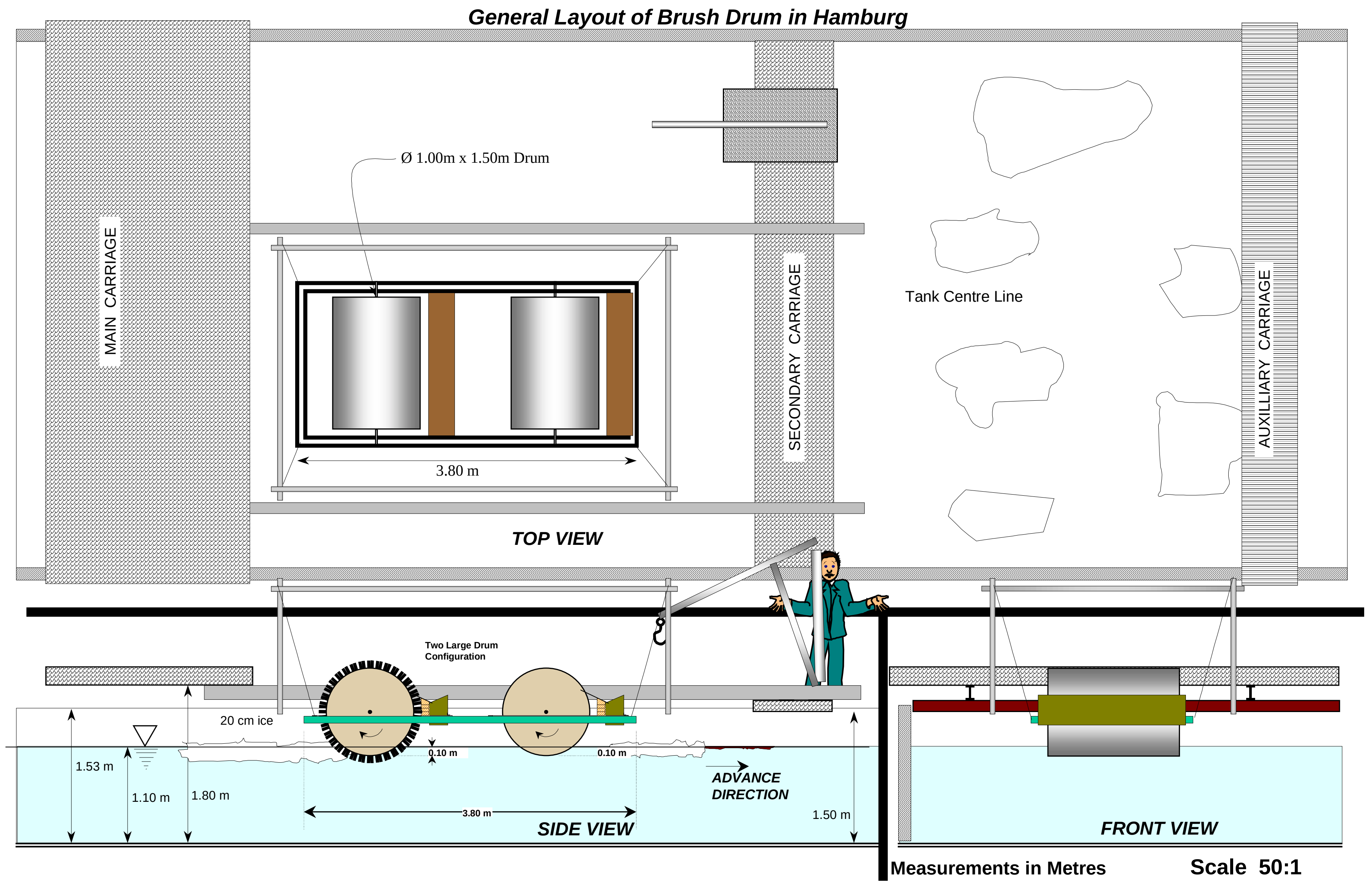
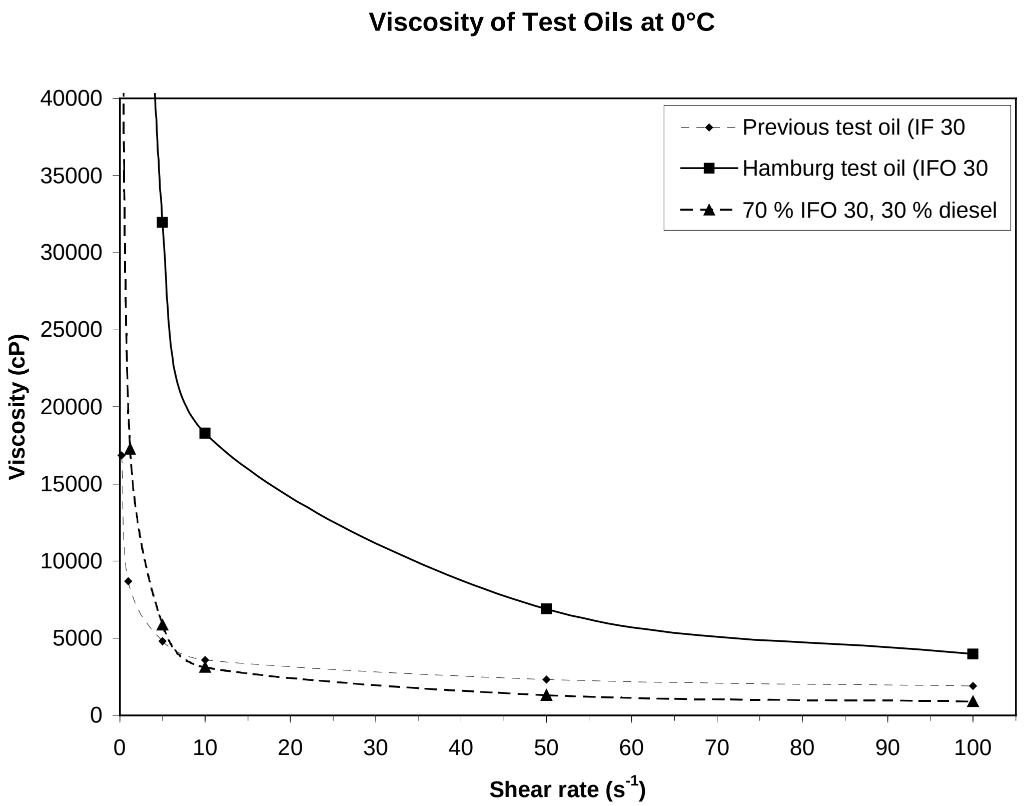


Figure D.2 Layout of the Brush Drum system in the HSVA test tank.

Appendix E – Oil Properties



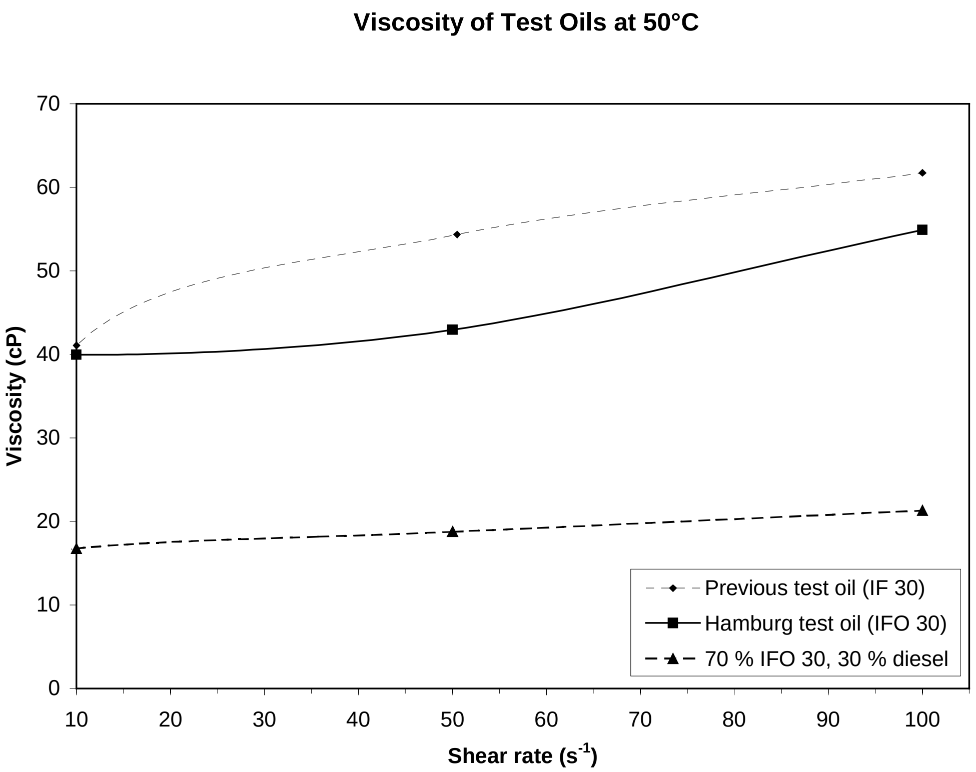


Figure E.1 Viscosity of test oils at test temperature (0^oC) and at 50^oC.