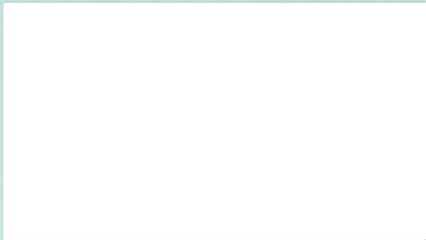


THE DEVELOPMENT OF A BOOM AND
SKIMMER FOR THE RECOVERY OF
OIL SPILT IN WATERWAYS

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**The Development of a Boom and Skimmer for the
Recovery of Oil Spilt in Waterways**

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Abstract

The two and a half billion dollars spent in cleaning up the *Exxon Valdez* spill in Prince William Sound is one of many indications of how seriously environmental damage is viewed today. Due to the massive problems encountered during spills, clean-ups remain time consuming and costly. Thus the aim of this study is to develop a more efficient method, which will be the design and development of an oil reclaimer to operate in moderate sea conditions. The feasibility of the concept will be evaluated against existing methods.

For an oil recovery method to be feasible, it must be efficient and cost effective. It is impossible to determine the efficiency of an oil recovery craft from the ratio of actual oil recovered from a spill over theoretical values measured during tests, which are conducted under controlled conditions, as the recovered amounts are dependant on factors unique to a particular spill. For example (as discussed in Annexure B), the time lapse between a spill and when recovery operations commence, the prevailing weather conditions, the availability of personnel and equipment and the accessibility to the spill site are factors which effect the outcome of oil recovery operations. Thus it is impossible to predict the amount of oil which will be recovered during a clean-up operation. However, test results are used to compare equipment in terms of, for example, oil recovery rate, which is dependant on the crafts oil recovery speed, the width of the skimming path of the craft, the percentage water recovered with oil, and the limitation imposed by the storage of the recovered oil.

Spill clean-up experts have concluded that small contained spills can be effectively removed but a more effective response to a major spill is to remove as much pollution as possible to minimise environmental damage. One of the most environmentally effective clean-up methods for both scenarios is to utilise a boom/skimmer combination craft with a wide sweep area and a higher operating velocity than that of existing methods, to clean over a larger surface area. Thus, the prototype boom/skimmer combination was developed with this aim.

This study covers the broad aspects of oil spills. In the following literature survey, section 1.1 deals with the strengths and weaknesses of existing spill oil removal techniques, and conclusions are made regarding the requirements for an effective oil recovery craft. These requirements are determined from a study on the varying circumstances and problems associated with five major oil spills described in Annexure B. Hydraulic modelling and open channel flow are covered in Section 1.2 and 1.3 respectively.

Chapter 2 covers the development of the boom and skimmer through model tests and prototypes. The booms and skimmer are developed separately in Sections 2.2 - 2.4 and 2.5 - 2.6 respectively. The boom configuration was developed from 1/22 scale model tests and the skimmer from large-scale model tests. Owing to strict pollution regulations recently enforced for Durban harbour, it was not possible to test the skimmer in a swell using oil, and thus sawdust was used to simulate it. Thereafter, a test using oil was conducted in a dam at the Strategic Fuel Fund (SFF) tank farm at Saldanha Bay under calm conditions to confirm the crafts capability to recover oil.

Discussed in Chapter 3 are the conclusions made on the concept developed. Basically, an efficient and cost effective craft can be manufactured to meet the requirements of Section 2.1. Ideas for further research are detailed in Chapter 4.

The tank used for model testing is described in Annexure A. In Annexure B, case studies of past spills are dealt with, along with difficulties experienced during clean-up of these spills. The section covers marine law on compensation, as well as prevention and causes of spills. Annexure C covers the environmental effects of oil at sea and on land. Annexure D contains the detailed drawings of the models and prototypes used during the study.

Preface

The work contained in this thesis is my own, unless indicated to the contrary, in the text, and has not been submitted (in part, or whole) to any other University or Technikon.

The research work was carried out at the Department of Mechanical Engineering, Technikon Natal, and was supervised by Professor M. Walker and Mr S. Wallace.

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Problem Statement

The purpose of this investigation is to experimentally design, develop and evaluate an oil reclaimer prototype which must recover oil spillages more effectively than existing equipment under moderate sea conditions.

Subproblems

1. The first subproblem is to design and develop a working oil reclaimer model to operate in simulated moderate weather conditions for the purpose of identifying the optimal configuration for reclaiming spilt crude oil in environmentally sensitive waterways.
2. The second subproblem is to assess oil recovery capabilities of the model in terms of a simulated sea condition, thickness of oil film, and speed of model in order to determine the range of effective operation.
3. The third subproblem is to evaluate the oil recovery capabilities of the developed oil reclaimer model against existing methods of recovery by using the theory of similarity in model testing in order to determine effectiveness.
4. The fourth subproblem is to design and construct a prototype based on the developed model design to operate as an oil reclaimer in Durban Harbour for comprehensive testing purposes.

5. The fifth subproblem is to determine the performance capabilities of the oil reclaimer prototype in the recovery of oil spills from natural waterways.
6. The sixth subproblem is to evaluate the feasibility of the prototype against existing methods in order to determine the efficiency and cost effectiveness of using it for crude oil spillage removal.

Initial Delimitations

1. The testing of the oil reclaimer will be limited to a prototype tested in Durban Harbour.
2. The crude oil used for tests on Durban Harbour will be limited to the grade available at the time of the tests in the Durban area.
3. The testing will be limited to crude oils which are pumpable by a centrifugal pump and will not include high viscosity oil with high wax concentration, oils with a specific gravity approaching that of water, or to include oils that have reached this condition due to weathering on the sea surface.
4. The size of the crude oil slick created on Durban Harbour for testing purposes will depend on what is acceptable to the Durban Port Authority.
5. The tests will not be conducted to cater for conditions of low temperature where

the viscosity of crude oil increases to the point where the prototype is no longer effective.

Initial Assumptions

1. Due to the differences in specific gravity, mineral oil separates from water and floats on the surface. It deteriorates from exposure to the elements and its density and viscosity increase. The oil will sink when its specific gravity becomes greater than that of the water it is floating on. It is assumed that the characteristics of all crude oils change in a similar manner and rate from exposure on the sea surface.
2. Support craft, pumps and other such machinery required for the tests will be available when required. Owners or authorised personnel in charge of such equipment have been approached and have agreed to loan this equipment for the duration of the tests. It is assumed that such equipment will be available for the tests.
3. It is assumed that the theory of similarity in testing of models holds for the design and evaluation of this method operating under moderate sea conditions, based on prototype tests carried out in Durban Harbour.
4. Authorised personnel of companies with access to crude oil have been approached and have agreed to supply crude oil for the tests, and therefore it is assumed that such oil will be available.

Chapter 1 : Literature Survey

1.0 Introduction

When evaluating cost effectiveness of oil recovery equipment, the following aspects must be considered:

1. the impact of oil pollution on the environment compared with the cost of prevention, and
2. the probability of a spill occurring compared with the cost of holding an oil spill response plan on standby.

The most difficult problem encountered when containing a spill and thus preventing it from reaching a shoreline to cause environmental damage, is the rapid spread of oil which can cover a large surface over a short period. This aspect was highlighted in the oil spill contingency plans for Prince William Sound before the 1989 *Exxon Valdez* oil spill where it was stated that for a spill of that magnitude, it was inevitable that oil would impact the shoreline. Dr. N. Michel, a science advisor to the National Oceanic and Atmospheric Administration of the USA, who participated in the *Amoco Cadiz* and *Exxon Valdez* clean-up efforts, stated that in the case of an exposed rocky beach with much wave action, little oil is left after one year and on quieter beaches, it persists for 2-3 years. In her opinion, bird and fish life replace themselves during this period [1, 2].

However, when a spill impacts a shoreline, it is generally required to be removed by local law and public demand and previous clean-up costs have been very expensive. Therefore, in the event of a large oil spillage, the aim is to reduce environmental damage and clean-

up costs by removing the maximum amount of oil from a waterway before it reaches the shore. However, when planning spill prevention techniques, it becomes impossible to develop a single strategy as the circumstances under which they occur vary considerably.

Furthermore, authorities charged with oil pollution control are reluctant to outlay large sums of money on oil pollution equipment which will only be required in the event of an oil spillage and therefore may never be used. Such equipment needs to be stored and maintained in good working condition, and personnel are required to be trained and kept on stand-by. Authorities utilise dual purpose oil recovery craft to reduce the cost of their oil spill response methods. Thus a requirement for the craft developed during this study is that it can be manufactured at low cost [3, 4].

Thus authorities which provide oil spill clean-up services will always require more effective clean-up equipment to reduce environmental damage and the aim of this study is to provide for that need.

1.1 Oil spill containment and recovery equipment

Oil spill containment equipment can be divided into four main categories:

1. oil recovery craft,
2. oil skimmers,
3. booms, which contain an oil spill and prevent it from spreading or to isolate a coastline from oil pollution on the sea, and
4. a combined boom/skimmer.

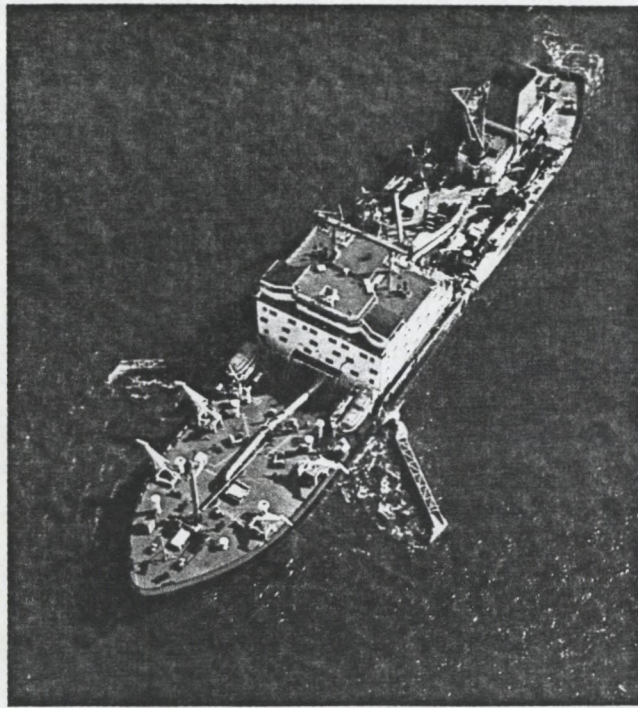


Figure 1.2. Dredger *Nordsee* with extended sweep arms

The rigid arms, which are manufactured by Dutch Oil Spill Equipment, are constructed from steel and incorporate a collection chamber containing a skimmer driven by a hydraulic pump. The arms direct the oil into the collection chamber from where the oil/water emulsion is pumped to the vessel's storage tanks. The sweep arms are suspended from removable davits and are lowered into the sea when the oil recovery operation commences. They float independently of the vessel and have a recovery rate typically of 500 m³/hr [3 - 5].

A similar system, the *Soopress*, has a flexible arm which directs the slick into the dredger hopper through an aperture cut through the hull. The arm consists of a chain of independent inflatable units manufactured in Norway. The flexible arm can operate in seas with up to a 3m swell (trough to crest) which is an advantage over

1.1.1 Oil recovery craft.

Manufacturers of oil control equipment have developed dual purpose vessels, such as dredgers and harbour work boats, which may be converted at short notice to recover oil. Many nations have made use of this option [4].

Germany is the only nation to have invested in a diverse range of oil recovery craft and equipment which can recover oil under different conditions [4].

Sweep arms

Rigid or flexible booms are fitted to any suitable vessel with a large oil storage capacity to enable it to be used to collect oil. Dredgers are the best choice as they can work close in-shore; consequently they are close to a berth where they can be converted to oil recovery mode without delay. They have large storage capacities where oil can settle and separate from water (refer to Figures 1.1 and 1.2).

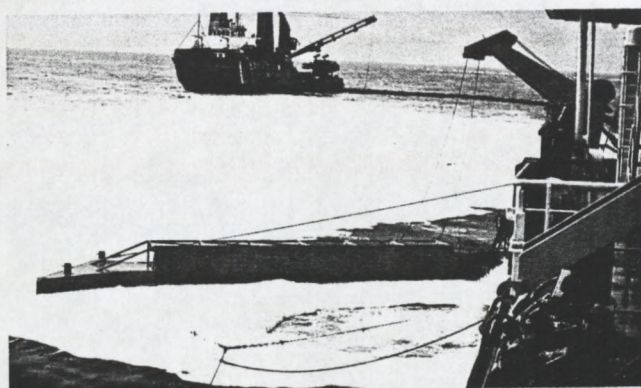


Figure 1.1. Sweep arms in operation

the rigid boom type which can operate in a sea of only 1,5m. Although the flexible arms operate better in rough seas, their collection efficiency suffers under strong currents and high winds. The rigid arm structure can withstand winds up to force 9, but their collection efficiency suffers from turbulence under such conditions. The U.S. Coast Guard have fitted rigid arms to some of their dredgers and tugs [2, 3, 4].

Six dredgers have been adapted for oil skimming in the Netherlands. Germany has converted one dredger, the *Nordsee*, and has fitted sweep arms to two specially built tug/buoy laying vessels; the *Mellum* and the *Scharhorn*. Both have oil storage facilities [4, 5].

The U.S. Coast Guard have fitted sweep arms to dynamic skimming vessels which are stationed in Prince William Sound. These vessels have storage capacities of 22 000m³. During the *Exxon Valdez* clean-up, a tanker fitted with sweep arms was used to recover crude spilt in the open waters of the Sound. However a high percentage of water was recovered with the crude [2, 5].

During a four hour test where chocolate mousse (a viscous emulsion of deteriorated crude oil and sea water; see Annexure C) was deliberately spilt, the converted trailing suction dredger *Cosmos*, with a sweep width of 55m, collected 93m³ or nearly 70% of the initial amount spilt. A year later, the tanker *Katina* spilt 1630m³ of heavy fuel oil after a collision with another vessel. The *Cosmos* dropped its load of dredged material and arrived at the scene 8 hours after the spill. With the assistance of two smaller tankers, 50 % of the spill was recovered [3].

Two tugs with oil spill clean-up capability, the *Crammond* and *Dalmeny*, have recently been built for British Petroleum (BP) to provide towage and escort services at Howard Point oil terminal in the United Kingdom. In pollution control mode, the tugs have side sweep oil recovery systems made up of a towed boom and a rotating rope mop skimmer. A large hold is fitted at the stern of the vessel to house the equipment which is handled by a 30 ton crane [6].

Ro-Clean's OMI pollution control vessels (*Polcat*)

OMI (Oil Mop International) pollution control catamarans (*Polcat*), built by Ro-Clean Ltd of the United Kingdom, are multi-purpose vessels capable of general purpose activities and can be converted into oil spill recovery vessels when required. They are catamarans which are 22m in length. Oil absorbent rope runs longitudinally between the two hulls at the same speed as the vessel. This results in the relative velocity between the rope and the water through which the vessel is passing, equalling zero. Therefore, the rope dips in and out of the water and consequently this concept is known as the ZRV (Zero Relative Velocity) principle. The oil absorbed in the rope is squeezed out

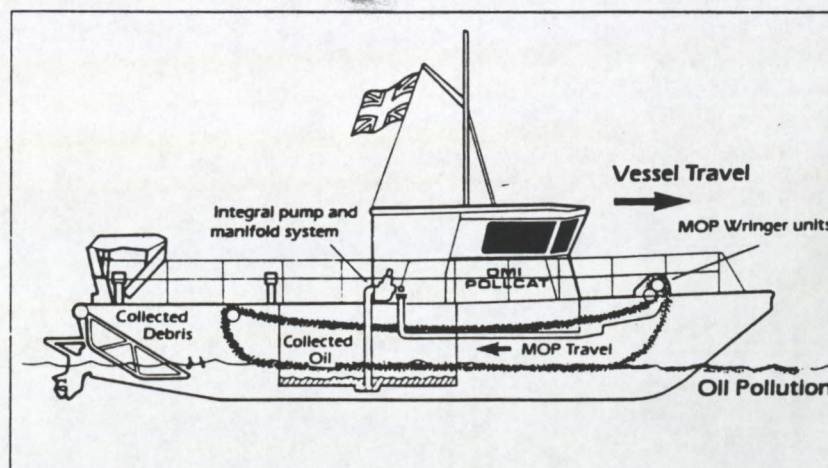


Figure 1.3. Cross section of a *Polcat*

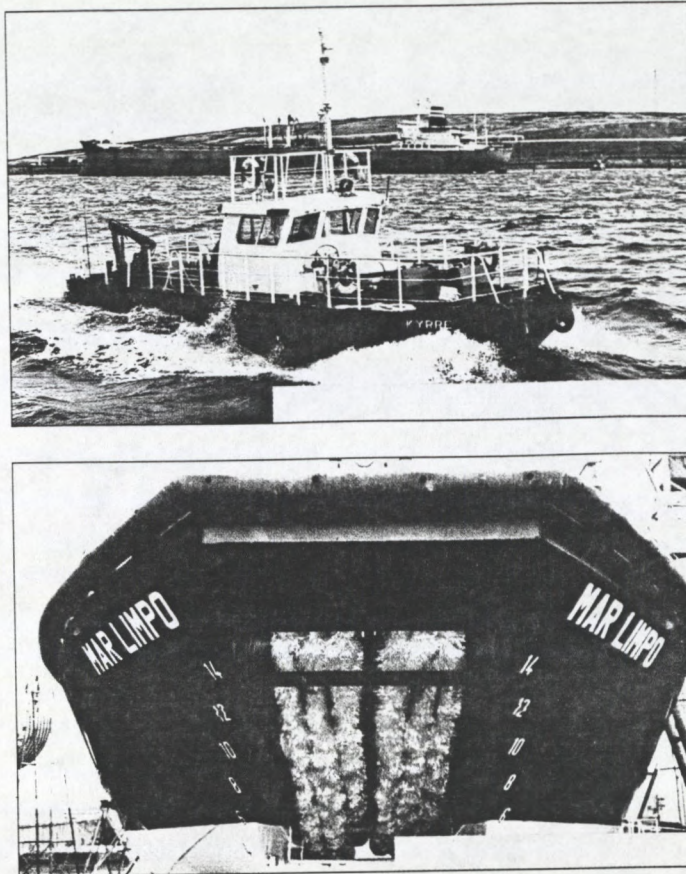


Figure 1.4. Ro-Clean's *Polcat* in operation (top); view of oil mop (bottom)

when the rope passes through two rollers after leaving the water. The recovered oil is pumped to oil storage tanks aboard the vessel. Oleophilic mops are used as they attract the greatest variety of oils. (See Figures 1.3 and 1.4). These vessels, when in oil recovery mode, are effective at speeds of up to 5 knots. The maximum oil recovery rate is 150 tons/hr and they can recover in a swell of up to 2m. They are capable of operating on a thick layer of oil with an optimum oil recovery rate. The largest craft has a skimming width (the distance between the two hulls) of 5m, and the vessel provides storage for 100m³ of recovered oil [7].

Lurring twin hulled vessels

The hull of this multi-purpose vessel splits down the centre to form a "V" as shown in Figure 1.5. The apex or pivot point of the "V" is situated at the stern of the vessel. When the vessel passes through a slick, oil collects in the apex of the "V" and is pumped to storage tanks in the vessel. Germany has two such vessels; the larger having a skimming width of 45m and storage capacity for 790m³ of recovered oil. These vessels also dual function as bunkering vessels [4, 5].

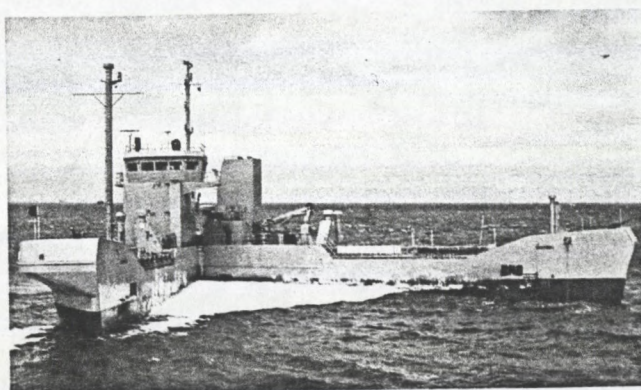


Figure 1.5. Twin-hulled vessel *Bottsand*

***MPOSS* catamarans (multi-purpose oil skimming systems)**

The *MPOSS*, shown in Figure 1.6, is a self propelled catamaran-type vessel which separates and recovers the oil layer from the water surface and thereafter pumps it into storage tanks. It is 33m long, 12m wide and has a storage capacity of 300m³ [4, 5].

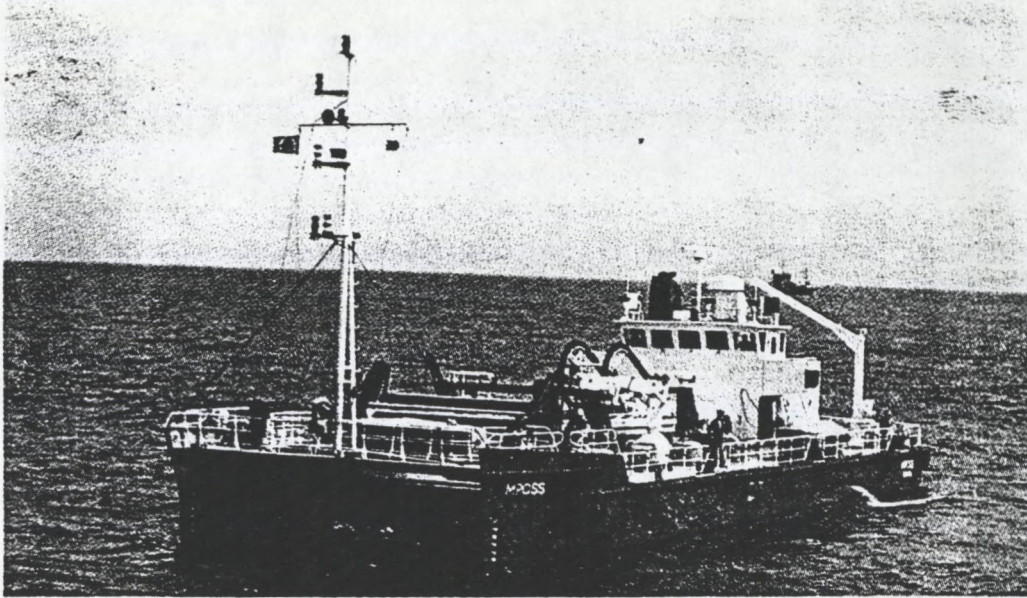


Figure 1.6. *MPOSS* catamaran

1.1.2 Skimmers

There are four basic types of skimmers:

1. rotary disc skimmers,
2. weir skimmers,
3. oil absorbent or oleophilic rope skimmers, and
4. vacuum pumps with skimmer heads.

Rotary disc skimmers

As shown in Figure 1.7, a rotary skimmer floats within a slick. Oil adheres to partly immersed rotating oleophilic (attracts oil) discs and is wiped off by scrapers over a collection point situated within the skimmer. The recovered oil is pumped from the collection point to storage. Oil recovery performance drops off with an increase in sea swell [8].

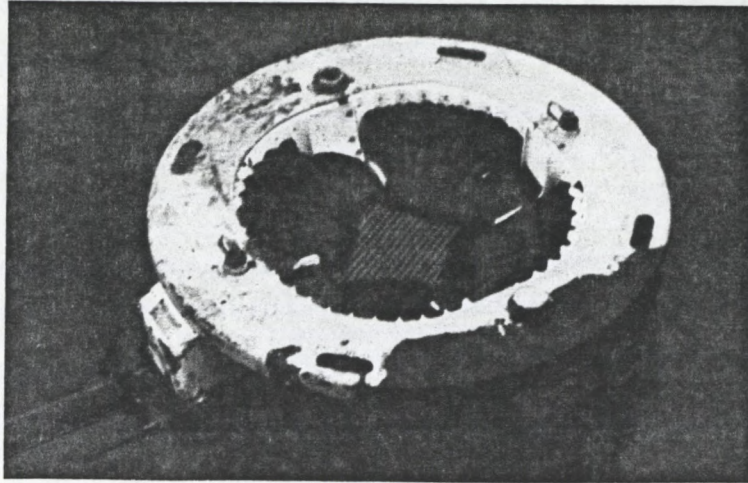


Figure 1.7. A rotary disc skimmer in operation

There are numerous skimmers on the market. Listed here are the specifications of some of the products as supplied by manufacturers.

(A) **Vikoma Seaskimmer range.** The largest in this range is the *Seaskimmer 100K* shown in Figure 1.8

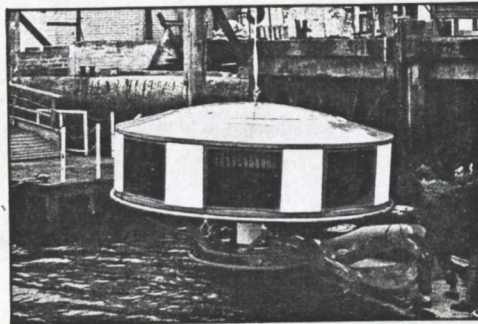


Figure 1.8. Vikoma *Seaskimmer 100K*

The skimmer has been designed for:

- (i) operation in shallow water of minimum depth 1,2m,
- (ii) stability in rough off-shore weather conditions, and
- (iii) a recovery rate of a maximum of 100 tons/hr with water content of 2%.

The skimmer has a mass of 1,2 tons and incorporates eight banks of twelve oleophilic rotating discs. Oil adheres to the discs and is scraped off over a central reservoir in the skimmer. The oil is pumped from the reservoir to storage. The screw pump is hydraulically powered by a hydraulic system driven by air cooled marine engines [9].

(B) Vikoma Oilwolf (Sweep). This skimmer has the following characteristics:

- (i) recovers oils of high viscosity, and
- (ii) can free float in a slick or be used in a boom configuration.

This skimmer has an arrangement of horizontal toothed discs. The teeth have a specially cut profile which pulls and pushes viscous lumps and mats of oil into the skimmer body between the two rotating disc banks. A screw pump dispatches the oil to storage. Most of the water, initially recovered with the oil, is removed during this process. The pump is powered by a diesel-hydraulic powerpack, standing on a quay or support vessel alongside the skimmer [10].

(C) Vikoma Sea Devil.

This skimmer, shown in Figure 1.9, has the following characteristics:

- (i) it can be easily transported,
- (ii) it can operate in floating debris,
- (iii) it can pump viscous oils, including heavy fuel oil, viscous weathered and emulsified crude oil,
- (iv) it can recover up to 100 tons/hr with a 2% water content depending

on the viscosity of the oil, and

- (v) it is compact and easily transported.

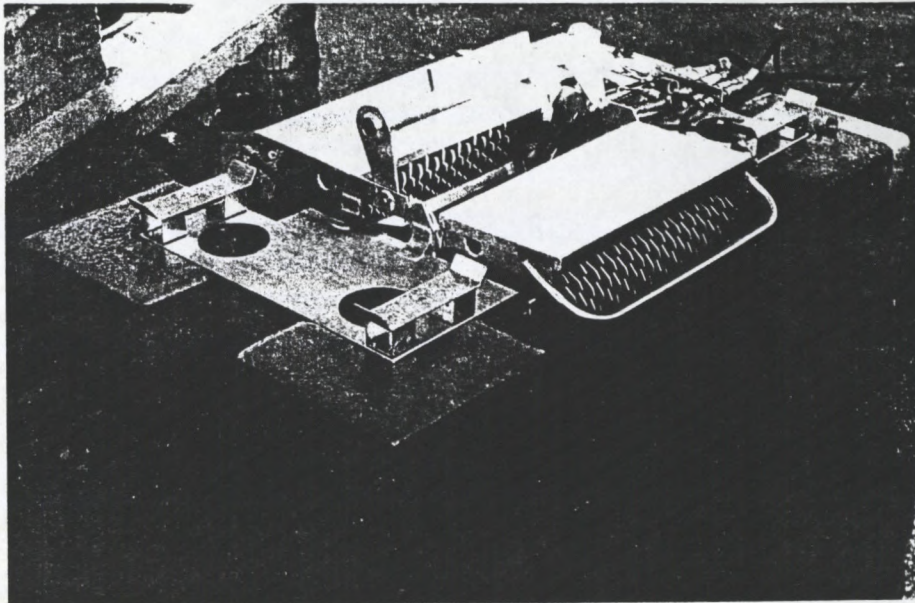


Figure 1.9. Vikoma *Sea Devil*

The *Sea Devil* is driven by a hydraulic pump powered by an external power supply. The skimmer comprises two banks of patent star discs which are hinge mounted to allow manoeuvrability to enhance performance and prevent damage. The Archimedean screw oil recovery pump used is reversible to clear any debris caught in the discs. Vikoma claims that the *Sea Devil* is the most effective skimmer on the market for recovering heavy oil [11, 12].

The skimmer was tested on two occasions in a circular tank containing a layer of heavy fuel oil approximately 50mm thick in January and April 1992. The temperature of the tank was -6 and 12 degrees Centigrade respectively. The average discharge rate was 67 m³/hr with a water content of 1% [12].

(D) **Clean Ocean Vessels (COV).** This twin hulled craft incorporates a rotary disc skimmer. They:

- (i) are stable in seas up to Force 6 and are able to maintain a constant freeboard (height of weather deck above the water line) throughout the recovery operation,
- (ii) have a high oil recovery rate (not specified),
- (iii) are capable of separating the water from the recovered oil during operation,
- (iv) are capable of rapid deployment in the event of an oil spill,
- (v) are very manoeuvrable and capable of a speed of 7 knots, and
- (vi) have oil storage tanks.

The *COV* is a twin hulled catamaran with a maximum length of 30m and width of 12m. Each hull incorporates two oil storage tanks. The bow angle is set at 60 degrees to the direction of movement in order to deflect the oil between the hulls.

Two heavy revolving drums, which are mounted between the hulls, can rotate at a maximum speed of 100 rpm. Each drum is fitted with scavenger blades which increase the length of the drum. When the drum is rotated, the oil/water waste is picked up on the drum surface and passes down to the scavenger blade where it is scraped off. Any solid objects are crushed by the drums. The recovered oil flows into a trough from which all the solid debris is screened by a sieve. The recovered oil is pumped to the storage tanks.

The vessel can be pushed, towed by a tug or self-propelled. Each end is constructed with the same profile, and thus can be manoeuvred in both directions during recovery operations, eliminating the time consuming U-turn at the end of each sweep.

The skimmer can recover a wide range of oil of different viscosities, and can also recover chocolate mousse [13].

- (E) **Elastec Inc.** This skimmer, shown in Figure 1.10, consists of an aluminum frame that holds two rotating floating drums. They are made from proprietary plastic material that attracts oil but repels water when rotated through a slick. The recovered oil is scraped off by wiper blades and is pumped to a storage tank. There are two light-weight models named the *TDS 118* and *TDS 136*. No oil recovery rates are given [14].

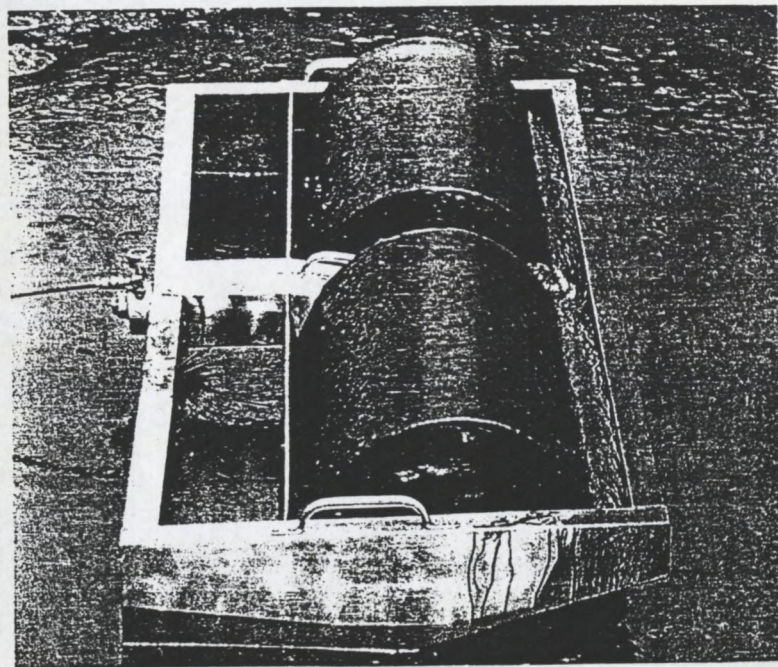


Figure 1.10. Elastec skimmer

Weir skimmers

A weir skimmer floats independently in the slick and the oil passes over a weir opening into the skimmer from where it is pumped to storage. The lip of the weir must be positioned at the level of the oil/water interface below the water surface to allow oil with minimum water content to enter the skimmer. The depth of weir height can be adjusted for different oils and slicks of varying thickness. The performance of weirs drops off rapidly with a worsening sea state. The width of the weir opening is limited to 2m to enable it to align with the oil/water interface in a swell. However, weir skimmers recover large amounts of water with the oil, which can be in excess of 80% [8, 12].

Listed here are some of the weir skimmers on the market:

(A) **Vikoma Cascade LP 3000.**

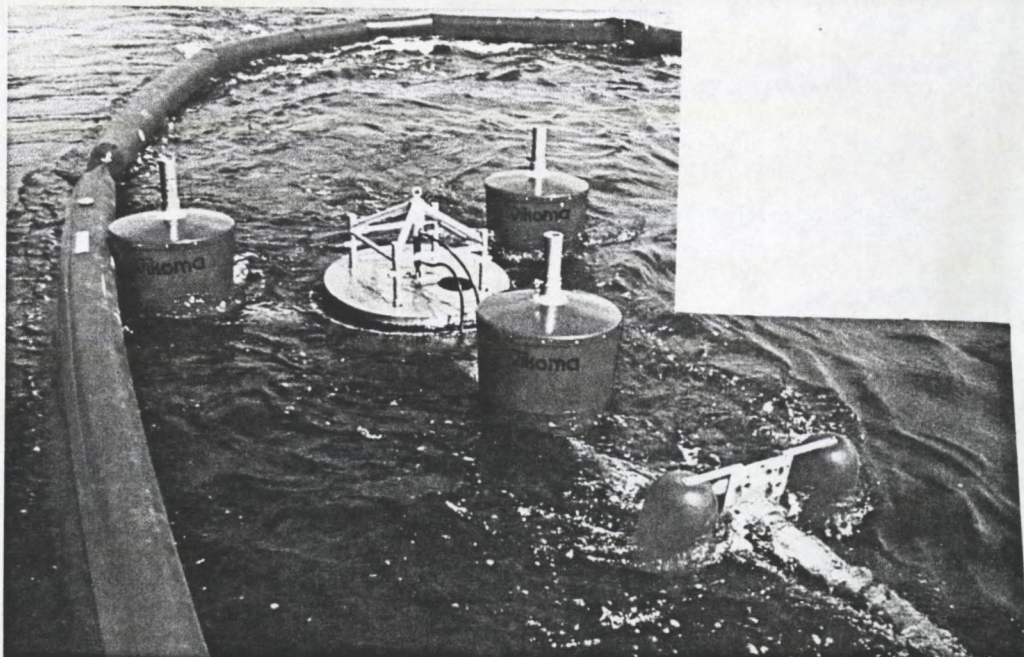


Figure 1.11. *Vikoma Cascade LP 3000*

Shown in Figure 1.11, this skimmer has the following characteristics [15]:

- (i) it can be operated in tow array from a vessel at speeds up to 1 m/sec,
- (ii) it can recover 183 m³/hr, and
- (iii) it can handle solids up to 30mm in diameter.

(B) **Vikoma *Vikoskim* skimmer.** This weir skimmer, shown in Figure 1.12, is incorporated into a 4m length section of a Vikoma boom. The section can be added into a conventional boom layout and oil, contained by the boom, flows over the weir into the skimmer to be pumped to storage. The weir depth below water surface is set by pumping ballast into a buoyancy tank which is attached to the skimmer. The hydraulically driven Archimedes screw pump can recover up to 100 tons/hr [16].

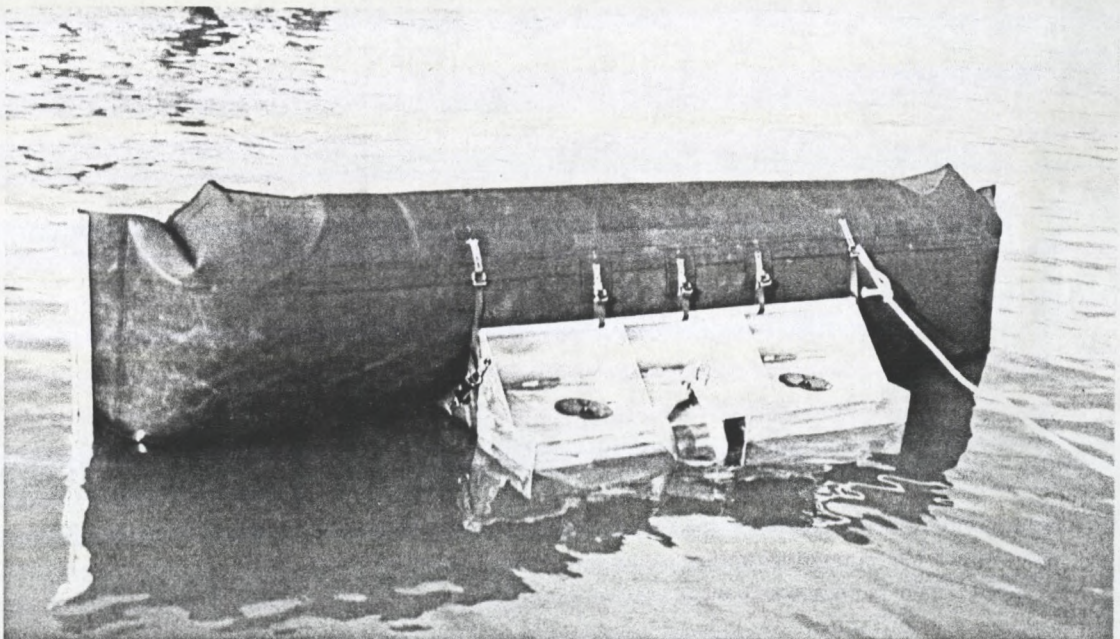


Figure 1.12. Vikoma *Vikoskim* skimmer

- (C) **Ro-Clean international's Ro-skim.** This is a similar system to the *Vikoskim*, where the weir skimmer forms part of the boom. In this system however, three buoyancy chambers are incorporated in the skirt of the boom and are filled with compressed air to provide vertical adjustment to the depth of the weir lip. The built-in hydraulic screw type pump can handle seaweed and debris which is mixed in with the oil. The maximum recovery rate of the skimmer is 100 m³/hr [17].
- (D) **G.T. series.** Shown in Figure 1.13, the G.T. weir skimmer consists of a hopper which lies below the oil/water interface. The oil layer flowing into the hopper is pumped to storage by a modified Archimedean screw pump positioned on the bottom. The pump has radial suction and axial discharge and is fitted with rotating cutting knives in the discharge area to ensure that thin obstacles are cut into small pieces to prevent clogging of the discharge hose. The skimmer is kept afloat by three floats.

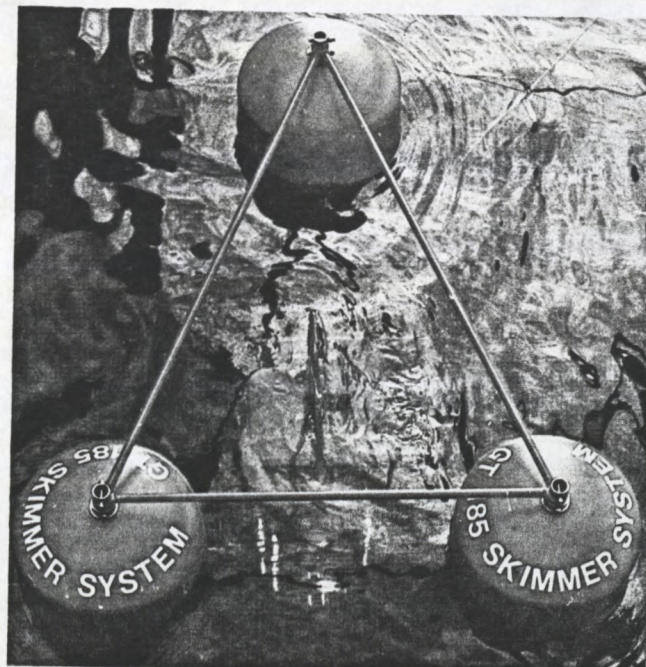


Figure 1.13. G 185 skimmer

An adaptor plate is fitted to the skimmer, which causes the hopper to automatically sink when the pump rate is increased, allowing more oil to flow into the hopper when recovering a thick oil layer, or rise when the pump rate is decreased to skim a thin oil layer. When the skimmer is recovering viscous oils, the adaptor plate is removed to ensure a large opening to allow the oil to pour into the hopper. A hydraulic power pack supplies power to the pump. The hydraulic and suction hoses are stored on a reel when the skimmer is not in use. There are two models available, the *G-185* and *G-260* which recover 65 m³/hr and 100 m³/hr respectively [18].

- (E) **Desmi's *Desroil* skimmer.** The *Desroil* is a lightweight weir skimmer which has been designed to recover debris-contaminated oil and emulsions of medium and high viscosities. The weir depth is set by pneumatic controls.

The pump is an Archimedes screw type which can pump up to pressures of 10⁶ Pa. A hydraulic power pack supplies power to the pump. A cutting knife section on the inlet cuts up any debris entering the pump. The skimmer can be deployed from a ship or shore crane and can pass through a 0,6m diameter manhole to recover oil from a tank. The *Desroil* has a mass of 70 kg, and a length, width and height of 0,55m, 0,36m, and 0,53m respectively. It has a maximum oil recovery rate of 100 m³/hr [19].

The South African Sea Fisheries, Port of Durban Pollution Control and SFF Pollution Control have purchased these skimmers.

Combined weir/rotary disc skimmers

This type of skimmer combines the rotary disc and weir principles. Oil adheres to rotating discs which carry it over a weir into a pump well, from where it is pumped to storage.

Described here are some of the models of this type:

- (A) **Framo ACW-400.** Shown in Figures 1.14 and 1.15, the *ACW-400* is manufactured by the Norwegian company Frank Mohn. The skimmer is designed to operate in sea of Force 4-5 (Beaufort) with wave height of 2-3m.

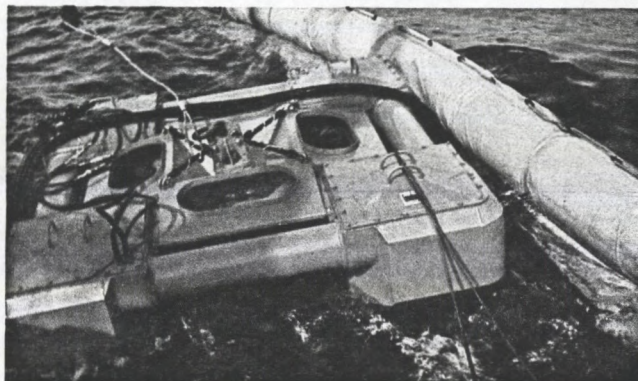


Figure 1.14. The Framo *ACW-400* skimmer

The *ACW-400* can handle a variety of oils from light diesel oil to cold viscous crude and bunker oil, and can also be used to recover chemicals. When this skimmer is recovering viscous oils, the weir is lowered below the surface to allow the oil to gravitate into the hopper, thereby enhancing the oil recovery of the spinning discs. A high volume weir can be fitted when recovering viscous oil or

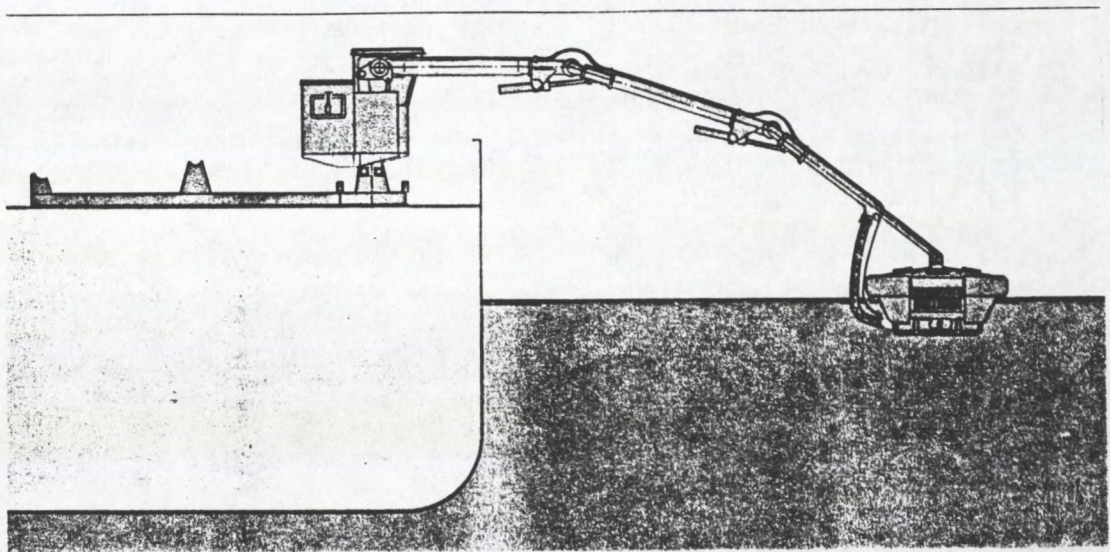
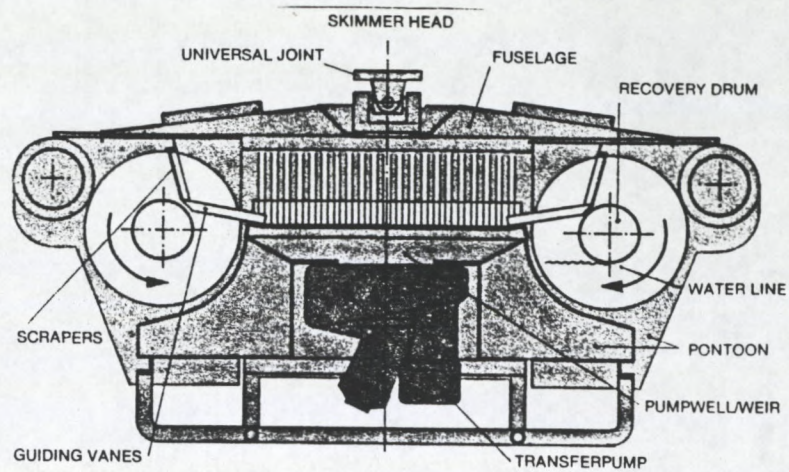


Figure 1.15. Layout and operation of the *ACW-400*

a thick layer of oil. Under this condition, the recovery rate is limited only by the pump capacity.

The *ACW-400* is operated by a single person. It can be fitted through a butterworth (nossel jet tank cleaning system) size hole to discharge oil from tanks on a disabled ship. When used to recover an oil slick, it can be deployed from a vessel by lowering it over the side with a crane. The weir skimmer has a length,

width and height of 3,4m, 2,5m, and 3,4m respectively, and a mass of 7 tons.

The system was approved by the Norwegian authorities for the North Sea contingency plans after its excellent performance during the *Ekofisk* blowout clean-up in May 1977. The skimmer is used in many parts of the world, including Germany and Prince William Sound [5, 20].

- (B) **Walosep skimmer.** This weir/rotary disc skimmer, shown in Figure 1.16, has a mass of 400kg and a pumping capacity of 90 m³/hr [5].

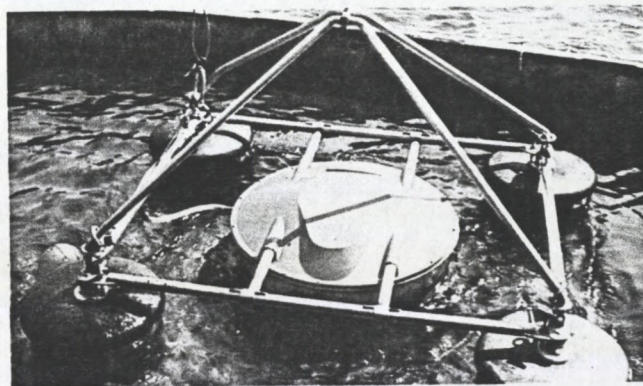


Figure 1.16. Walosep W1/W3 skimmer

Oil absorbent or oleophilic rope skimmers

Oil recovered from the sea using mechanical means is usually mixed with sea water. Thus, separation is required at additional expense. To solve this problem, materials like polypropylene, which absorb oil but repel water, are used for oil recovery. Rope skimmers utilise two squeegee rollers which propel a continuous loop of polypropylene fibre rope through the contaminated water where it absorbs oil. The rope returns through the rollers where the oil is squeezed out. Thereafter it is

returned to the water to absorb more oil. Described here are two of this type which are available [21]:

- (A) **Ro-Clean International's *Sea Mop 4090*.** Shown in Figure 1.17, the *Sea Mop 4090* is manufactured by Ro - Clean International, which also manufactures the *OMI* pollution control vessel described earlier. The rollers are propelled by power from a portable power pack. Four continuous loops of oleophilic mop can recover 24 m³/hr of weathered oil and have a maximum capacity of 35 m³/hr. The water content of the recovered oil is usually less than 10%. The pump can be detached and used as a fire pump or fitted to a heavy oil weir skimmer. The pump has a rated capacity of 100 m³/hr at 10⁵ Pa pressure [22].

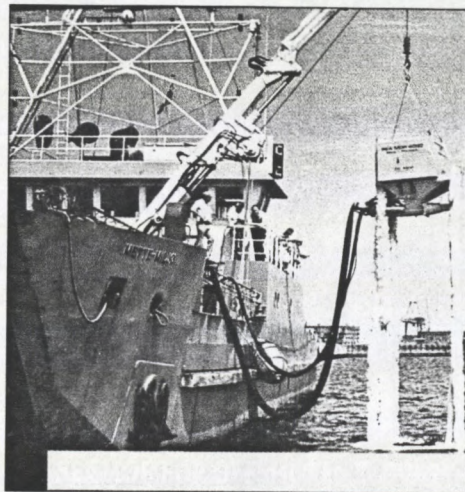


Figure 1.17. Ro-Clean's *Sea Mop 4090*

The *Mark IV-16* model, which can handle approximately 34 m³/hr, was used during the *Exxon Valdez* clean-up. A rope with a mass of 1kg can recover 27kg of oil [14, 22].

(B) **Drizit rope skimmers.** The *Drizit 3000 Oil Skimmer* operates on the same principle as the *Sea Mop 4090*. The pump and power pack are housed in a trailer and can be towed to a spill site. The rope skimmer has a recovery rate of 3 tons/hr [23].

Vacuum tanks and skimmers

Vacuum tanks are used in instances where air is likely to be drawn in with oil, which can result in suction being lost on certain pumps, eg. the centrifugal pump. This often happens when the oil layer is very thin and therefore the skimmer must just touch the water surface to avoid a large amount of water being recovered with the oil.

The skimming head, shown in Figure 1.18, floats on the water surface and is connected by a flexible pipe to a vacuum tank. The vacuum induced in the tank draws the oil

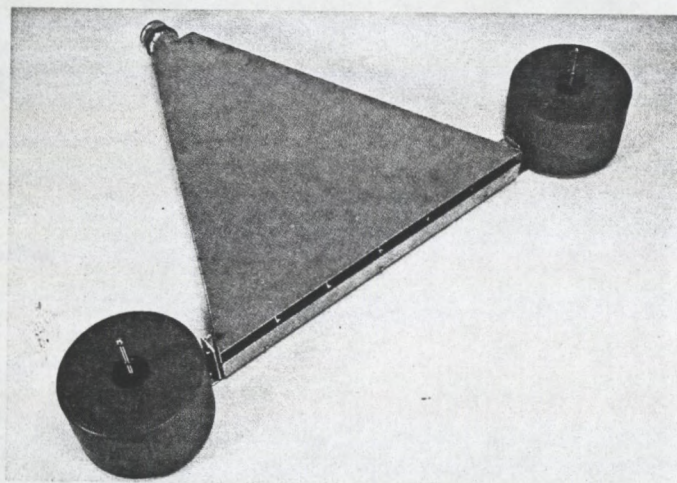


Figure 1.18. Skimming head-vacuum tank

layer off the water surface through the skimming head. A sewage cart operates on the suction principle and therefore is suitable for oil spill recovery. Sewage tanks were used

during the *Amoco Cadiz* spill clean-up [24, 25].

Slickbar's *Transvac 500-D* shown in Figure 1.19 is a self-contained high-suction pressure pump which has a recovery rate of 135 m³/hr. It incorporates a vacuum pump and a liquid - air - solid separator. The separator retains the solids, and air and liquid are discharged through separate ports. The skimming head floats on the surface to recover the oil layer [24].

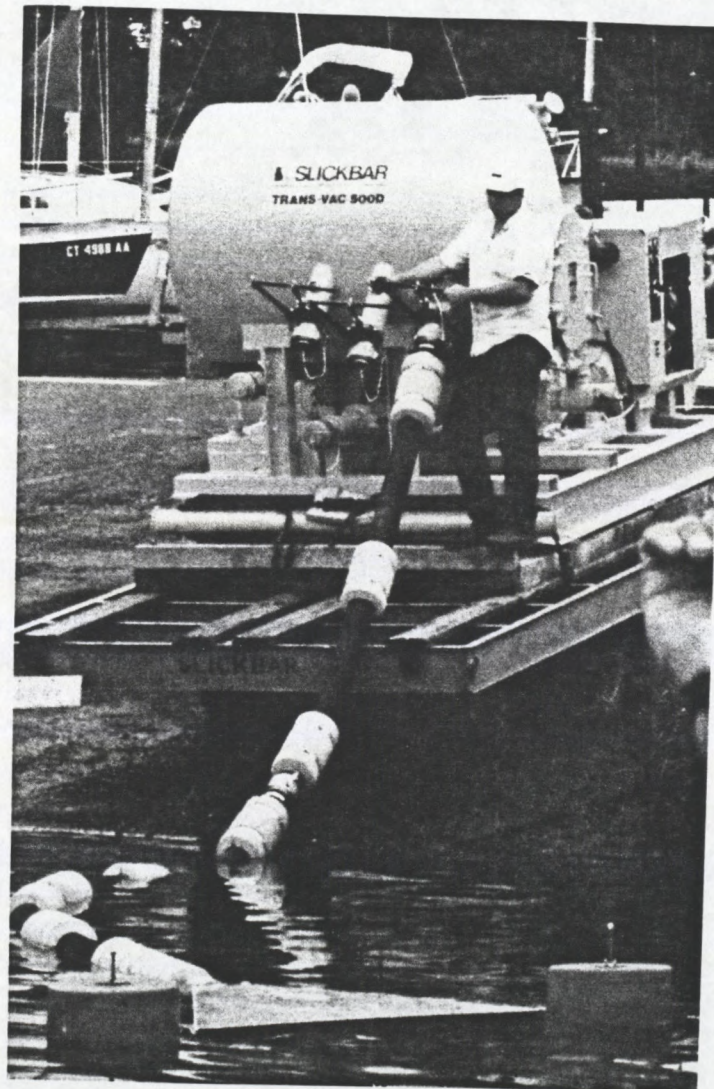


Figure 1.19. Layout of Slickbar's *Trans Vac 500D* vacuum tank skimming system

1.1.3 Booms

When oil is spilt on the sea surface, it is usually contained or deflected from sensitive areas by the use of booms. Booms are best described as floating barriers which prevent the spread of oil beyond the area they circumscribe. The limitations of booms are seldom appreciated and the problems caused by the rapid spread of oil, the effects of tides, currents and wave action on oil spill clean-up are usually underestimated. Booms can be held stationary to contain a spill or towed through the water to recover the spill in its path. Stationary booms are held in position by cables attached to anchors, and the force of the current on the boom may be taken as:

$$F = 26 \cdot A v^2 \quad (1)$$

where F is the current force, A is area of the boom, and v is the current velocity [26].

Booms should be towed by vessels capable of manoeuvring at low speeds, and the point of tow should be on the turning point of the vessel. Fishing boats towing booms were utilised during the *Exxon Valdez* clean-up. Skimmers were used to recover the oil caught in the boom. A boom being towed by two vessels to collect oil during the *Exxon Valdez* spill is shown in Figure 1.20 [26].

Normally boom designs incorporate the following features [26]:

- (i) a freeboard to prevent or reduce splash-over,
- (ii) a sub-surface skirt to prevent or reduce escape of oil under boom,
- (iii) some form of floatation chamber,

- (iv) a longitudinal tension member (chain or wire) to withstand the effect of wind, waves and current, and
- (v) a towing or anchoring coupling.

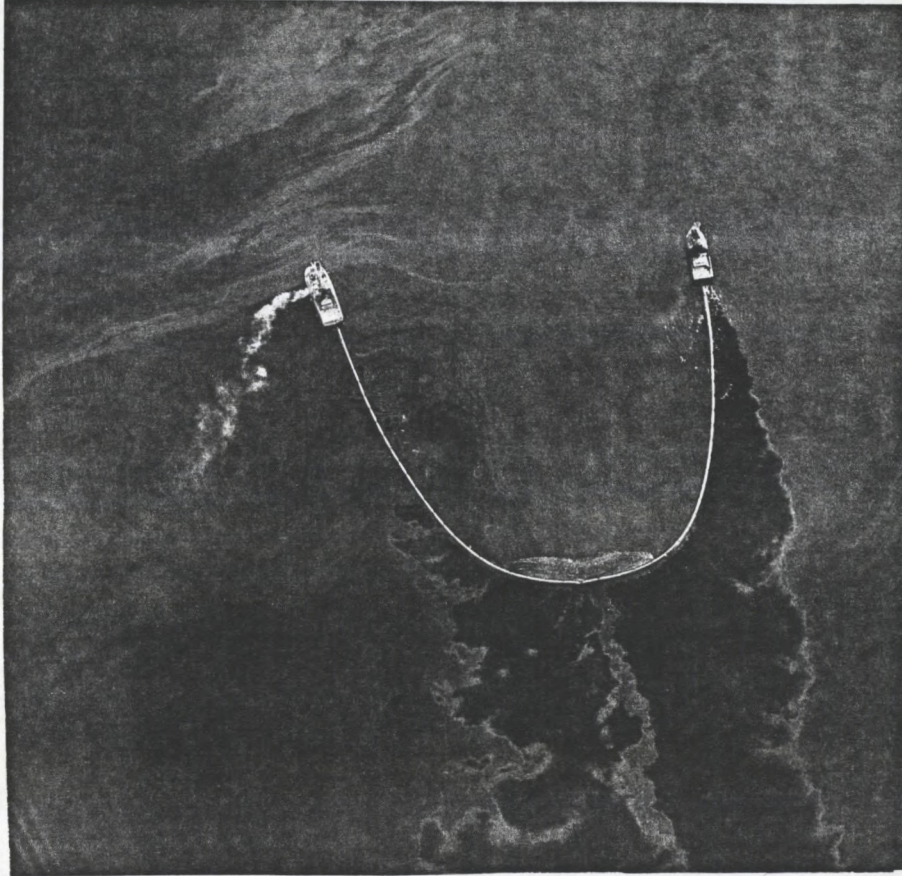


Figure 1.20. Two vessels towing a boom in tandem recovering oil during the *Exxon Valdez* clean-up. Leaking oil seen re-surfacing behind the boom.

Oil leakage under boom skirt

An important characteristic of a boom is its oil containment or deflection capability. A boom, which is generally held at 45 degrees to the current or tow direction, can withstand a current or tow velocity of 0,5 m/sec before oil escapes under the skirt, irrespective of the skirt depth. Wind and waves are capable of creating velocities

which exceed this value, causing leakage. Oil leaking under a boom will surface 2 - 10 metres behind it (the cause of leakage is discussed in section 2.2.4). Figure 1.20 shows oil which has escaped under a towed boom re-surfacing behind it. In addition, any attachment points along the face of the boom could result in turbulence and the formation of a vortex which will draw oil under the skirt [26].

Testing of booms

Two boom configurations were tested for oil retention capability in the *Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT)* in Leonardo, New Jersey. The booms were towed at different speeds and the amount of oil leakage under the skirt was measured. During the tests, a nozzle-shaped configuration was compared with a "V" shaped one. The nozzle-shaped configuration showed greater efficiency at high towing speeds but was less efficient at low speeds [27].

In a second test, diversionary booms were set at two different angles (20 and 32 degrees) to the direction of flow and tested for oil loss. The first began to leak oil when the tow speed reached 0,8 m/sec and lost 50% of the oil when the tow speed was increased to 1,67 m/sec. When the boom angle was increased to 32 degrees, oil began to leak at a tow speed of 0,5 m/sec and 50% of oil was lost when the speed was increased to 1,26 m/sec. Leakage was first observed at the cusps of the configuration [27].

It was concluded that the 20 degree angle boom performed more effectively than the 32 degree angle boom, and the additional length of boom required to cover the equivalent sweep of the 32 degree configuration was justified by greater efficiency [27].

Current boom types

Booms are usually sectional and supplied in lengths of between 10 - 100 metres. Sections may be joined on site. The booms are stored on skips or reels, and are inflated with air to give buoyancy when required [10].

There are numerous booms manufactured by various companies. Listed here is a description of some of the booms currently marketed:

- (A) **Vikoma Shore/Beach Guardian.** This boom (draught - 0,390m; freeboard - 0,254m), shown in Figure 1.21 and 1.22, is designed to be used in shallow water where they become stranded at low tide. When other booms are stranded, they become unstable and tilt over, causing them to be ineffective. This problem is overcome by the special design of the ballast chamber in the skirt of the *Guardian* type as shown in Figure 1.21. The skirt of the guardian has a vertical perforated inner membrane which acts as a tension member and prevents the boom from being rolled over when stranded.

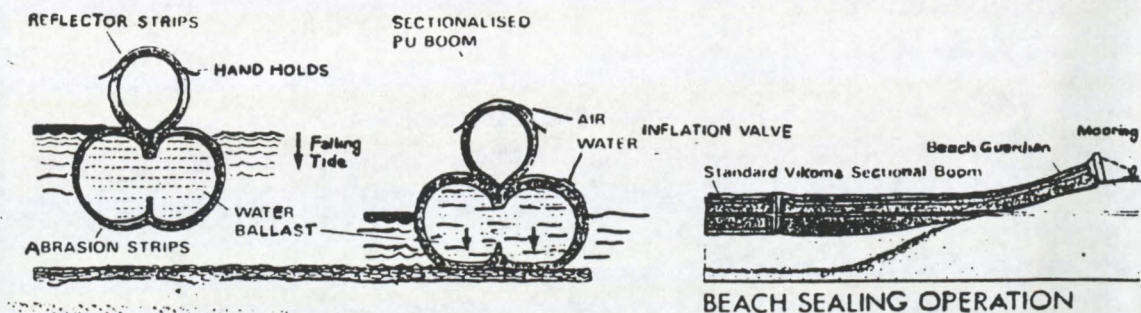


Figure 1.21. Principle of *Guardian* type segmented boom with water ballast used for sealing on beach at low tide in shallow water

(D) **Covalca oil booms.** The Colvalca oil boom (freeboard - 0,35m; draught - 0,5m) is manufactured by Covalca Plastici of Italy. They are formed by a continuous flexible PVC skirt supported by cylindrical, expanded PVC floats and are supplied in sections with a maximum length of 50m.

The largest is the *Off-Shore 85/1020* and it [31]:

- (i) is manufactured from buoyant materials, and thus is unsinkable, requiring no inflation,
- (ii) has a high resistance to salt water, U.V. radiation, temperature, and hydrocarbons, and is fire resistant,
- (iii) is stable in adverse weather conditions, and
- (iv) is resistant to winds of up to 100 km/hr.

(E) **Aerazur's Balear 333.** The *Balear* boom (freeboard - 0,54m; draught - 0,75m), shown in Figure 1.25, is designed for flexibility in a larger swell. The boom is made up of multiple cells which have the advantage of being more flexible in a swell than inflatable booms, which tend to be too rigid. The principle of operation is similar to that of other booms. The booms have a double skin which offers extra protection against damage. They can be deployed in a current of 1 to 2 m/sec or towed at that speed. No angle of deployment to flow direction is given [32].

The boom has a high resistance to punctures, abrasion, hydrocarbons and ultra-violet light and is designed for rapid deployment. A length of 250m can be deployed in 15 minutes [28].

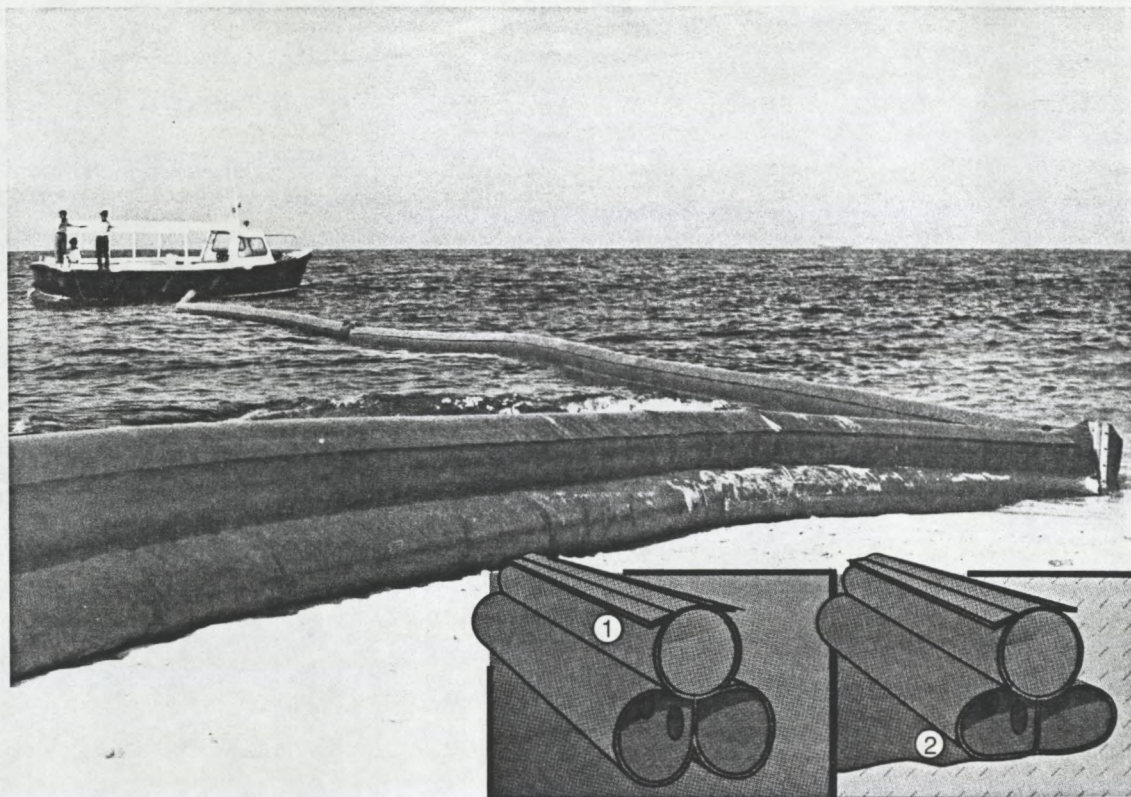


Figure 1.22. Vikoma *Shore Guardian* boom

Cross section showing:

1. splash flap deflector for choppy waves
2. when aground, water ballast tube provides tidal seal with beach

(B) **The Vikoma *Ocean Guardian* boom.** As shown in Figure 1.23, the *Ocean Guardian* (freeboard - 0,645m; draught - 0,710m) is a conventional boom designed for open sea deployment. It is fitted with a splash flap deflector for choppy seas. A length of between 200 and 500 metres can be stored on a reel [29].

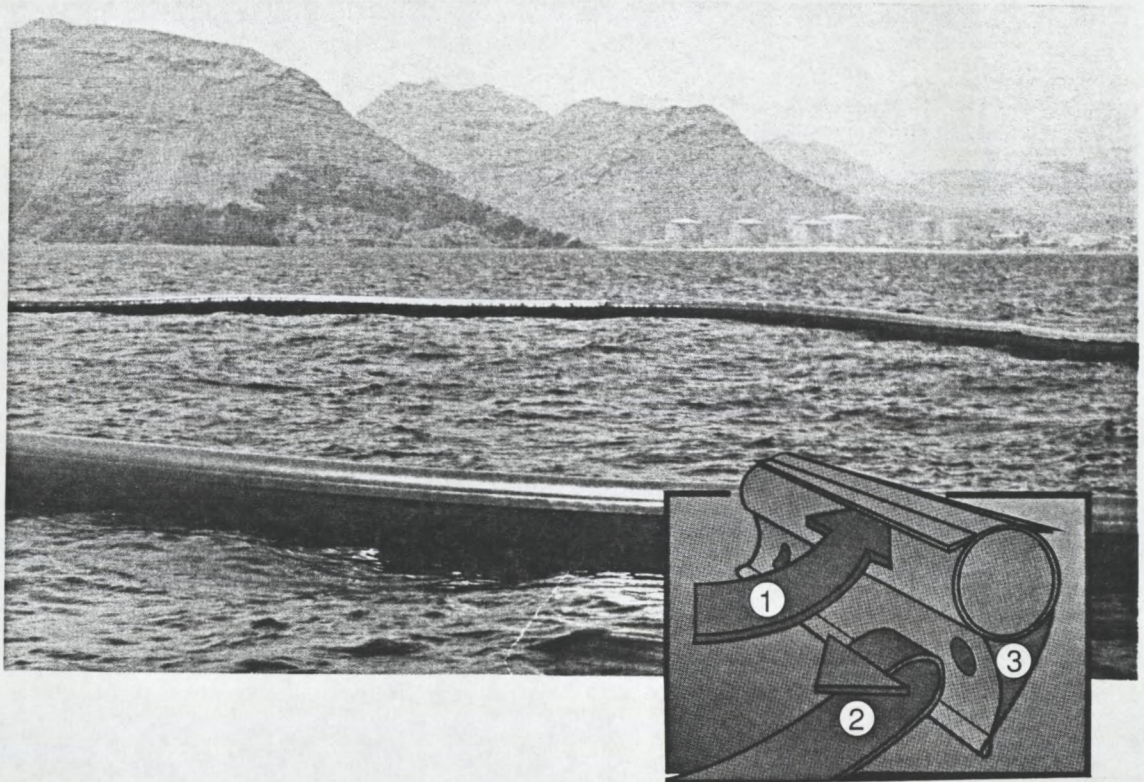


Figure 1.23. Vikoma *Ocean Guardian*

Cross section showing:

1. splashflap deflector for choppy waves
2. curved forward underwater shape
3. water ballast for stability

(C) **Vikoma *High Sprint booms 1800***. The *High Sprint* boom (freeboard - 0,750m; draught - 1,050m), shown in Figure 1.24, is used for off-shore deployment. It consists of a buoyancy chamber above the water line which is filled with compressed air. A galvanised steel ballast chain is sewn into the fabric skirt of the boom to ensure a concave underwater profile when the boom is towed [30].

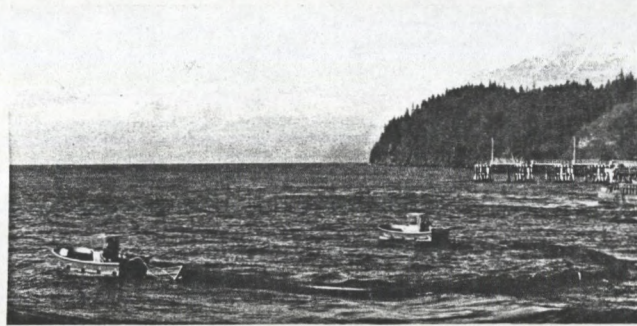
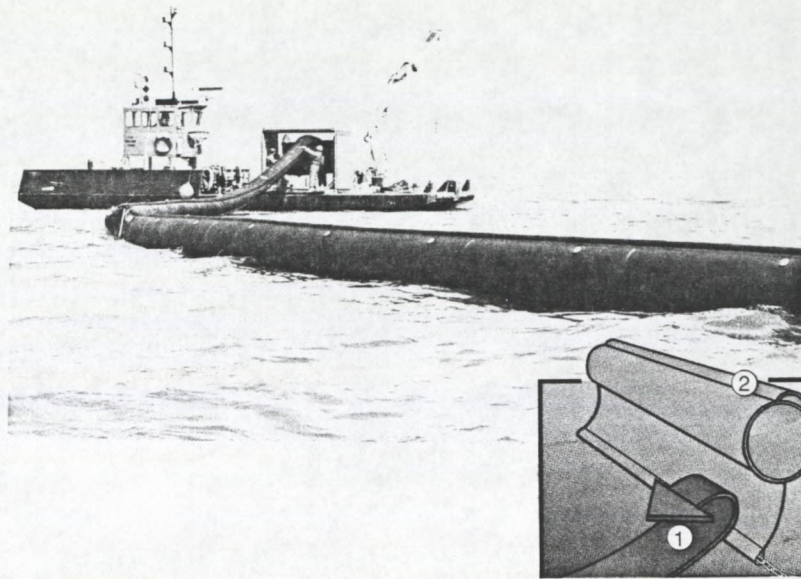


Figure 1.24. Vikoma *High Sprint 1800* boom

Cross section showing:

1. forward curved under water shape
2. air feeder sleeve

Each boom section comes in a standard length of 50m and each buoyancy chamber is 3m in length and is sealed from the adjacent one to ensure the boom remains afloat in the event of a chamber being punctured. A boom with a length of 500m can be deployed in 20 minutes. The boom is efficient in waves of up to 2,5m in height, and stable in currents of up to 3,5 m/sec [30].

(D) **Covalca oil booms.** The Colvalca oil boom (freeboard - 0,35m; draught - 0,5m) is manufactured by Covalca Plastici of Italy. They are formed by a continuous flexible PVC skirt supported by cylindrical, expanded PVC floats and are supplied in sections with a maximum length of 50m.

The largest is the *Off-Shore 85/1020* and it [31]:

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- (ii) has a high resistance to salt water, U.V. radiation, temperature, and hydrocarbons, and is fire resistant,
- (iii) is stable in adverse weather conditions, and
- (iv) is resistant to winds of up to 100 km/hr.

(E) **Aerazur's *Balear 333*.** The *Balear* boom (freeboard - 0,54m; draught - 0,75m), shown in Figure 1.25, is designed for flexibility in a larger swell. The boom is made up of multiple cells which have the advantage of being more flexible in a swell than inflatable booms, which tend to be too rigid. The principle of operation is similar to that of other booms. The booms have a double skin which offers extra protection against damage. They can be deployed in a current of 1 to 2 m/sec or towed at that speed. No angle of deployment to flow direction is given [32].

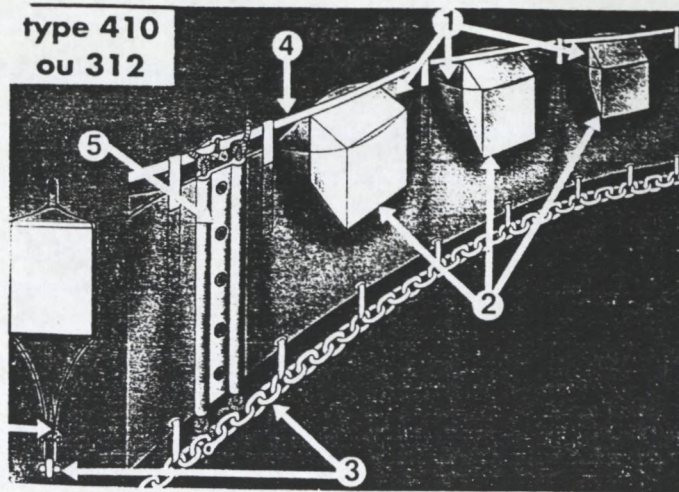


Figure 1.25. Layout of the *Balear 312* boom

1. floatation chamber
2. additional floats
3. ballast and traction chain
4. webbing
5. connecting rod and sideways system

(F) **Globe International Inc's *Oilfence 48*.**

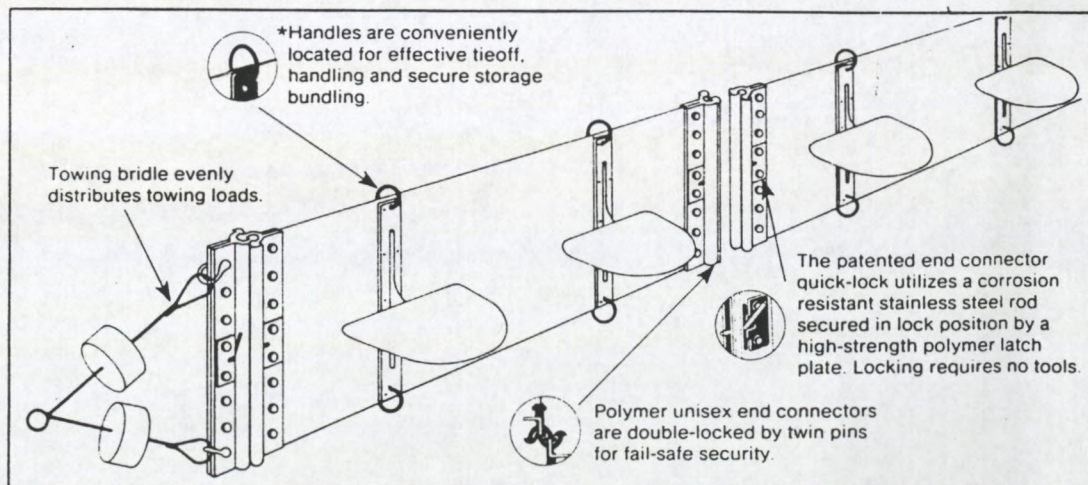


Figure 1.26. Layout of the *Oilfence*.

This boom (freeboard - 0,61m; draught - 0,61m) is designed for permanent installations such as oil platforms, oil rigs etc. It can encounter waves of height 1,5 - 2m. The design incorporates outrigger floats which ensure excellent stability. A smaller version, called the *Oilfence 36*, can be used on sweep systems on large skimmers that require booms with high tensile strengths and stability. *Oilfence* booms are used at the SFF terminal at Saldanha Bay [33].

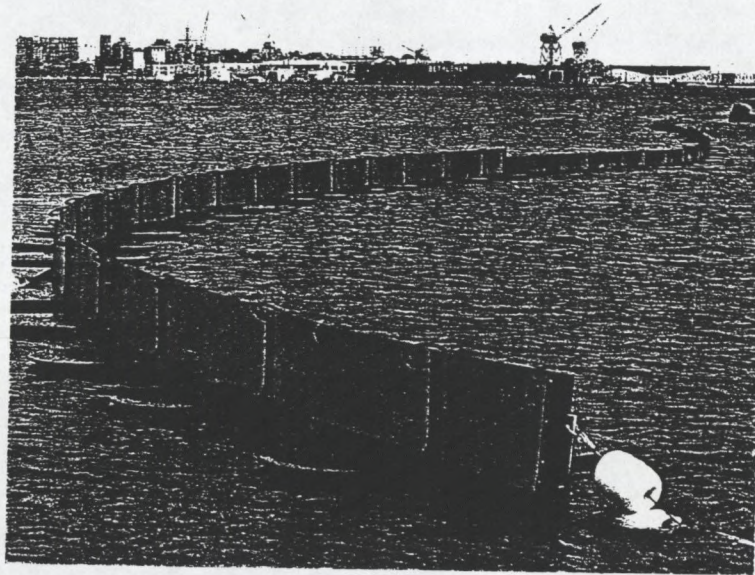


Figure 1.27. *Oilfence* in operation

1.1.4 Oil boom/skimmer combinations

In this system, booms are utilised to condense the oil to a central point where a skimmer is positioned to recover it. This method allows for oil spread over a wide area to be more effectively recovered.

Current boom/skimmer combinations

(A) **Vikoma's *Fasflow*.** The *Fastflow* is secured to the side of a vessel and towed through a slick at high speeds, as shown in Figure 1.28. The skimmer has been

designed to operate:

- (i) at speeds up to 3 m/sec,
- (ii) in a Force 6 wind,
- (iii) in waves up to 1m, and
- (iv) recover oil at a maximum rate of 100 m³/hr.

Two diversionary booms, each 10m in length, extend out from the front end of the skimmer to form a "V" to direct polluted water in. A chamber in the skimmer reduces the velocity of flow entering it and directs oil over an internal weir plate into a settling chamber where it is recovered. Part of the water content in the oil separates out in this chamber [34].

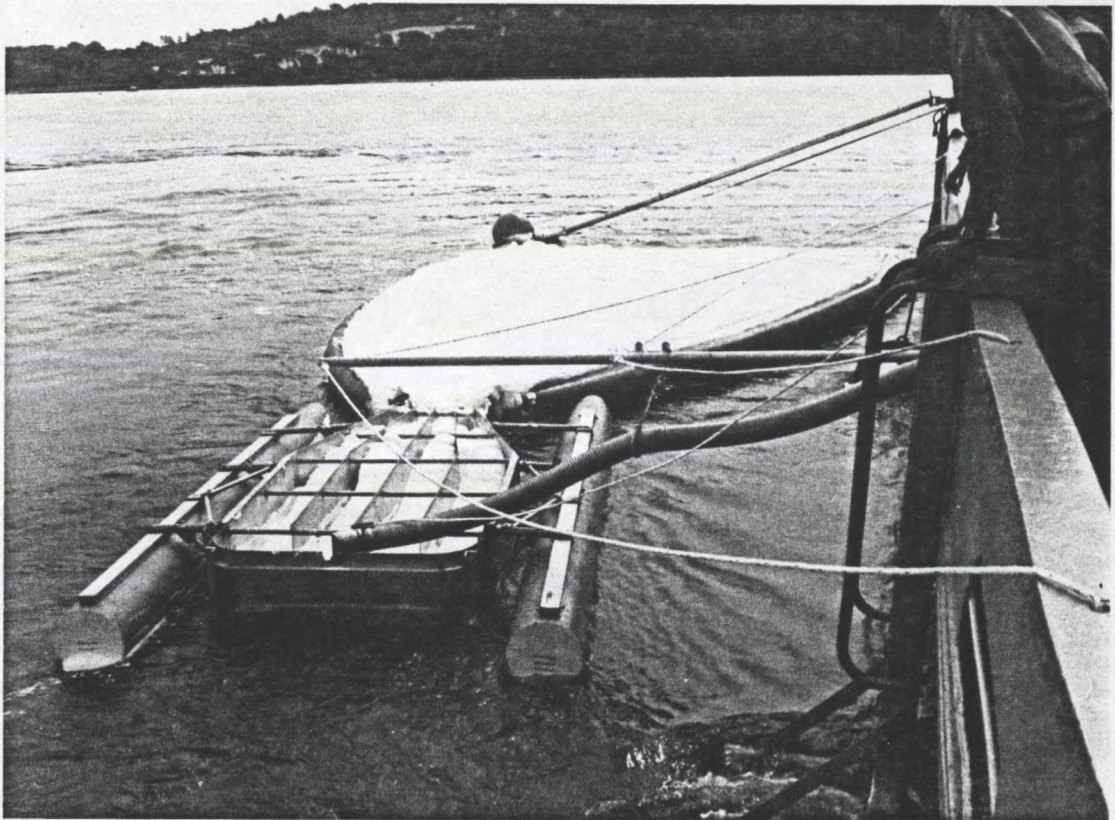


Figure 1.28. Vikoma *Fasflow*

(B) **Vikoma's Weir Boom Rapide.** The *Weir Boom Rapide*, shown in Figure 1.29, consists of a boom with a number of weirs formed as integral parts. The weirs consist of a number of slits in the boom over which any oil, trapped within the boom, passes before being recovered. The depth below the water surface of these weirs is set by adjusting the pressure of the integral air tube which provides buoyancy to the boom. Hydraulic vane pumps are situated in collection chambers behind the weirs to recover the incoming oil. These receive hydraulic power through a line which forms an integral part of the boom. The hydraulic power pack is carried by the support vessel. The vane pump can recover viscous crude oils and emulsions which are pumped to a tank on the support vessel via a delivery line built into the boom [35].

The weir boom is deployed between a minimum of two towing vessels. Oil trapped between these two vessels is guided down the deflector booms to the weir booms from where it is dispatched for storage. If a third vessel is used, two such weir boom combinations can be deployed from a centre support/oil storage vessel. The boom/weir combinations are stored, deployed and recovered on powered reels on the support vessels.

The weir/boom combination has been designed to [35]:

- (i) recover oil at a maximum rate of 600 tons/hr,
- (ii) recover oil in currents of up to 1.5 m/sec, and
- (iii) have a maximum skimming width of 300m for a three ship configuration.

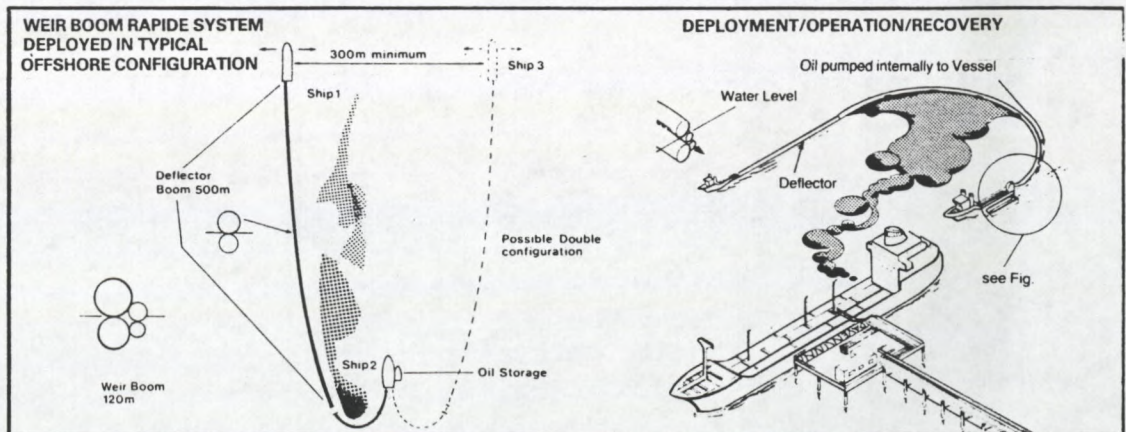
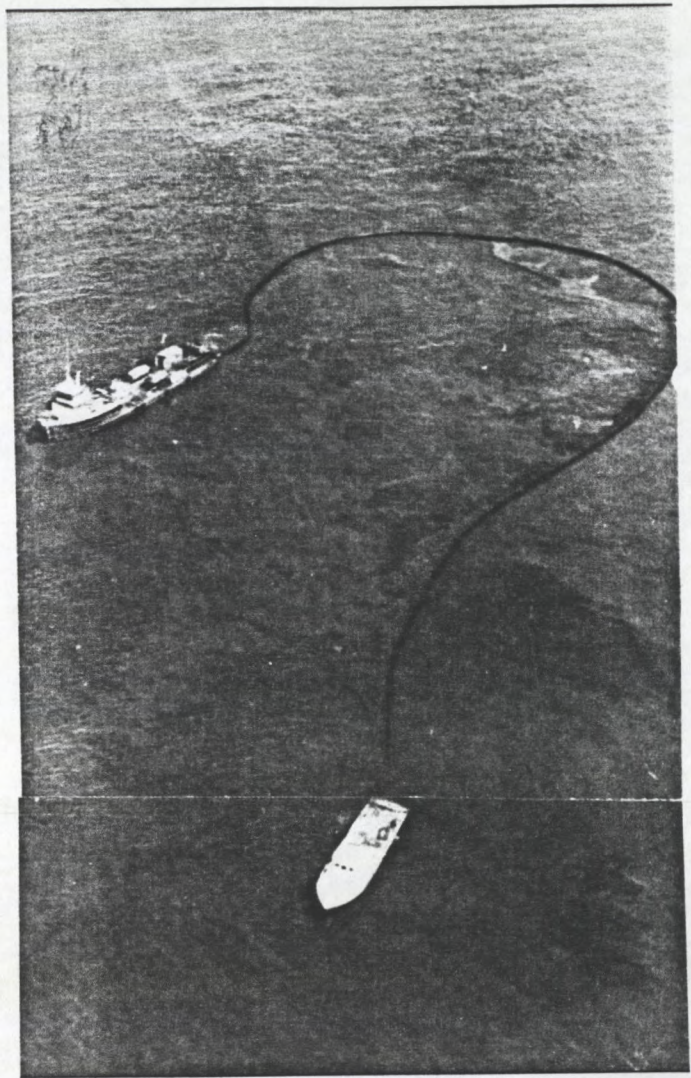
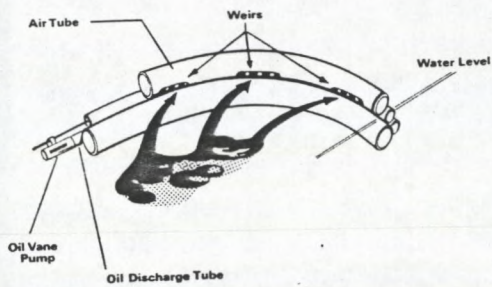
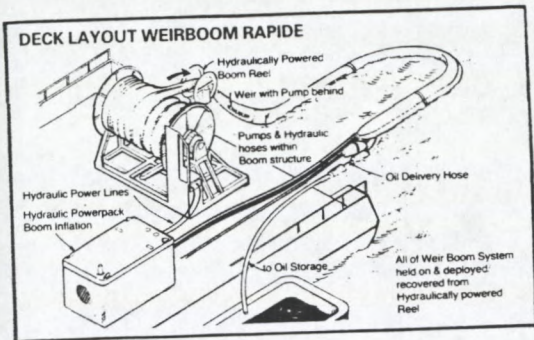


Figure 1.29. Vikoma Weir Boom Rapide

(C) **Allmaritim's FIOCS 800.** This configuration consists of a boom, which is normally towed by two support vessels (see Figure 1.30). Oil trapped by the boom is recovered by any free floating skimmer, such as the Framo *Transrec* or *Desmi*, which is deployed from one of the support vessels. The booms are stored on reels on the support vessel. The boom utilises a bottom net to prevent trapped oil escaping from the boom. This is held to the side of the vessel by an outrigger. A second vessel leads the deflector boom ahead and guides the spilt oil to the boom trap area. The configuration has a skirt depth of 1,5m and a freeboard of 0,6m. It is efficient at recovering oil up to a speed of 0,8 m/sec, and can operate in seas up to Force 4. The thickness of the layer of oil trapped by the boom can reach 0,6m [36].

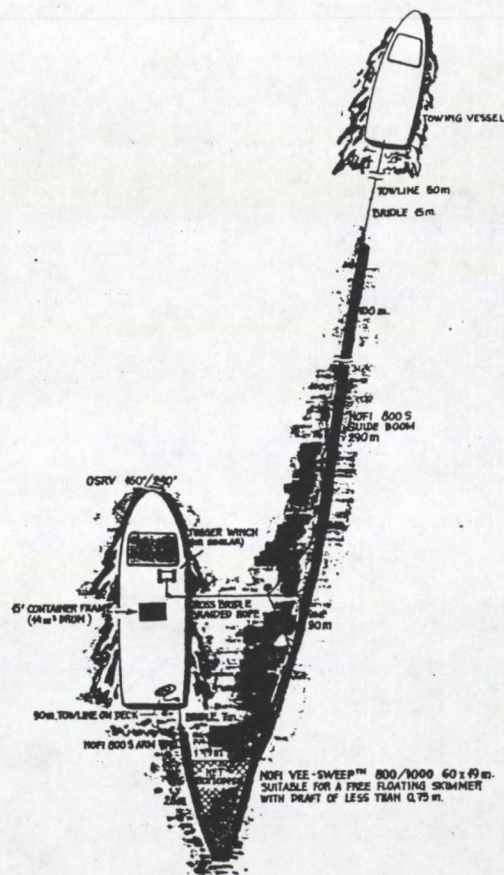


Figure 1.30. Layout of FIOCS 800

1.1.5 Alternative methods

Oil not recovered by mechanical means may be dispersed by either dispersants, oil absorbent material or by burning.

Dispersants

Chemical dispersants can be used to combat oil pollution by breaking up an oil slick into tiny droplets. These become suspended in the water column (the sub-surface sea currents which can be vertical) and are rapidly diluted by the turbulent motion of the sea. Dispersion of the slick prevents the formation of persistent water-in-oil emulsions and residues which are difficult to clean up. In a dispersed form oil is removed through degradation by micro-organisms which occur naturally at sea, or by dissolution [37].

In cases where it is impractical to use mechanical means to recover oil, eg. where the shoreline is an inaccessible cliff face, chemical dispersants at sea may provide the only removal method; thereby protecting resources in its path and preventing the slick from impacting the shore. Countries such as Britain and Norway which have craggy and inaccessible coastlines, and which suffer from severe weather in winter, make use of dispersants to combat oil spills. However, dispersants have limitations. Their usage should be carefully controlled [37, 38].

Mechanism of chemical dispersion: The key to dispersion of oil is the exposure of the surface area of the oil to the natural process of oxidation and biodegradation, converting it into water, carbon dioxide, oxygen, inorganic salt and inert material. By breaking the slick into finely dispersed droplets, the combined surface area is greater than the original

slick. Oil droplets do not rise as fast to the surface as large amounts of oil and therefore become dispersed. In the case of oils with low specific gravities, even smaller droplets are required to overcome their greater buoyancy [37].

One of the difficulties when applying dispersants is to determine the required amount necessary to disperse the oil. The thickness of the oil layer can vary considerably over short distances and there are often patches of apparently clear water between the slicks. It is thus impossible to apply the correct amount at every point [8].

The key component of a dispersant is a surface-active agent (surfactant) which has a molecular structure such that one part of the molecule has an affinity for oil (oleophilic) and the other an affinity for water (hydrophilic). When evenly applied and mixed into floating oil, the molecules of the dispersant become arranged at the oil - water interface, reducing the interfacial tension between the oil and water. The action of the sea swell break up the slick into fine droplets. Dispersants prevent the coalescence of the oil droplets and the reformation of a slick. Turbulence generated by a rough sea will cause rapid natural dispersal of an oil slick. Dispersants accelerate this process [37].

Dispersants must contain a solvent which will penetrate through the oil layer to distribute the surfactant. However, dispersants are ineffective on highly viscous oil as they tend to run off the oil before the solvent can penetrate, and cannot be used to disperse a mousse after it has formed. Also, some oils become viscous after they have been weathered at sea and therefore dispersants are ineffective after this stage. In general, dispersants cannot be used on a slick which is one or two days old [37].

Methods of application: The method of application depends on the type of dispersant, the size and location of the spill, and the availability of vessels and aircraft for applying the dispersants on a slick [37].

There are two types of dispersants. The hydrocarbon based dispersants are applied to the oil in a dosage of 1 part of dispersant to between 1 to 3 parts of oil. Concentrate dispersants, which are alcohol or glycol solvent based, can be applied as-is or pre-diluted with sea water. A dosage of 1 part of oil to between 5 to 30 parts of oil are typical. Concentrates have largely superseded hydrocarbon based dispersants [37].

When specialised equipment is not available, a fire hose which includes apparatus to mix dispersant in with the sea water stream may be used. However, it is difficult to obtain the required dosage of approximately 1 part of dispersant to 10 parts of seawater and this usually results in unnecessary wastage of dispersant [37].

Hydrocarbon based and diluted concentrate dispersants cannot be applied by fire hose as they must be mixed in with the oil. This is achieved by spraying the dispersant from nozzles fitted to a vessel like that shown in Figure 1.31, which churns the dispersant into a slick in its wake. The average spray width is usually 30m [36].

When utilising dispersants to remove a slick, typical problems such as fragmentation or formation of windrows, which are narrow bands of oil, and low treatment rate are still encountered. This is overcome by applying dispersant from a low flying aircraft which has the advantage of rapid response, high application speed and good surveillance capability,

ensuring that heavy concentrations of oil are located [37, 39].

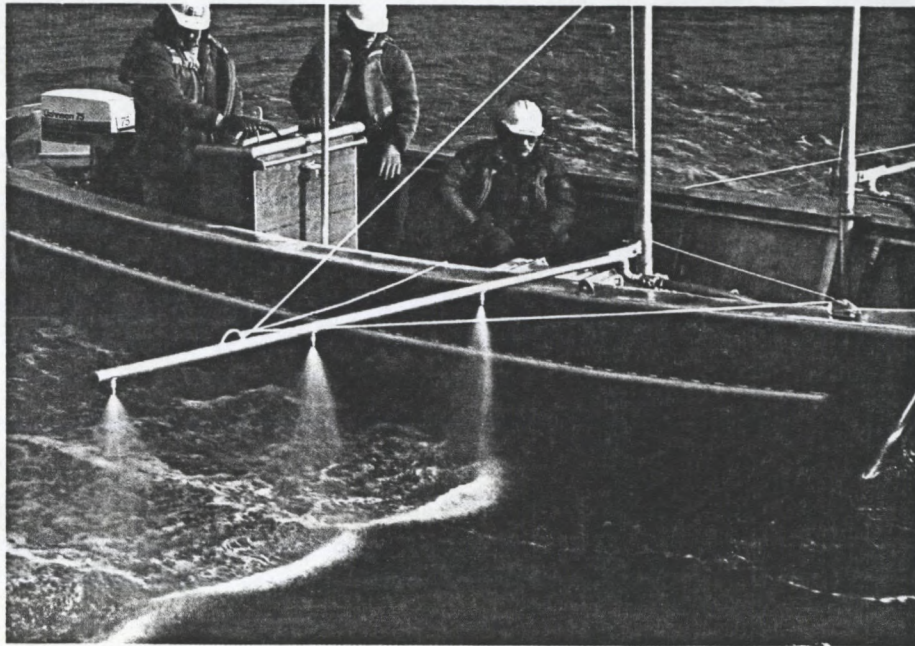


Figure 1.31. Dispersants being applied to a spill from a work boat

Specially converted or crop spraying aircraft are used to spray dispersant onto a slick. The typical application rate is 22 - 45 litres per acre, which is the same as that required for ship borne application. A spill of 4000 tons of crude may require the application of approximately 200 tons of dispersant within 24 hours. This can be achieved using aircraft like the Douglas DC6. The altitude of spraying should vary between 5 - 15m [39].

To determine the effectiveness of spraying, an observer aircraft should be utilized to monitor the slick's dispersal and to determine if excessive amounts of dispersant are being used [39].

Britain has eight Dakota aircraft for oil pollution prevention. The aircraft are on 30 minutes standby and each can carry 6800 litres of dispersant [38].

Environmental considerations: Dispersants, like oil, are toxic to the environment and are persistent. During the *Torrey Canyon* spill, 10 000 tons of dispersant was applied to the spillage and was so toxic that it destroyed the intertidal life such as crustaceans that had previously survived the spill. Although modern dispersants are not as toxic as the older type, their application still invokes controversy as they have the affect of removing the slick out of sight by breaking it down into small droplets, enabling it to penetrate below the water surface and thereby making it more available to harm the environment. The droplets can contaminate fish eggs, larvae, kelp, and sea creatures such as lobsters and sea urchins which would have escaped the effect of pollution if the oil was left on the sea surface. The oil droplets also contaminate fish, which affect the mammals and birds that eat them. Fishing bans are usually imposed in an area affected by a spill [8, 37, 38].

In shallow waters where water exchange is poor, dispersant application is not recommended as it can result in concentrations of oil droplets in water which persist for long periods. Despite this greater risk, the controlled application of dispersants in these situations may on occasions be beneficial as it may reduce damage to adjacent ecologically sensitive shorelines. Dispersants may not be used in areas where there are shellfish beds [8, 37].

Parameters to be considered when selecting a dispersant are as follows:

- (i) toxicity of the dispersant to marine life, along with that of the mixture of dispersant and oil should be evaluated, with consideration to filter feeding organisms,
- (ii) the persistency of the dispersant should be of the same magnitude as that of the oil to be dispersed, and
- (iii) the viscosity and pour point of the oil spilt must be considered with reference to the ambient temperature when evaluating the effectiveness of a dispersant.

A team from the Environmental Department at Norway's Institute for Continental Shelf and Petroleum Technology Research (IKU) has produced a series of books detailing the likely effectiveness of various chemicals as well as the deadlines for optimal use of mechanical and chemical measures to combat slicks [8, 37, 38].

Straw and plant fibres

Straw, which can absorb up to 15 times its weight in oil, was deployed in the form of mats to mop up oil on the beaches on the Shetland Islands after the *Braer* spill. They were also deployed to form a protective barrier around salmon farms on the Islands. A total of two kilometres of mat was deployed.

Unlike booms, straw mats can be deployed in a Force 12 gale without being blown away.

Barley straw is the best material, but ultimately any straw can be used [40].

Fibres from plants such as milkweed floss, cotton and kenaf act as sponges to mop up spilt oil and can absorb more than synthetic materials such as polypropylene. Milkweed absorbs 40 times its weight in oil compared to polypropylene which absorbs only 10 times its weight. Because these fibres are hollow, they have great potential for absorbing oil through their unusually waxy tissue, which is critical for high oil absorption performance. When the waxy layer is artificially destroyed, milkweed had similar absorption properties to polypropylene.

Natural fibre has the advantage of being biodegradable. Milkweed has been the most successful fibre tested. It has the added advantage of being reusable after the oil has been squeezed out. During the first squeeze, 90% of the absorbed oil can be removed, and by the third squeeze, this amount is reduced to 75%. Both straw and weed must be recovered after it has collected oil and disposed of. This can be costly [41].

Fertilizer

Researchers at the University of Texas have developed a bead which is coated with palladium activated titanium dioxide fertilizer, to catalyse the break down of oil in sunlight. Other types of beads, which have been developed, soak up oil to form floating clumps. These disintegrate into white sand-like particles. So far, these beads have only been laboratory tested [41].

The growth of bacteria (responsible for the disposal of oil through the process of biodegradation) depends on the availability of oxygen and nutrients, particularly phosphorous and nitrogen. These nutrients are in short supply during an oil spill and by

implementing a technique called "Bioremediation" to supplement these nutrients, the bacteria populations can be increased and the natural biodegradation of the oil is accelerated. After interacting with oil, they leave behind an asphalt hydrocarbon which is non-toxic. Polluted shoreline in Prince William Sound, which had been hosed down, was treated with slow release water soluble fertilizer containing nitrogen, phosphorous and urea. Within a few weeks of treatment an increase in the rate of breakdown of residual oil by microbes was noted in the treated area (see Figure 1.32).



Figure 1.32. Fertilizer applied to a test grid (right bottom corner) on a previously oil impacted beach during the *Exxon Valdez* clean-up shows a noticeable improvement when compared to the untreated area.

Natural break-down of oil in sandy sediments is more difficult than on pebble beaches because the oil permeates further below the surface. Bacteria is active to a depth of 0,3m. The ground matter has a larger surface area and therefore less oxygen. The fertilizer manufacturer Elf Aquitaine have added oleic acid to their oil treatment fertilizer which they claim catalyses the degradation process in sandy sediments [1, 38].

A UK based company, Imbach Biological Services, is marketing a cultured bacteria formula which uses oil as a source of nourishment. The bacteria are supplied in free flowing granules or powder form, which also contain the necessary surfucants, and is a cereal-based carrier. The product was used to combat a spill leaking from a tanker barge after a collision in Galveston Bay. The 1900m³ spill was contained by booms and the oil eating microbes were used to help clean the spill [1, 42].

In-situ burning

In-situ burning involves burning the oil where it floats on the sea surface after a spill. However, the rapid spread of oil on the surfaces creates problems as the surface layer of oil can become very thin, and the cooling effect of the underlying water layer can prevent combustion from taking place. In-situ burning is only feasible when the oil layer is thick, the volatile elements have not evaporated and the oil has not emulsified with water. Therefore, it should take place within 18 - 36 hours after a spill while the oil is still volatile. Further, it is dangerous to incinerate recovered oil waste as chlorinated dioxin may result from the burning of anything with salt water. However, in-situ burning is still a response option [2, 8, 43].

RAF Buccaneers were used to drop Napalm on the stranded *Torrey Canyon* in 1967 to set it alight in order to burn off the remaining oil aboard. The attempt failed and the slick contaminated 220 kilometres of coastline. Despite this, it was suggested that the burning methods could be used to clean up the *Braer* spill on the Shetlands [38].

The approved oil spill contingency plan for Prince William Sound in existence at the

time of the *Exxon Valdez* spill plainly indicated that in the case of a catastrophic spill, the use of dispersants and in - situ burning would comprise the principal strategy for combatting an oil spill. During the clean-up, relevant authorities in Alaska did not permit burning, only allowing a test burn at Goose Island which disposed of 67m³. On the second day after the spill, a storm passed through the Sound which emulsified the oil with water putting an end to further plans for in-situ burning [2].

An oil/water emulsion, which is no longer volatile, can be made combustible by adding an emulsion breaker. Researchers have found that 97% of the oil of a weathered 50% oil/water emulsion could be burnt off after an emulsion breaker had been added [43].

1.1.6 Testing and evaluation of oil pollution combat equipment

Authorities have seldom tested different booms and skimmers to compare their performances. The most successful test on record was a joint Canadian - United States exercise. Approximately 80m³ of specially treated crude oil was intentionally spilt into the sea off Newfoundland in September 1987. The purpose was to compare the performance of different makes of booms and skimmers [44].

The oil selected was *Brent Crude* from the North Sea, which was treated by adding slack wax to give it similar properties to a typically high wax Grand Banks crude. This type is uncharacteristic of most crude oils in that it possesses low adhesive properties. The oil, which had a relative density of 0.84, was poured into the sea in a position where the current would carry it away from the shore of Newfoundland.

The boom types used for tests were:

- (i) *Ohmsett*
- (ii) *Ro-Boom*
- (iii) *Vikoma*

The test plan was that the booms would be towed through the water at between 0.26 - 0.5 m/sec and the oil would be poured into the boom catenary. The oil retaining integrity of the boom would then be observed for 1 hour. Thereafter, three skimmers would be deployed for 20 minutes each and the recovered quantities of oil measured [44].

The skimmers used for the recovery tests were:

- (i) Framo *ACW400*,
- (ii) Pharos Marine *G 185*,
- (iii) *HOS (Heavy Oil Skimmer)*; an innovative oleophilic rotary disc skimmer designed by the US Coast Guard.

Initially, the oil was poured into the catenary of *Ro-Boom* while it was being towed in a "J" formation by two cutters. The *Ohmsett* boom was deployed into a position behind *Ro-Boom* to catch any leaking oil, and to be in a position to capture the oil after being released when the *Ro-Boom* test was complete. During the *Ro-Boom* test, a 15 knot wind started to blow which caused the *Ohmsett* boom to twist. Attempts to hold it in a catenary formation failed, and the *Ohmsett* boom fell progressively behind the *Ro-Boom*.

After 90 minutes, the oil in the catenary of *Ro-Boom* was 30cm thick. Some oil had splashed over the boom and leaked under the skirt. The end of the boom was released to allow the retained oil to flow into the *Ohmsett* boom catenary which was lagging 1 km behind the *Ro-Boom*. After 40 minutes, approximately 80% of the oil was in the *Ohmsett* boom catenary. The remaining 20% was caught by the *Vikoma* boom which was deployed behind the *Ohmsett* boom. After a period of 56 minutes, the oil was released from the *Ohmsett* boom into the *Vikoma* boom. However, the tow speed of the *Vikoma* boom had been increased to over 0.56 m/sec and oil began leaking from under the skirt, forming a 3mm thick slick behind. The towing speed was increased to 1,7 m/sec causing all the oil remaining in the catenary to be lost.

Both the *Ro-Boom* and *Vikoma* booms were deployed to contain the lost oil, and between 80 and 90% was recollected. At this point, the skimmers were deployed to recover the oil. The *HOS (Heavy Oil Skimmer)* was the first to be deployed and was observed to recover no measurable amount of oil. This was because the oil selected had low adhesive properties and therefore had difficulty sticking to the oleophilic discs of the skimmer. The second skimmer to be deployed was the *Framo ACW-400*, which was observed to recover 16 m³/hr. The manufacturer's maximum recovery rate is specified as 400 m³/hr.

During the tests, the support arms used to suspend both the *HOS* and *Framo ACW-400* skimmers had difficulty in keeping the skimmers at water level, causing them to be frequently submerged by the roll of the vessel and swell of the sea. This resulted in a high percentage of water being drawn in with the recovered oil.

As the weather was deteriorating and night was approaching, a visco - elastic agent called *Elastrol* was added to the oil. This increases the elastic and adhesive properties of oil, and is added to increase the oil recovery rate.

The Pharos Marine *G 185* was the third skimmer deployed and was observed to recover 23 m³/hr of oil emulsion with no free water. The pump operated at 60% of full speed. The *HOS* was redeployed on the treated slick and the recovery rate increased to 13,5 m³/hr. The test was suspended due to adverse weather conditions and failing light. A flight 18 hours later over the slick showed that it had almost disappeared and the remainder was rapidly dispersing [44].

The results of the recovery rate of the three skimmers were as follows :

Skimmer	Recovery Rate of Emulsion (m ³ /hr)	Oil Recovery Rate (m ³ /hr)
Framo <i>ACW-400</i>	22	14
<i>G 185</i>	19	9
<i>HOS</i>	11	4

Table 1.1. Recovery rate of skimmers - Newfoundland tests

It is impossible to directly compare these results as the Framo *ACW-400* was tested before *Elastrol* was added and the *G 185* after. *Elastrol*, which increases the viscosity of oil, would likely reduce the flow of oil over the weir of the *G 185*, reducing its

efficiency. The *HOS* skimmer which had damaged a drum during the tests, was tested on an unsuitable oil. The Framo *ACW-400* had difficulty in following the swell and frequently became submerged, causing a large percentage of water to be drawn in with the recovered oil [44].

Subsequently in Ottawa, Canada, during 1988, a series of tests were carried out on three offshore skimmers in a large wave basin having a length of 120m, a width of 60m and a depth 3m. The following skimmers were tested:

- (i) Framo *ACW-400*,
- (ii) *G 185*, and
- (iii) *Walosep W-2*.

Each skimmer was tested with each of the three following oils:

- (i) *IPL Sweet*; a conventional crude oil,
- (ii) *Terra Nova C-O9*; a waxy crude from Grand Banks, and
- (iii) *Bunker C* oil.

Each skimming test lasted between four to six hours, during which the recovered oil was recycled back into the basin to allow it to weather and emulsify to simulate real conditions. Part of each test was conducted in a simulated swell, which had a 4 second interval between crests and a wave height varying from 0,4m to 0,8m. Near the end of each test, *Elastol* was added to the oils to evaluate its affect on the recovery rate. The conclusions of the test were as follows [45]:

Framo ACW-400: The *ACW-400* recovered oils in the 0,01 - 0,3 Pa.s viscosity range at recovery rates of 30 - 50 m³/hr. As the viscosity was increased above 1 Pa.s, the recovery rates dropped to 5 - 10 m³/hr. Although the unit operated reliably throughout the trials and effectively in calm waters, the pitching action of the skimmer led to a high water content in the recovered oil which reduced its feasibility as an off-shore skimmer.

G 185: The *G 185* recovered oils and emulsion at a steady 25 - 30 m³/hr regardless of wave action or viscosity (in the range of 0,01 - 10 Pa.s). In general, the skimmer operated well and reliably during the tests and followed the waves well. The skimmer was fitted with adapter plates which adjusted the height of the weir to suit the oil being recovered. When high viscosity oil is being recovered, the adaptor plates are removed. However the tests concluded that the removal of these plates detracted from the skimmer's performance [45].

Walosep W-2: The *W-2* recovered a steady 14 - 16 m³/hr of emulsion in the 0,01 - 0,2 Pa.s range. When recovering very viscous oils (over 100 Pa.s), the recovery rate fell to 2 - 5 m³/hr. The skimmer was operated with a power pack which failed to deliver the required power, and therefore was not being operated to specification. The skimmer operated reliably and followed the waves well. On visual observation, the *W-2* rated the best for recovering gelled pieces of Grand Banks crude at colder temperatures.

With the addition of *Elastol* to the oil, the recovery rate of the *Walosep W-2* increased by 15 - 40%, while that of the *Framo ACW-400* remained unchanged, although the water-in-oil entrainment increased. The *G 185* recovery rate dropped by 25 - 35%, and

an increase of water-in-oil entrainment was noted. In addition, *Elastol* caused oil pumping difficulties and treated oil became more difficult to clean off the equipment [45].

1.1.7 Additional oil pollution combat equipment

Chocolate mousse emulsion breaker

A drawback to the recovery of emulsified oil is that less than half the quantity recovered is oil, with the remainder being water. By introducing an emulsion breaker to the recovered emulsion, the water component can be extracted, reducing the total quantity, and the recovered oil is then easier to dispose of. When a skimmer recovers an oil/water emulsion, a metering device introduces the correct dosage of emulsion breaker into the intake. The normal dosage is one litre of breaker to one ton of emulsion [10].

The Unitor oil bag

The Unitor bags, which have a capacity range of 10 - 1000 m³, can be used to collect oil from damaged tankers as shown in Figure 1.33, or to store oil recovered from an oil slick. The bags are reusable and have an inner plastic lining which is removed after use and disposed of. The bag is made of polymer-coated fabric, is 1,3mm thick and has a breaking strain of 1000kg. It is light and requires very little maintenance. Within minutes, the bag can be launched from a damaged tanker and oil can be transferred into it from a ruptured tank. In the event of a fire, the bag can be towed away. The bags can be airlifted to a casualty as shown in Figure 1.34 [46].

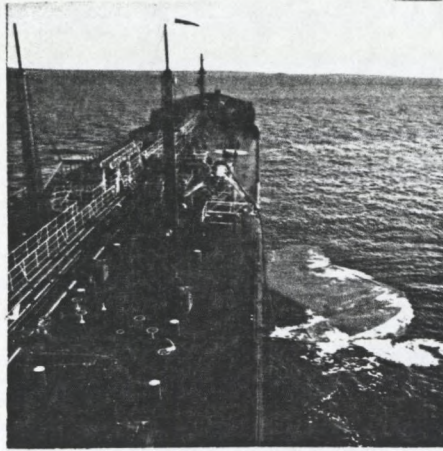


Figure 1.33. Oil pumped from a tanker into a Unitor oil bag

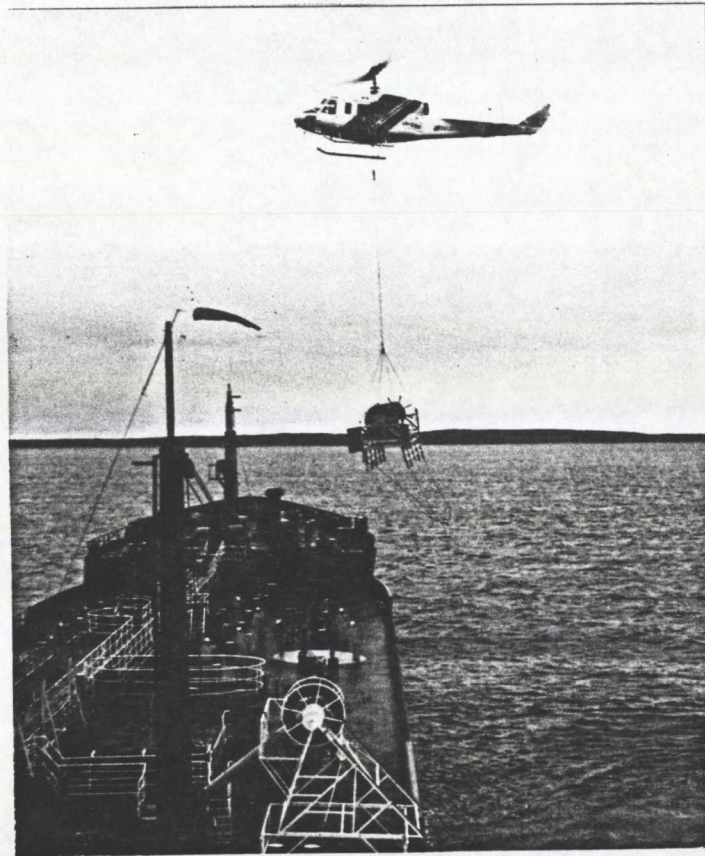


Figure 1.34. Oil bag being airlifted to a tanker

During skimming operations, the bag can be towed alongside or astern of a support vessel as shown in Figure 1.35. The bag automatically assumes a hydrodynamically efficient shape and a wave, which would normally toss a vessel upwards and resist its

passage, will pass through the bag. When full, the bags can be towed at 8 knots by a comparatively small vessel [46].



Figure 1.35. Unitor oil bag being towed behind a tug

Tankers are often required to be kept idle while on standby in many ports to offer storage for an oil cargo from any tanker in distress. The bags offer a very cost effective alternative in terms of purchase price, maintenance and storage to replace this service. The bags require little deck space and therefore can be conveniently carried by tankers. The bags can provide storage for oil spilt in inaccessible shorelines, and, due to a shallow draught, can be used to recover oil from marshes [46].

There are three types of bags [8, 45, 46]:

- (i) small bags which are airlifted to a spill by helicopter,
- (ii) bags which are carried as a permanent installation on a tanker with rapid launching facilities and a connection already made to the emergency manifold, and
- (iii) bags for skimmer usage which incorporate piping to allow for drainage of

water recovered with oil, after separation.

1.1.8 Summary of existing clean-up methods

Oil recovery craft and skimmers

Dual purpose craft have reduced the financial implications of oil spill combat preparation. Vessels with storage tanks for recovered oil such as dredgers or purpose built tugs can be fitted with sweep arms. However, in the event of a major spill, these vessels will be of limited use as they have a relatively small storage capacity. For example, the dredger *Noordsee* has a storage capacity of 5400m³, and the nett volume of oil recovered is considerably less as a high percentage of water is present in the oil/water mixture recovered by the sweep arms. Also, the conversion to oil recovery mode absorbs valuable response time. The *Lurring* twin hull vessels, which can be used as service vessels for a port, are also limited by storage capacity and cost [5].

The *OMI* pollution control vessels and *MPOSS* catamarans have some advantage in recovering oil with a low water content, but they are limited by sweep (5 and 12 metres respectively) and storage facilities [7].

Skimmers are seldom suitable for a wide range of oils of different viscosities. The performance of weir skimmers drops off when operating on high viscosity oils which experience difficulty in flowing over the weir; a problem which can be overcome by fitting rotor discs to the skimmer [12].

Rotor disc skimmers rely on the adhesion properties of oil which sticks to the discs as

they pass through a slick. Therefore, these skimmers are not suitable for recovering oil with low adhesion properties [8].

Oil recovered by oleophilic rope skimmers has a low water content as their ropes absorb oil and not water. The disadvantage with these skimmers is the low oil recovery rate.

The recovery performance of skimmers depends on the conditions at the spill site. For example, the *Framo ACW-400* skimmer is rated as having a maximum recovery rate of 400 m³/hr for a slick 0,2m thick. However slicks are typically much thinner. During field trials, the skimmer was observed to recover 3 - 50 m³/hr [20, 44, 45].

Booms

The maximum tow/current speed established independently at which oil can be retained by a boom without leakage is given as 0,5 m/sec for a boom angle of 45 degrees to the flow direction, irrespective of the skirt depth. At this speed, a large slick would take a very long time to clean up. For example, 6 hours after the *Exxon Valdez* had run aground, a slick 8000m by 300m had formed and was still spreading. It would take four and a half hours to complete a sweep across the length of the slick, by which time the slick would have spread further and begun to fragment, making the task more difficult [26].

Boom/skimmer combinations

Boom/skimmer combinations are the most suitable mechanical means for oil spill recovery as they have large skimming widths.

One combination called the *Fastflow* is claimed by the manufacturer Vikoma to operate up to a velocity of 3 m/sec. The Vikoma's *Weir Boom Rapide* has a skimming width of 300m and is claimed to operate at a velocity of 2 m/sec. No oil loss figures have been given at this velocity [34, 35].

Alternative methods

- (A) Dispersants: Dispersants are the most effective method of combatting oil pollution in countries such as Norway and Britain with craggy coastlines and which experience bad weather in winter. However dispersant themselves are toxic to the environment and they do not eliminate the toxic effect of oil. They can also effect sea life which normally would have escaped the effects of oil if it was left on the sea surface [38].
- (B) Straw and plant fibre: Straw and plant fibres are a cheap means to absorb oil off the sea surface. However, once on the surface, such straw/fibre needs to be recovered and disposed of. The *Exxon Valdez* slick would have required 2000 tons of straw to be scattered over the 8000 by 300m slick and thereafter collected. Such an undertaking would be impractical.
- (C) In-situ burning: Experiments are still being conducted with this method. However there has been no case where this method has proved successful. Burning also results in the atmosphere becoming polluted. After the strickened *Castillo de Bellver* caught fire off Saldanha, a large black cloud developed over the town of Riebeek Kasteel in the Swartland, which started to rain oil, causing environmental

damage to the area [43, 48].

1.1.9 Conclusions

Mechanical means, if the equipment can collect the oil in sufficient quantity, is the most environmentally friendly method to remove oil from the sea surface. This goal can best be achieved using a boom/skimmer combination built to meet the following requirements:

1. *Low cost.* Authorities are reluctant to outlay capital on equipment which will only be used in the event of a spill in their region.
2. *Rapid deployment time.* Quick response to oil spillage is of vital importance to prevent damage to the environment. Thus deployment of oil spill response equipment should be simple and quick. The equipment should be easily transportable.
3. *A wide skimming sweep.* The sweep should be sufficiently wide to enable enough water surface area to be swept by the craft, to reduce clean-up time.
4. *A high operational velocity.* The velocity should be higher than that of existing equipment, which is approximately 0.5 m/sec.
5. *Buoyancy.* The booms and skimmers should be extremely buoyant and have minimal inertia so that equipment will remain on the water surface at all times.

This is to prevent large amounts of water entering the skimmer in the event of it becoming submerged by the swell.

6. *Good oil/water separation.* The skimmer must prevent the mixing of oil and water during recovery. Therefore, the flow down booms and into the oil trap of the skimmer must occur without turbulence. High water contents with the recovered oil will add to the storage requirements and will require costly separation treatment.
7. *Pump versatility.* Skimmer pumps should pump a wide range of oils of different viscosities at the same rate at which the oil is being recovered.
8. *Sufficient oil storage facilities.* The recovered oil must be pumped to a storage facility of adequate size to deal with the spill.

1.2 Hydraulic modelling

1.2.1 Similarity

Partial solutions to determine the forces and power required to propel a waterborne craft at a required velocity can be obtained using dimensional analysis methods. The accuracy of these methods will depend on how many of the relevant factors which influence the craft's performance are utilised in formulating the equation. Models give a more accurate prediction and dimensional analysis is best used to equate model performances to that of full size prototypes. Models are scaled by using a similarity method [49].

There are three main methods of similarity which are:

(A) Geometric similarity

The model is geometrically similar to the full - scale prototype. A one - tenth scale model means each length is one tenth the size of the full scale prototype. However, the flow conditions for a model are unlikely to simulate those for a full scale prototype as the width of the boundary layer does not shrink by the scaled amount, and Reynold's Number is very unlikely to be equal [49].

(B) Kinematic similarity

This requires that the shape of the streamlines for the model and the prototype must be the same. Obviously the shape of the model (which governs the direction of flow) must be similar to the prototype, and thus geometric similarity is a prerequisite for kinematic similarity. However, this is insufficient to ensure kinematic similarity as forces, which govern flow direction, are not scaled adequately in a geometric model due to the presence of viscous forces and boundary layers which also are not scaled [49].

(C) Dynamic similarity

The basic requirement is that any forces acting on or within a model must be equal to the corresponding force ratio acting on the prototype. The forces acting on a body can be categorised as follows:

- (i) external forces which are the result of gravity, or pressure differences through a system,

- (ii) forces resulting from the movement of the fluid, such as viscous forces, surface tension,
- (iii) drag forces on the submerged surface of a body, and
- (iv) forces related to fluid motion such as inertia, or centrifugal forces.

All forces which act on a body must be reduced by the same proportion during a test on a model, and the sum of these forces must produce the same scaled resultant vector [49, 50].

1.2.2 Forces within a dynamically similar model system

The following forces act on a model during testing:

(A) Inertia force

Inertia force is the hypothetical force equal but opposite in direction to the force which causes motion of a body and is defined in terms of dimensional analysis as:

$$F_i \propto \rho L^3 v^3 \quad (2)$$

where ρ is the density of fluid, L is the characteristic length, and v is the velocity of the body.

Every force acting in a fluid system, which accelerates a fluid in a particular direction, must be opposed by an inertia force. For this reason, inertia force is commonly used in force ratios to define the particular requirements for dynamic similarity [49].

(B) Gravitational Forces

Waves, wakes of ships etc are dominated by the effects of gravity. In terms of dimensional analysis, gravity is defined as:

$$F_g \propto \rho L^3 g \quad (3)$$

where g is the acceleration of a body due to gravity.

Gravitational force is opposed by inertial force, and therefore the ratio of gravitational force/inertial force is used in dynamic similarity, and is defined as:

$$\frac{F_g}{F_i} \propto \frac{v^2}{L g} = \text{CONSTANT} \quad (4)$$

The square root of this ratio is known as the Froude Number [49]:

$$F = \frac{v}{(L g)^{1/2}} \quad (5)$$

The model and prototype should operate at the same number. The length used in this equation should be one which affects the flow, eg. the depth of a spillway or the length of a ship. In addition, the model and prototype should also be geometrically similar [49].

Froude Numbers are used to test hull designs. For example, the horizontal distance between two successive crests of the bow waves caused by a small craft should correspond to the distance between the bow and stern as shown in Figure 1.36(a). Should the former distance be greater resulting in the stern of the vessel lying in the trough between the waves, the vessel will squat by the stern, as shown

in Figure 1.36(b). Therefore, during model testing, the model should be operated at the same Froude Number as the planned vessel and it should be ensured that the bow wave formations are correct [49, 50].

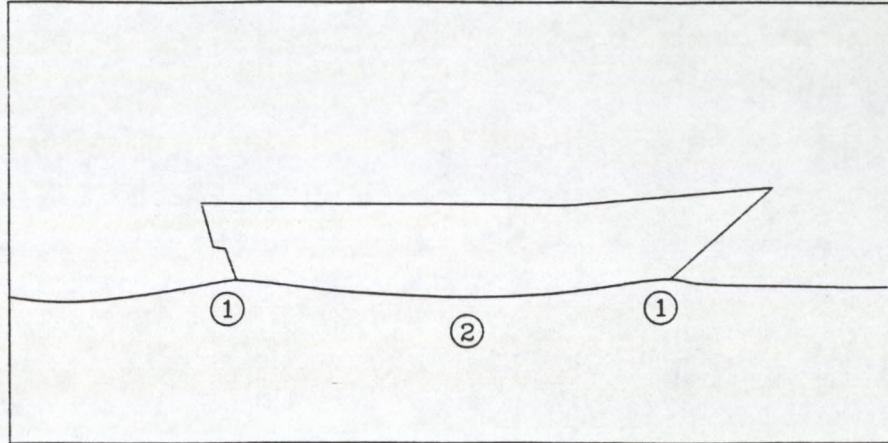


Figure 1.36(a) Correct position of trough, vessel on even keel.

- (1) wave crests at bow and stern
- (2) trough lying midships

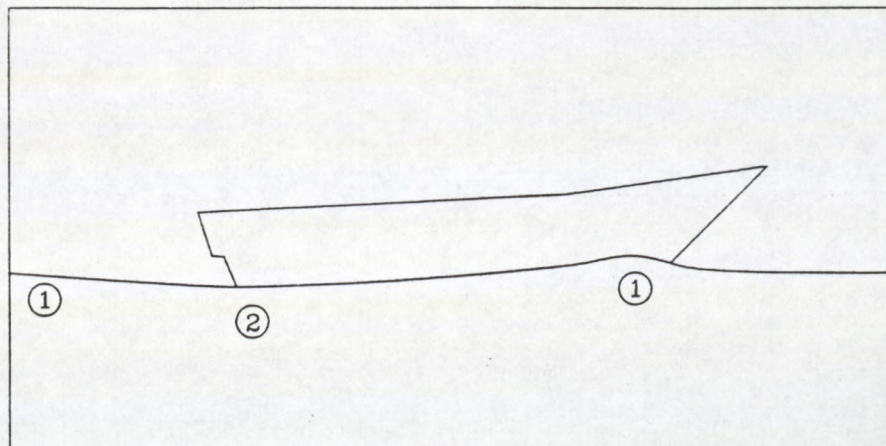


Figure 1.36 (b). Incorrect position of trough, vessel squats by stern

- (1) wave crests at bow and astern of vessel
- (2) trough lying at stern.

(C) **Viscous forces**

Viscous forces are related to the frictional drag forces as a fluid flows over the surface of a submerged body. Such forces are important when the flow is laminar (viz. streamline flow), when the viscous forces are strong relative to the inertial forces. Where there is the presence of a surface wave such as in the case of a partially submerged body (eg. a ship), the dynamic similarity equations should take gravitational effects into account [49].

The viscous force is derived as:

$$F_v \propto \mu \frac{v}{L} \quad (6)$$

where μ is dynamic viscosity.

The ratio of inertia forces/viscous forces is known as the Reynold's Number and is defined as:

$$\frac{F_i}{F_v} = \frac{\rho v L}{\mu} \quad (7)$$

(C) **Surface tension**

This is the study of the elastic or tensile force acting on the surface layer of a fluid. Surface tension can be defined as the force acting perpendicular to a line of unit length on the surface of a fluid. The ratio of inertial force/surface tension, known as the Weber Number, is defined as:

$$\frac{\rho v^2}{K} = \text{CONSTANT} \quad (8)$$

where K is the Bulk Modulus [49].

The effects of viscosity and surface tension on model flow become more significant as the scale selected for a model becomes smaller. Some studies have been conducted to determine the lower scale limit of models which can be selected before the flow becomes affected by factors such as viscosity and surface tension.

An experiment was conducted to determine the effects of surface tension on flow over a 90 degree "V" notch weir, a rectangular weir, and an ogee weir. An additive, which reduces surface tension by 60%, was added to the water and was found to vary the flow by only 4%. It was concluded that surface tension effects do not significantly influence the test results carried out on the flow around a model, with the exception of flow over a sharp edged weir with a depth of flow of 50mm or less [49].

The experiment further concluded that the lower scale limit is established by:

- (i) the roughness of the surface of the prototype which cannot be adequately scaled,
- (ii) viscosity of the fluid and the thickness of the boundary layer,
- (iii) accuracy of instrumentation available, and
- (iv) the accuracy at which the model can reproduce the prototype [49].

1.2.3 Scale errors

It is not possible for a model being tested at a certain speed to operate at the same Froude and Reynold's Number. For example, if a 1/100 geometrically scaled model is to be tested at the same Froude Number and in the same fluid medium as its prototype, the test velocity will equal 1/10 of the prototype velocity. However, if the model is to be tested at the same Reynold's Number as the prototype, the velocity will be equal to the inverse of the scale, which in this case will be 10 times the prototype speed. Therefore, separate tests will be required when testing for the effects of gravity and drag on a model [49].

For the given example, if the frictional drag test is to be carried out at a practical but lower model test speed, the numeric value of the Reynold's Number will have to be increased by changing the fluid medium of the test to one with an increased density and lower viscosity. The correct Reynold's Number can be selected through trial and error using different fluids. Alternatively, the drag component of a model can be calculated by using data collected from experiments measuring the drag forces on a plate similar to the wetted surface of the prototype [49].

The models should not be considerably smaller than the prototype as the flow conditions may change from turbulent to laminar. In this manner, forces, which may be neglected for a prototype, become relevant for a model.

If additional forces are considered, different scales are required to be used on the plane where their effects are dominant. It is therefore impractical to construct a geometrically

similar model with the aim of modelling a prototype in all respects. However, if the most dominant force affecting a system is used to scale a model, the other forces, which are left out, can be ignored and considered as scale errors [49].

1.2.4 The effect of a boundary layer on flow.

A boundary layer, which can be regarded as a drag layer, is present around the wetted surfaces of a channel or body. The boundary layer can also be regarded as a layer adjacent to the surface which has lost momentum energy which equals the frictional drag. The flow is held stationary on the wetted surface of the channel or body by the effect of friction and thereafter it increases to full stream velocity. The effects of viscous stresses, which are proportional to the velocity gradient and normal to the flow, are experienced within the layer. The ratio of boundary layer thickness to the size of object decreases as the size of the body increases. For example, the boundary layer thickness of a model is proportionally larger than that of the prototype. The thickness of the boundary layer around an object also decreases with an increase of Reynold's Number. The effects of viscosity and the shear stresses are considered important within the boundary layer if it is thin, and outside the layer the flow can be considered inviscid. Behind the body, the boundary layers merge to form a relatively slow moving body of water known as the wake [49, 50].

Initially, the flow in the boundary layer is laminar until a point past the leading edge where the flow changes to turbulent, when the Reynold's Number reaches a value of approximately 2000. This will take place over a relatively short distance when the body is immersed in water [49].

In the turbulent boundary layer, the rough mean direction of the flow is parallel to the surface with random fluctuations in velocity direction and magnitude; the latter being in the order of a tenth of the main stream velocity. The rapid fluctuations in velocity result in eddy shear stresses which are related to the mean velocity gradient and are much greater than viscous stresses [49].

1.2.5 Squat

Ship squat is the increase in draught (vertical distance between water line and keel) caused by the forward motion of a vessel. Theoretically, water passing under a vessel should cause a pressure drop in metres equal to the velocity head ($v^2/2g$), where v equals the velocity of the craft, causing it to submerge by that amount. However, as the velocity within the boundary layer adjacent to the surface of a craft is considered to be equal to 10% of the actual velocity, this pressure drop is considerably reduced [51].

The effects of squat on a vessels increases when it sails into shallow waters where the resultant velocity under the keel is greater than its speed. Vessels have been reported to squat up to 2 metres before they run aground. The *Queen Elizabeth II*, while entering New York in August 1992, sailed over an uncharted reef and the resulting squat caused it to run aground [51].

1.3 Theory of open channel flow

Fluids like water, may flow through closed sections, like pipes or open channels. Both flow types have similarities in many respects, but open channel flow has a free surface which is subjected to atmospheric pressure. The flow on the free surface has various

characteristic which must be considered [52].

In the majority of cases, flow in channels is classified as an unsteady varied flow where the depth of flow fluctuates. This can occur rapidly or gradually. Flow in open channels is very rarely laminar [52].

1.3.1 Subcritical and supercritical flow

Depending on the Froude Number, flow in an open channel can be either supercritical or subcritical. At transition from subcritical to supercritical, the Froude Number is equal to unity and equation (5) can be expressed as:

$$v = (gD)^{1/2} \quad (9)$$

where depth D is the characteristic length.

If the Froude Number is less than unity, the flow is subcritical. In this state, the gravity forces are more pronounced, so the flow has a low velocity and is described as tranquil and in streamlines. If the Froude number is greater than unity, the flow is supercritical. In this state, the inertial forces become dominant and the flow can be described as rapid or torrential [52].

The flow in the super critical range is usually turbulent, but it is possible to have a condition where the flow is both supercritical and laminar. This condition is very rare and it will not be covered here [52].

As the flow in most channels is controlled by gravity, the Froude Number is dominant, and therefore the tests carried out on a model should be run at the same Froude Number as that of the prototype. For Froude Numbers of less than 3, the effect of friction can be regarded as negligible. Studies have indicated that an increase in the Froude Number results in an increase of the friction factor for open channel flow [52].

1.3.2 Channel geometry

There are various geometric elements which are relevant to calculations regarding open channel flow. They are as follows:

(A) Depth of flow (y)

The depth of flow is given as the vertical distance from the free surface to the lowest point of the channel section. This is different from the depth of flow section (D) which is the depth of flow normal to the direction of flow. For example, if the channel has a slope of 5 degrees:

$$y = \frac{D}{\cos(5^\circ)} \quad (10)$$

(B) Hydraulic radius (R)

This is the ratio of the cross-sectional area of flow (A) to wetted perimeter of the flow area (P):

$$R = \frac{A}{P} \quad (11)$$

(C) Hydraulic depth (D)

This is the ratio of water area to top width (T):

$$D = \frac{A}{T} \quad (12)$$

(D) Section factor for critical-flow computations (Z)

This is defined as [52]:

$$Z = A D^{\frac{3}{2}} = A \left(\frac{A}{T} \right)^{\frac{3}{2}} \quad (13)$$

1.3.3 Velocity distribution in channel section

Due to the effects of frictional drag of the channel sides and a free surface, the velocity of flow in a channel section is not uniform. The maximum velocity appears to occur at a depth of between 0,05 and 0,25 below the free surface, and this depth increases towards the sides [52].

The velocity distribution within a channel will also depend on other factors such as the roughness of the channel and the presence of bends. A disturbance at the entrance to a channel which is usually unavoidable will cause a small and insignificant spiral motion through the cross section of the channel flow. This action can be ignored.

The presence of a wind blowing over the water surface has little effect on the flow. The surface layer, on which an oil layer would float, is blown in the direction of the wind at 3% of its velocity [51, 52].

1.4 Energy and momentum principles

A variation of Bernoulli's theorem can be applied to open channel flow when determining the hydraulic energy contained by a moving body of water. This energy can be expressed as a pressure head of water in metres. The height of the channel bottom above a datum line used as a reference determines the potential energy (z), the depth of water above the channel bottom represents pressure energy of flow (y), and the velocity head ($v^2/2g$) represents the kinetic energy of the flow. The head loss (H_f) represents energy loss to friction, and is accounted for by a loss of potential energy. If there is a change in the depth of flow, eg. a decrease, there must be a corresponding increase in velocity, and therefore velocity head ($v^2/2g$). As shown in Figure 1.37, the total energy head upstream equals the total energy head downstream plus the head loss (h_f).

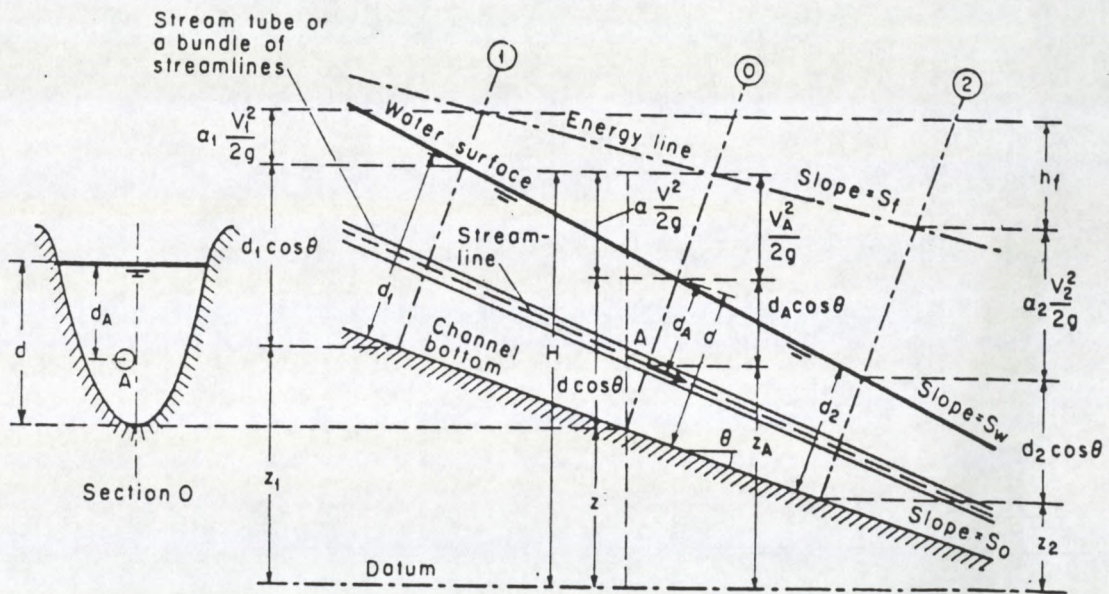


Figure 1.37. Energy in gradually varied open channel flow

The energy equation for channel flow can be expressed as follows:

$$z_1 + y_1 + \sigma \frac{v_1^2}{2g} = z_2 + y_2 + \sigma \frac{v_2^2}{2g} + h_f \quad (14)$$

where σ is the energy coefficient which is used to correct for uneven velocity head distribution within the flow [50].

1.4.1 Specific energy

Specific energy (E) is defined as the energy per square metre of water at any section of the channel measured with respect to the channel bottom. With $z = 0$, the energy equation becomes:

$$E = y + \sigma \frac{v^2}{2g} \quad (15)$$

From equation (15), the specific energy curve, as shown in Figure 1.38, can be plotted. The graph represents the depth of flow of a given channel on the vertical axis, with respect to the specific energy of flow on the horizontal axis. Point C represents the critical state of flow which corresponds to the minimum value of specific energy. For all other values of specific energy, the water depth has two values, the high stage (y_2') and low stage (y_1). The high stage, which is the greater depth, lies within the subcritical flow range, and the low stage lies within the supercritical flow range. As seen from the supercritical flow range on the curve, a decrease in depth corresponds to an increase in velocity head, resulting in an increase in specific energy. In the subcritical flow range, a decrease in velocity corresponds to an increase in depth and an increase in specific energy [51, 52].

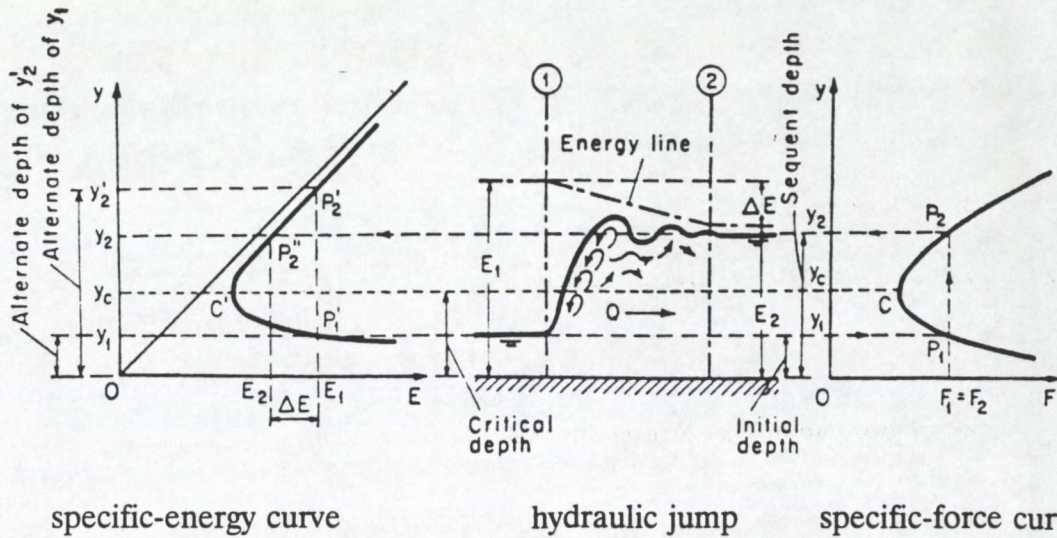


Figure 1.38. Hydraulic jump interpreted by specific energy and specific force

At the point of the critical state of flow, where the specific energy is at a minimum ($dE/dy = 0$), the equation for specific energy is given as:

$$\frac{v^2}{2g} = \frac{D}{2} \cos(\theta) \quad (16)$$

where θ is the slope of the channel.

This is the criterion for critical flow, which states that at the critical state, the velocity head equals half the hydraulic depth. The above equation can also be written as:

$$\frac{v}{(gL)^{1/2}} = 1 \quad (17)$$

1.4.2 Hydraulic jump

Hydraulic jump occurs in a waterway where fast moving water (Froude Number > 1)

enters a slow moving body of water (Froude Number < 1) over a relatively short distance. Hydraulic jump, as shown in Figure 1.38, is the disturbance caused at the point where the state of flow changes from supercritical to subcritical, resulting in an abrupt change in depth. Hydraulic jump can be seen at the bottom of spillways or where a cascade enters a pond [52, 53].

Hydraulic jump causes a large amount of energy to be lost through turbulence in creating the jump and therefore specific energy after a jump is less than before. Thus, the depth of flow after the jump is less than the high stage depth (y_2') and is referred to as the sequent depth (y_2). The specific energy (E_2) at the sequent depth is less than that at the low stage by an amount (ΔE), which equals the energy lost due to turbulence in the jump [52, 53].

1.4.3 Momentum in open-channel flow

The momentum of the flow passing a channel section per unit time is expressed by:

$$\frac{w Q v}{g} \quad (18)$$

where w equals the specific weight of the water ($\text{kg/m}^2 \text{ s}^2$), Q is discharge (m^3/s) and v is the mean velocity of flow (m/s) [52].

According to Newton's second law of motion, the change in momentum per unit time of a body in a flowing channel is equal to the resultant of all external forces acting on the body. By applying this principle to a channel with a large slope, the momentum

equation for the momentum change per unit time in the body of water enclosed between sections 1 and 2 shown in Figure 1.37 may be written as:

$$\frac{Q w_{sec}}{g} (v_2 - v_1) = P_1 - P_2 + (W \sin \theta) - F_f \quad (19)$$

where P_1, P_2 are the resultant pressure forces acting on the two sections, w_{sec} is the weight of water enclosed by the two sections, and F_f is the total external frictional force acting on the surface of the channel. In equation (19), P_1 and P_2 are assumed to be a hydrostatic distribution of pressure. [52, 53]

If we assume the reach to be very short, the external frictional forces and the weight effect of the water can be ignored. The momentum equation can then be expressed as:

$$F_s = \frac{Q^2}{g A} + z A \quad (20)$$

where F_s is the specific force/specific weight.

The function has two expressions. The first represents the momentum of the flow passing through the channel per unit time per unit weight of water, and the second is the force per unit weight of water. Assuming that the external forces and weight effect of the water between the two sections in the reach can be ignored, the specific forces at these sections are equal [52].

The specific-force curve can be plotted and compared with the specific-energy curve as shown in Figure 1.39. Both curves plot the two possible depths, which is dependant on whether the flow is supercritical or subcritical, for any given value of specific

energy/force. The exception to this is when the flow is at its critical depth, which corresponds to the minimum value of specific energy/force at the point where the supercritical and subcritical curves meet. The curves differ, in that, during transition from supercritical to subcritical, the specific force remains constant whereas the specific energy is reduced due to turbulence. Therefore specific force of flow at initial depth equals that at its sequent depth [52].

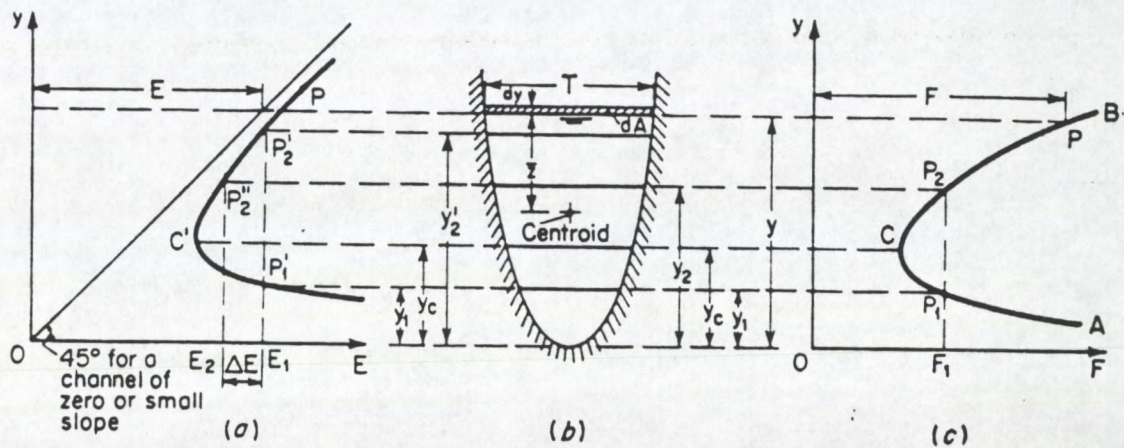


Figure 1.39. (a) specific - energy curve
 (b) channel - section
 (c) specific - force curve

Previously, it was assumed that external forces of friction and the weight effect of the water in the hydraulic jump are negligible because the jump takes place over a short distance, and thus the specific forces of the water at sections y_1 and y_2 can be considered equal. Therefore:

$$\frac{Q^2}{g A_1} + z_1 A_1 = \frac{Q^2}{g A_2} + z_2 A_2 \quad (21)$$

For a rectangular channel of width b :

$$Q = v_1 A_1 = v_2 A_2 \quad (22)$$

$$z_1 = \frac{y_1}{2} ; z_2 = \frac{y_2}{2} \quad (23)$$

$$F_1 = \frac{v_1}{(g y_1)^{1/2}} \quad (24)$$

Substituting equations (22), (23) and (24) into equation (21):

$$\left(\frac{y_2}{y_1}\right)^3 - (2F_1^2 + 1)\left(\frac{y_2}{y_1}\right) + 2F_1^2 = 0 \quad (25)$$

$$\left(\frac{y_2}{y_1}\right)^2 + \frac{y_2}{y_1} - 2F_1^2 = 0 \quad (26)$$

$$\left(\frac{y_2}{y_1}\right)^2 + \frac{y_2}{y_1} - 2F_1^2 = 0 \quad (27)$$

The solution to this quadratic equation is:

$$\frac{y_2}{y_1} = 0, 5[(1 + 8F_1^2)^{1/2} - 1] \quad (28)$$

It should be noted that the specific energy equation cannot be used to determine the ratio y_2/y_1 , as energy, which cannot be evaluated, is lost in the hydraulic jump [52].

1.4.4 Gradually varied flow

Gradually varied flow (G.V.F.) is when the depth of flow and hence velocity of flow vary along the length of the channel. The flow is considered to be steady, or the hydraulic characteristics of the flow remain constant, over the section under consideration. The following assumptions are made regarding the state of flow [52]:

- (i) the head loss for the given section is the same for uniform flow,
- (ii) the channel section is of constant alignment,

- (iii) the velocity distribution in the channel section is fixed, therefore the velocity-distribution coefficients at different points down the section are constant, and
- (iv) the roughness coefficient is independent of depth and constant throughout the section under consideration.

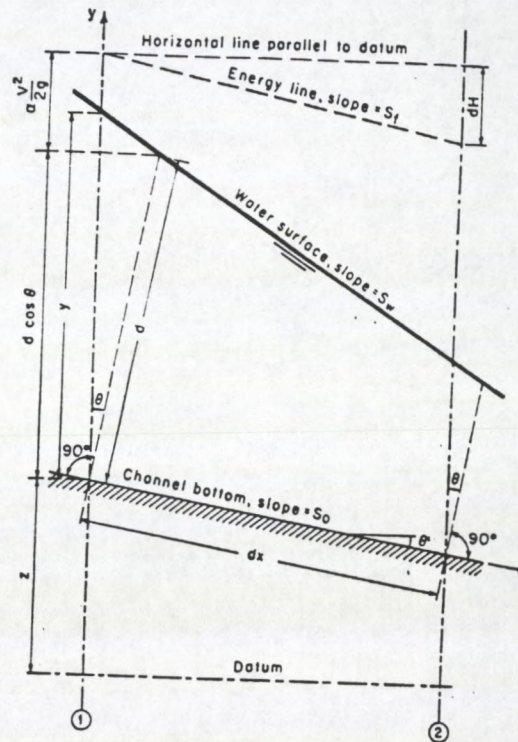


Figure 1.40. Derivation of the gradually-varied flow equation

Shown in Figure 1.40 is a section of channel where the depth of flow decreases down channel. Three slopes are evident:

- (i) the slope of the channel $S_o = \sin \theta$ where θ is the slope angle,
- (ii) the energy line slope S_f for a small section of channel, where the flow can be considered uniform. The energy line slope can be derived from the Manning formula where:

$$v = \frac{1}{n} R i \quad (29)$$

where v is velocity of flow, n is Manning's roughness coefficient, R is the hydraulic radius, and I is the slope gradient of channel for uniform flow. The gradients of the channel slope and the energy slope line are equal for uniform flow. Thus the change in potential height represents the required energy to overcome friction and therefore represents head loss. Thus [52]:

$$S_f = v R^{-1} n \quad (30)$$

(iii) The water surface slope S_w [52].

1.4.5 The direct step method

To determine the profile of the water surface flow in a G.V.F. channel, the length of the channel can be divided up into short reaches as shown in Figure 1.41, over which the depth varies. By assuming the head loss to be constant over a short reach, a profile of the water surface can be determined.

By equating the two heads at the end of the section 1 and 2, the following equation can be derived:

$$S_o \Delta x + y_1 + \delta \frac{v_1^2}{2g} = y_2 + \delta \frac{v_2^2}{2g} + S_f \Delta x \quad (31)$$

Solving for Δx :

$$\Delta x = \frac{E_1 - E_2}{S_o - S_f} \quad (32)$$

where E is the specific energy and Δx represents the horizontal length of the short reach in question [52].

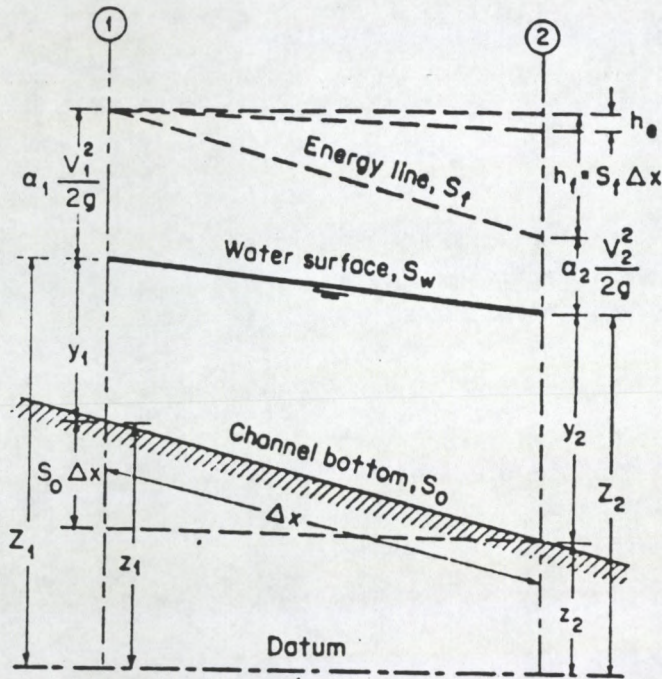


Figure 1.41. A channel reach for the derivation of the direct step method

By assuming a small change of depth, the horizontal length of the short reach Δx over which the depth change occurs can be calculated from equation (32). By continuing to assume different depths down the length of the reach, a table can be compiled of assumed depths and the total horizontal distance from the start of the reach at which each depth is positioned. Using this table, the water surface profile of the flow down the reach can be plotted. The computation of the profile is as follows:

Given: Flow (Q),
Mannings roughness coefficient (n),
Channel slope S_o ,
Energy coefficient σ , and
Width w and initial depth y_1 and area of flow A .

- (i) assume Δx and calculate new depth y_2 at point 2
- (ii) calculate new area A_2 and hydraulic radius R_2
- (iii) calculate v_2 and velocity head $v_2^2/2g$
- (iv) calculate specific energy E_2 and change in specific energy over short reach $\Delta E = E_2 - E_1$
- (v) calculate, using equation (30), the friction head loss H_{f2} at point 2
= energy slope line S_{f2} at point 2
- (vi) calculate mean friction head loss between points 1 and 2:

$$H_{f \text{ mean } 1-2} = \frac{S_{f1} + S_{f2}}{2} \quad (33)$$

- (vii) Calculate:

$$\Delta x = \frac{E_1 - E_2}{S_o - S_f} \quad (32)$$

Note: $S_{f1} = 0$.

- (viii) Total distance from start of reach $x_2 = \Delta x + x_1$. Note $x_1 = 0$.
- (ix) Assume next depth y_3 and repeat steps (i) - (viii). All numeric subscripts increase by 1 [52].

Chapter 2: Development and Testing of Prototypes

2.0 Introduction

This section deals with the design and development of an oil reclaimer which has to operate in moderate sea conditions and which will be more effective than existing equipment. The oil reclaimer was developed to meet the requirements for an effective oil recovery craft described previously. The prototypes were initially developed from models and thereafter a prototype, based on the design of the final successful model, was constructed and tested. The requirements to be met were:

- (i) the craft is to operate in moderate sea conditions (mean wave height of 1,0m),
- (ii) the craft should be of a simple fibreglass construction to ensure:
 - (a) low cost,
 - (b) fast deployment time,
 - (c) a buoyant craft - fibreglass has a similar relative density to water,
- (iii) the craft should operate at 1,2m/sec. (Note that most conventional booms operate at approximately 0,5m/sec),
- (iv) the craft will consist of a long boom to obtain a wide skimming area, and the booms must be flexible in order to ride the swell,
- (v) the method must direct the surface layer containing oil toward the recovery area without causing turbulence which will cause the oil and water to mix. This will prevent oil being recovered with a high water content, and
- (vi) the recovered oil should be pumped either to a shore installation, a support vessel or a Unitor Oil bag and not to on-board tanks. This is done

to avoid an increase in the craft inertia and thus adversely effect its buoyancy. In addition, recovery will not be limited by tank size as the bags or support vessel can be changed when full.

The development and testing of the booms and skimmer are handled separately.

2.1. Development and testing of boom models and prototypes

2.1.1. Objective

The objective is to develop a pair of booms which are held at an angle of 45 degrees to the flow. The inertia of the flow will divert the surface layer to the apex of the boom where the skimmer is to be positioned. The primary aim is to develop the booms such that they operate at a velocity of 1,2 m/sec without allowing oil leakage under the skirt or turbulence to be created.

The booms were developed from model tests carried out in a tank situated in the Fluids Laboratory at Technikon Natal, and thereafter a prototype based on the final successful model was constructed and tested. The tank is described in Annexure A.

2.1.2 Modelling

Scale

A scale of 22 : 1 was selected for the test channel to simulate moderate sea conditions having a mean wave height of 1,1m (refer to Annexure A).

Testing oil

Sunflower (Sun) oil was selected to simulate crude oil due to its availability. Vegetable oils, with the exception of Soya oil, have very similar viscosities. Sun oil has a density 920,7 kg/m³ and a viscosity 33,31 Centistokes at 37 degrees Celsius [54].

For a scale and maximum test speed of 22:1 and 0,5 m/sec respectively, the Reynold's Number of the test will equal:

$$\begin{aligned} \frac{L \cdot v}{\nu} &= \frac{1/22 \cdot 0,5}{33,31 \times 10^{-6}} \\ &= 682 \end{aligned}$$

where the kinematic viscosity (ν) = μ/ρ .

This simulates the Venezuelan crude oil *Pilow* with a viscosity of 1800 centistokes at 37 degrees Celsius [55].

The Reynold's Number for a full scale prototype at velocity of 1,2 m/sec will equal 667. Sun oil therefore, flowing through a 22:1 scale geometrically similar model simulates *Pilow* crude oil flowing through a full scale prototype.

Transposing of test results

The models were subjected to both frictional resistance (Reynold's Number) and to the effects of gravity (Froude Number). Frictional resistance is important when determining the power required to sail a craft, and the flow within the boundary layer.

The forces of gravity will effect the bow waves and waves caused by the passage of the model through water within the trap, and therefore this effect was considered prominent over the other dynamic forces effecting the model. Thus the test speed at which a particular percentage of oil was recovered from the tank was transposed to full scale speed using the Froude Number.

The effect of surface tension was considered negligible (see Section 1.2.2) and therefore was included in the scale error.

2.1.3 Methods of testing

The development of the boom was initiated with the testing of models in the test tank. For the initial boom tests, the effectiveness of the booms was determined by visual observation. The presence of turbulence or unsteady flow on the water surface in the trap would indicate the possibility of leakage. Thus a prerequisite for a successful model was a surface within the oil trap which lacked turbulence or signs of eddies. The direction of flow at any particular location within the trap was determined by holding a length of cotton in the flow.

In order to test the recovery potential of a model, a measured amount of sun oil was poured into the tank, ahead of the configuration which recovered the oil. The recovered amount was measured and the results transposed using the Froude Number to predict the full scale recovery potential.

In all tank tests, the booms were held stationary in the test channel by a harness, and the

flow initiated through it by the water wheel described in Annexure A. This simulates the conditions of the boom drawn through the water. During all boom tests, the harness held the booms at an angle of 45 degrees to the direction of flow. All model tests were run at five different speeds, viz. 0,2, 0,3, 0,4, 0,5 and 0,6 m/sec.

Before the development of the booms began, an initial test was conducted on a conventional boom configuration in order to determine flow pattern characteristics.

2.1.4 Initial observations - conventional boom test

In the literature (Section 1.1.3), the speed at which a boom can be drawn through the water before oil escapes under the skirt is given as 0,5 m/sec for a boom angle of 45 degrees. This is irrespective of the depth of skirt.

The first test was carried out on a conventional rigid boom shown in Figure 2.1 to observe the flow and determine the causes of oil loss. Provisions were made to alter the depth of the skirt. The velocity of flow was gradually increased from 0,25 m/sec to 0,76 m/sec. The model simulated conditions where a floating boom is held by anchors in a current.

As shown in Figure 2.1, the flow was observed to separate into layers of different velocities before passing under the skirt. The upper flow layer lost velocity as it reached the boom, resulting in an increase of pressure. The lower flow layer passed under the skirt of the boom, and a pressure difference was created between the foot of the boom and the water surface ahead of the boom, which induces flow down the face of the boom.

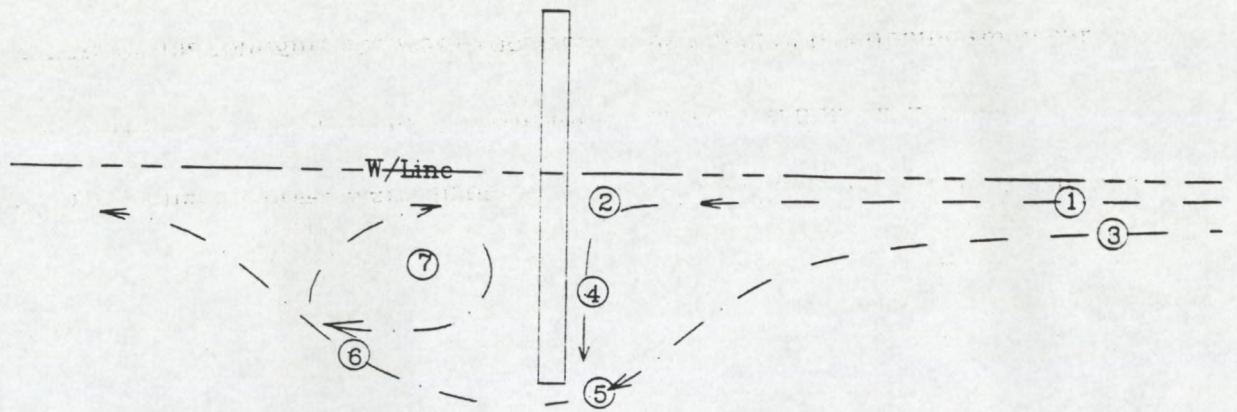


Figure 2.1. Oil flow pattern around boom

1. upper flow layer
2. flow loses velocity ahead of boom-static pressure rises
3. lower flow layer
4. flow down face of boom
5. low pressure at foot of boom
6. flow behind boom
7. eddies in lee of boom

This flow increased in magnitude as the velocity of the current under the boom was increased. From these observations it was assumed that when the current increased to over 0,5 m/sec, the flow down the face of the boom increases such that it becomes strong enough to overcome the buoyancy force keeping the oil on the surface and thus draws it under the skirt.

The flow passed under the skirt of the boom and resurfaced a substantial distance past it. Eddie currents were observed immediately behind the boom, and it was assumed that these eddies peel off from the flow under the skirt and come to rest behind the boom.

In this manner, some of the oil escaping under the boom is retained behind it.

The presence of waves which rebounded off the skirt against the direction of flow were also observed. These waves vanish after rebounding some distance ahead of the boom. Tests were run at four different skirt depths, viz. 15, 35, 75 and 100 mm. The distance ahead of the boom at which the rebounding wave disappeared was measured and plotted in Figure 2.2. It was noted that this distance reached a maximum for all different skirt depths when the flow velocity reached 0,45 m/sec, and thereafter rapidly reduced to a narrow strip ahead of the boom. The flow within this narrow strip was observed to be vertically down the boom face. However, in order to develop a relationship between the depth of the boom and the distance ahead of it at which the rebounding wave disappears, it will be necessary to undertake more comprehensive tests, which is unnecessary here.

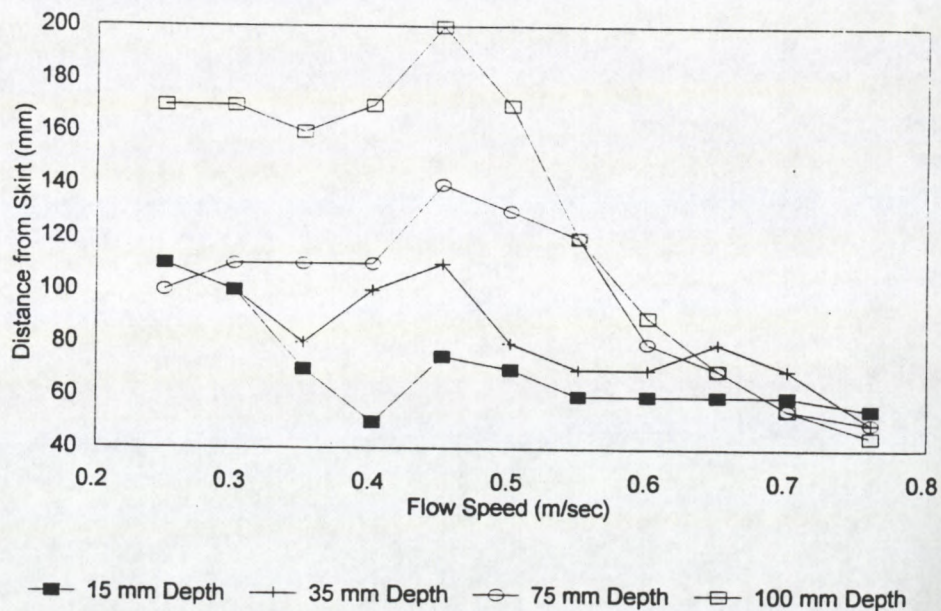


Figure 2.2. Re-bounding waves off skirt: distance from skirt vs speed

In conclusion, this test gave an understanding of the flow characteristics around a conventional boom. When a boom is drawn through the water at velocities of below 0,5 m/sec, a wide band is formed ahead of the boom which retains the oil. When the velocity is increased to over 0,5 m/sec, this band narrows to a thin strip with a high velocity down the face of the boom. It is this current that is responsible for oil leakage.

Booms designed to retain oil at velocities in excess of 0,5 m/sec must speed up the surface layer containing the oil to match the speed at which it is being towed through the water. In addition, they should incorporate an oil trap located ahead of the boom which prevents the formation of the vertical flow down the boom face responsible for oil leakage. Also, the booms must allow the retained oil to remain floating on the surface while allowing any excess water, drawn into the trap with the oil, to exit without allowing oil to escape.

2.2 The design, construction and testing of model boom configurations

This sections deals with the development of the boom configuration. Descriptions of boom designs No 1 - 3, which were unsuccessful, have been placed in Annexure D. Detailed drawings of all the booms and prototypes can also be found in Annexure D.

2.2.1 Boom design No 4

Boom design No 4 incorporated a shrouded trap to recover the surface flow layer containing oil. The oil layer was deflected by deflector floats into the trap where it would remain on the surface while water, recovered with the oil layer, separated and exited the trap through the water drains cut in the trap bottom.

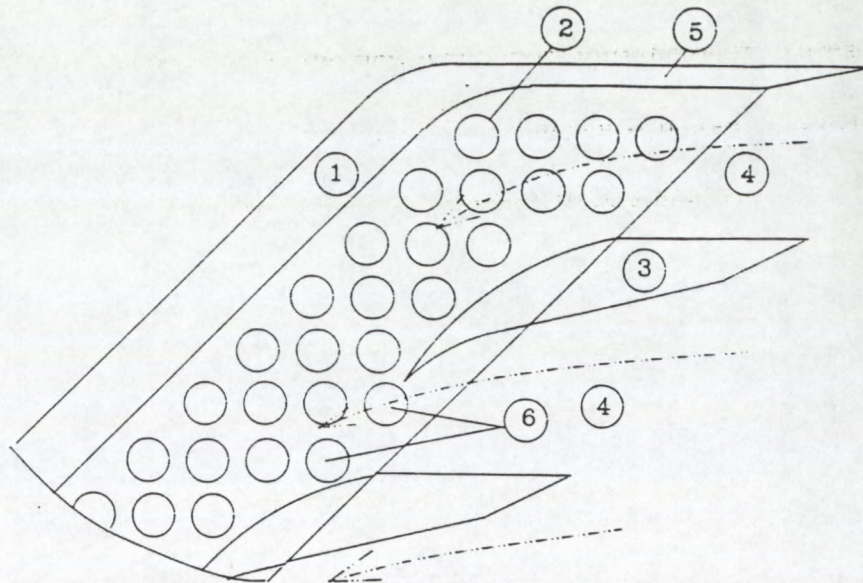


Figure 2.3. Principle of operation of boom design No 4 (top view)

1. rear float
2. oil Trap
3. front deflector float
4. trap entry
5. end float
6. water drain holes

The boom was held at an angle of 45 degrees to the flow direction in the test channel as shown in Figure 2.4. During the recovery process, the surface layer containing oil must enter the boom through the trap entry without shock to minimise the mixing of oil and water. The trap entry consisted of passages cut through the leading face of the boom, the lower lip of which must be positioned close to the oil/water interface to prevent a large percentage of water being recovered.

The front floats act as deflectors to divert the flow through the trap entry. The leading

face of the spear-shaped floats lay parallel to the flow while the lagging face deflected the flow through the trap entry. The floats extended into the trap and were curved in such a manner as to deflect the incoming flow in line with the trap flow. The rear float ran down the length of rear face of the boom, tapering up to the water surface to prevent drag and turbulence behind the boom. The total combined area of drain holes were increased by 50% above that calculated for boom design No 3, giving a total area of $0,00345\text{m}^2$ over a length of $0,2\text{m}$. The leading side of the boom was sealed to prevent flow out through that side. All floats were made from polystyrene and the trap from rigid plastic sheet.

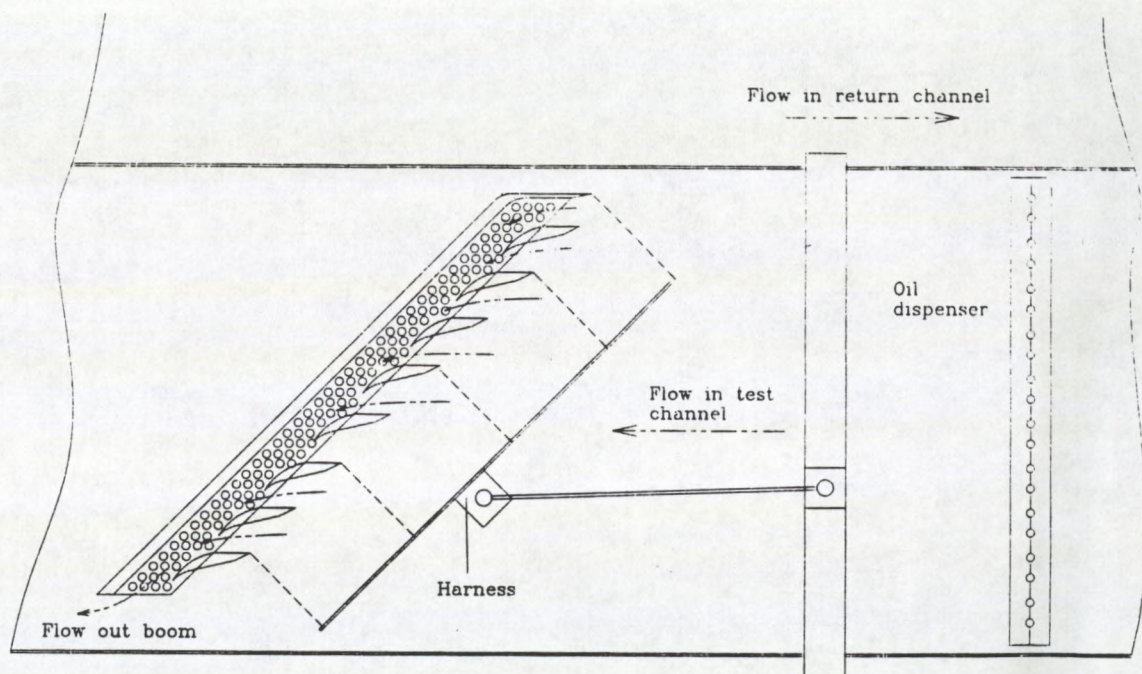


Figure 2.4. Layout of boom design No 4 in test channel

When the boom was tested at low flow rates, the flow into the trap was noted to be satisfactory. However at high flow rates the trap became flooded and was submerged by the flow. It was concluded that the trap must be re-designed to accommodate the drainage of the separated water to prevent flooding. The re-designed boom would only consist of the front and rear floats, and therefore would not have an enclosed trap.

2.2.2 Boom design No 5

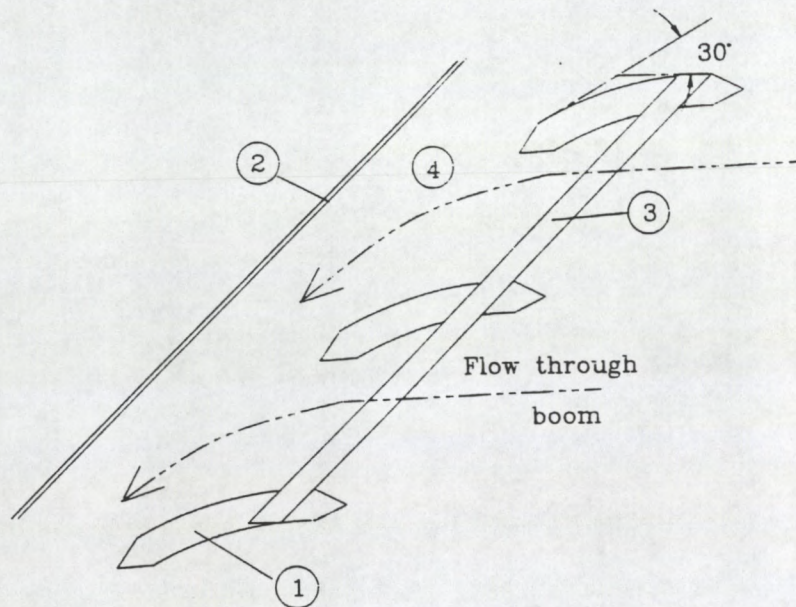


Figure 2.5. Principle of boom design No 5

1. deflector floats
2. rear boom
3. bracket
4. oil trap

The purpose of this configuration was to determine the effect of positioning small curved deflectors ahead of a boom. This configuration was held rigidly in place in the test channel. The deflector floats were made from 0,5mm mild steel sheet with polystyrene glued in place. The ends of the floats were pointed to deflect the flow down the sides of the floats. The boom consisted of a flat 2mm steel sheet which was held rigidly in place at 45 degrees to the direction of flow by a bracket attached to the sides of the test channel.

It was anticipated that the curved floats would deflect the flow through 30 degrees before passing into the oil trap, which had no bottom. The boom at the rear of the trap would deflect the flow a further 15 degrees to align it with the trap flow. The surface layer containing oil would remain on the surface of the trap, while the excess water, once separated from the oil, would escape under the boom.

The presence of the floats would shroud the trap from the incoming flow, and would reduce the force on the boom by deflecting the flow through 30 degrees. Thus it was anticipated that the current down the face of the boom and the accompanying oil leakage would be prevented.

The line of floats did not run parallel with the leading face of the boom, but tapered out at an angle of 4 degrees, thereby increasing the surface area of the trap. This was to accommodate the additional oil entering the trap down the length of the boom.

During testing, no current down the face of the boom was observed. However, as the velocity of flow was increased, turbulence was observed down the wetted surface of the sides of the floats, as shown in Figure 2.6.

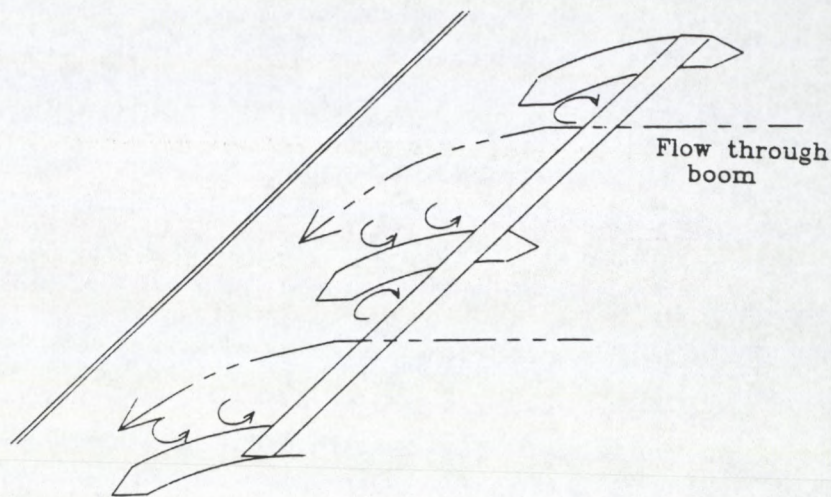


Figure 2.6. Turbulence observed in flow through boom design No 5

It was concluded that the presence of curved surfaces on the deflector floats should be avoided. Thus the deflector floats should be triangular with flat sides.

2.2.3 Boom design No 6

This configuration consisted of a line of five triangular deflector floats positioned ahead of a boom. The floats and the boom were constructed from polystyrene. The floats were held in line by a mild steel bracket. The boom was connected to the line of floats by stays made from fishing line. Stays were also used to attach the line of floats to the harness, which was bolted to the side of the test channel. The boom configuration floated independently.

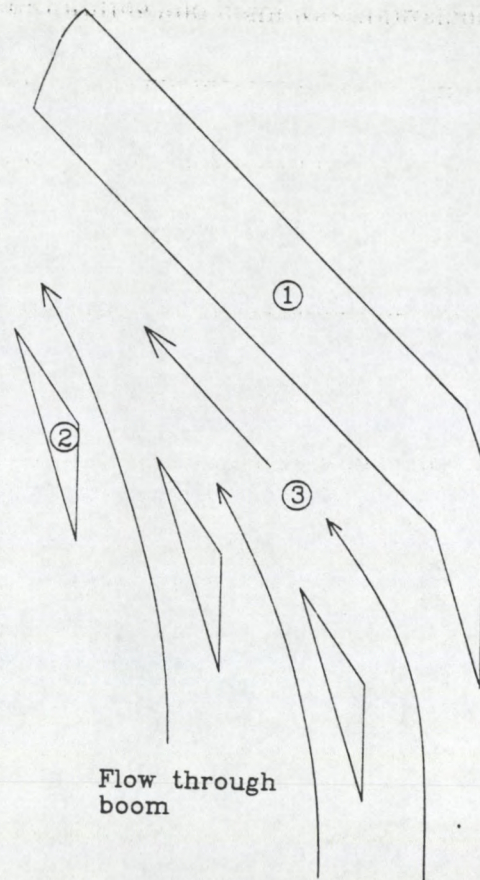


Figure 2.7. Flow through boom design No 6

1. boom
2. deflector floats
3. oil trap

The base angles of the deflector floats were 17,5 degrees each. The leading side of the float was positioned parallel to the flow, and therefore the base side was held at an angle of 17,5 degrees to the flow. The third side (the after-part of the deflector float) was held at 35 degrees to the direction of flow. It was anticipated that the surface layers of flow, after making contact with the line of floats, would pass between them and be initially deflected through 17,5 degrees by the base side of the floats. Thereafter, it would be deflected through a further 17,5 degrees by the third side of the adjacent float to give

a total deflection of 35 degrees. Next the flow would pass into the oil trap area which lay between the line of floats and the boom. The boom, which was held at 45 degrees to the flow, would deflect the surface flow through a further 10 degrees.

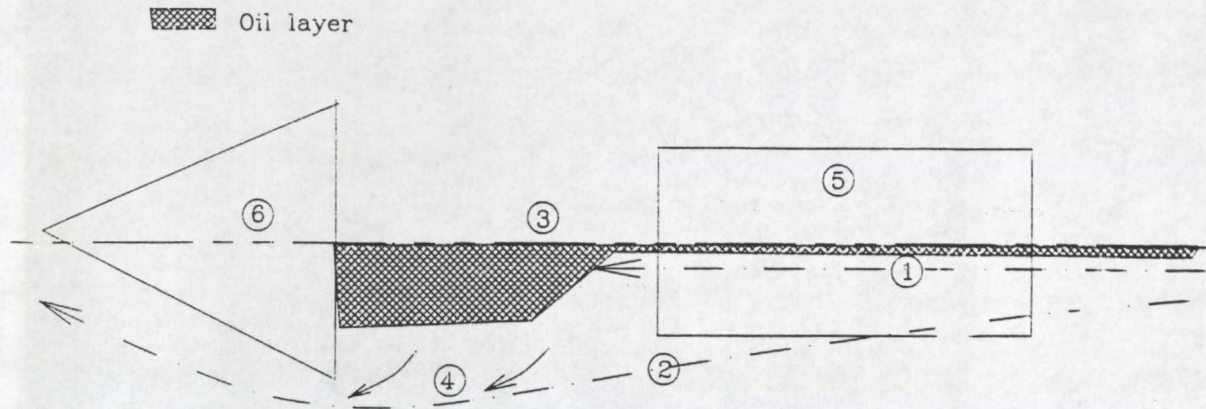


Figure 2.8. Anticipated flow pattern around boom design No 6

1. upper flow layer
2. lower flow layer
3. oil layer caught in trap
4. water separated from oil leaving trap
5. deflector float
6. boom

As shown in Figure 2.8, the function of the floats is to deflect the upper flow layer through an initial 35 degrees and to shroud the flow in the trap from the force of the incoming flow. The presence of the floats would prevent flow down the face of the boom which causes oil leakage under a conventional boom. In the trap area, oil will separate from the water and float on the surface. The excess water would be forced to lower water

layers by the incoming flow and merge with the flow passing under the boom. The line of the floats tapered away from the boom face at an angle of 4 degrees to allow the surface area of the trap to increase to accommodate the incoming flow of oil down its length. The momentum of the flow passing into the trap would drive the surface layer of oil down the trap to an oil collection point for recovery.

During testing, the flow through this configuration was observed to follow the predicted and designed pattern. The flow entered and passed down the trap without the presence of a current which would draw the surface layer under the boom causing leakage.

The following was concluded:

- (i) the subsequent model must comprise two sets of booms and floats to deflect the surface layer to the centre of the configuration for collection, and
- (ii) oil collection tests must now commence and therefore the configurations must incorporate a skimmer.

2.2.4 Boom design No 7

In this configuration, the booms and floats were made from polystyrene. The skimmer was made from fibreglass and incorporated a brass suction pipe. The same operation principle used for boom design No 6 was utilised in this configuration. As shown in Figure 2.9, two sets of symmetric booms, each lying at 45 degrees to the flow, were linked at the vertex of the configuration by the skimmer. The angle between the booms equalled 90 degrees. Each boom had a bank of three deflector floats positioned ahead.

The surface flow layer was diverted by each boom towards to their vertex where a skimmer was positioned to recover the floating oil.

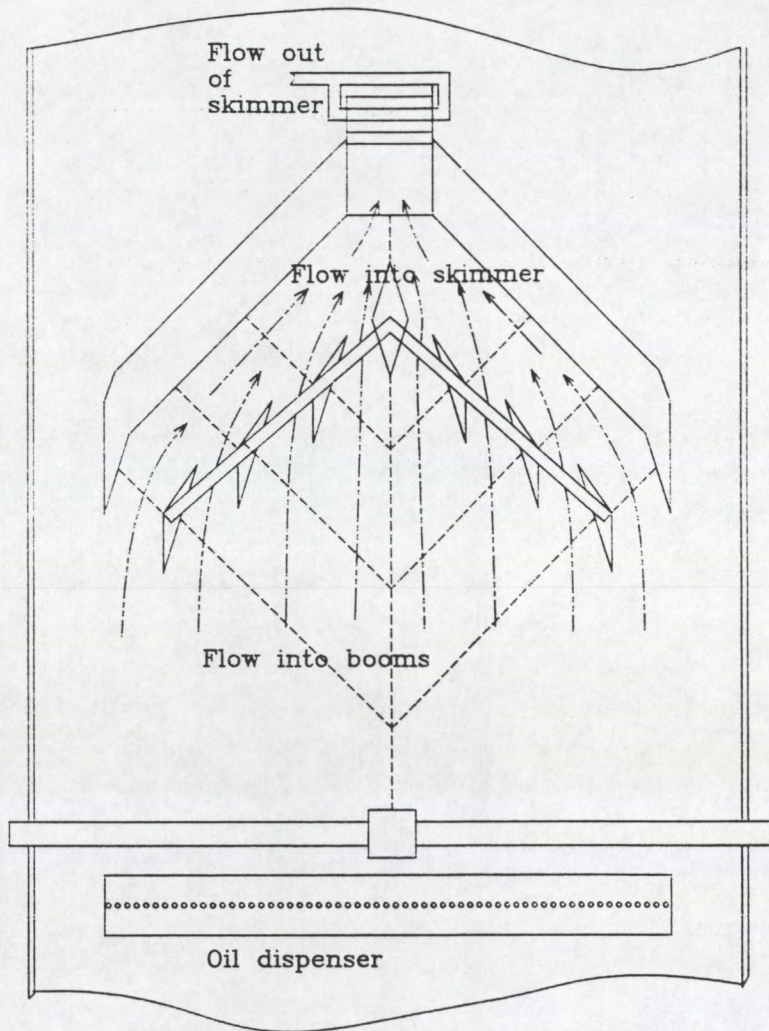


Figure 2.9. Layout and anticipated flow pattern through boom design No 7 in test channel

The end of the harness, positioned down the centre line of the configuration, was attached to the skimmer. The floats were attached to the harness by stays as shown in Figure 2.9. As shown in Figure 2.10, it was anticipated that the surface flow containing floating oil from the trap would enter the skimmer by passing over the weir which was

lying 9mm below the water surface. The surface layer would flow directly into the suction pipe to be recovered. The suction pipe had a line of 4mm holes drilled across its width which were positioned just below the water surface to recover the floating oil. A separation plate separated the weir from the lower skimmer. The lower layer of the incoming flow, which was assumed to be separated from the oil, would pass into the lower skimmer. The flow passing under the skimmer would create a low pressure which would induce the flow of excess water out the drain.

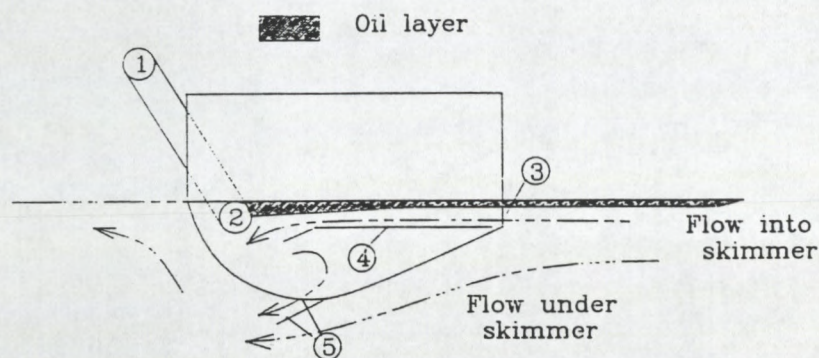


Figure 2.10. Principle of operation of skimmer used for boom design No 7

1. discharge from skimmer
2. suction pipe
3. weir
4. separation plate (upper/lower skimmer)
5. water drain

The suction pipe was connected by a plastic tube to a gear oil recovery pump which pumped the oil recovered from the skimmer to a measuring flask. When it was observed that all the water recovered with the oil had separated, the amount of oil was measured.

For the test, a measured amount of sun oil was gradually poured into an oil dispenser, which spanned the width of the test channel. This created a layer of oil across the surface of the test channel which flowed into the boom configuration to be recovered. A filter spanning the width of the test channel was positioned behind the configuration to recover any oil which escaped through it. During the test, the configuration was carefully observed to determine points of leakage and oil was observed to be leaking from under the skimmer. The skimmer was seen to break the water surface on occasions. The test results are shown in Table 2.1.

Model Speed (m/sec)	Volume of oil used for test (ml)	Volume of oil recovered (ml)	Percentage oil recovered
0,28	90	47	52%
0,35	90	40	44%
0,42	90	35	39%
0,48	90	10	11%
0,53	90	trace	0%

Table 2.1. Oil recovery - boom design No 7

The transposed results (with $v_p = 4.69v_m$) are given in Table 2.2.

Test speed (m/sec)	Transposed speed (m/sec)	Percentage oil recovered
0,28	1,31	52%
0,35	1,64	44%
0,42	1,96	39%
0,48	2,25	11%
0,53	2,48	0%

Table 2.2. Transposed recovery results - boom design No 7

Thus it was concluded that oil was not being lost from the booms but from under the skimmer and therefore it had to be redesigned.

2.2.5 Boom design No 8

The same booms used in design No 7 were used for this configuration. The skimmer was removed and replaced by a wedge shaped skimmer (as shown in Figure 2.11), which incorporated a brass suction pipe. The wedge skimmer was made from fibreglass.

The wedge skimmer consisted of an inverted weir through which the surface layer entered. It was anticipated that the momentum of flow would force the surface layer up the inclined entry channel of the skimmer which was held above the water surface. This channel was filled with water held there under vacuum. The profile of the inclined channel was initially rectangular which gradually became triangular and corrugated (see Figure D.13 - Annexure D for more details). The suction pipe spanned the width of the top of the inclined channel, which was the highest point of the skimmer. Holes, 4mm in

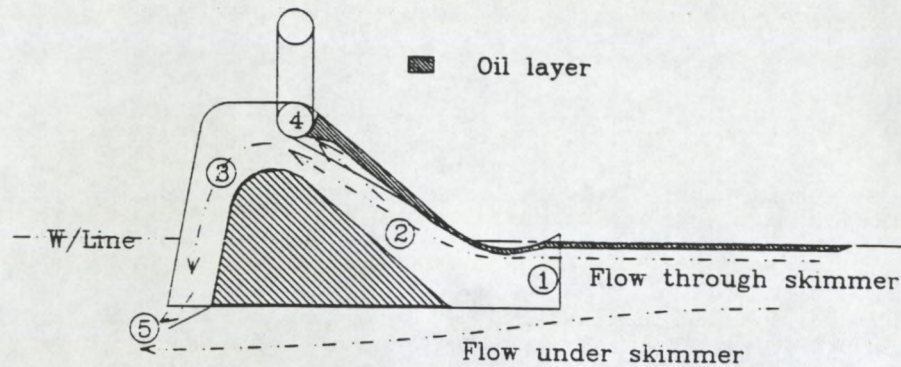


Figure 2.11. Principle of operation of skimmer used for boom design No 8

1. skimmer entry
2. inclined entry channel
3. exit channel
4. oil suction pipe
5. water drain

size, were drilled in the suction pipe such that they were in line with the triangular corrugation at the top of the inclined channel. After the suction pipe, the channel descended back to water surface datum, carrying the flow to the water drain at the bottom rear of the skimmer.

It was anticipated that the surface layer containing oil would enter through the trap entry, which consisted of an inverted weir, and rise up the inclined channel. During the passage, oil would rise to the highest point, viz. the apex of each triangular corrugation. From this point it would be drawn out of the skimmer through the suction pipe. The remaining water separated from the oil would continue down the channel and exit the

skimmer through the excess water drain. It would merge with the flow passing under the skimmer.

The skimmer had a flat bottom which would ensure that the flow under the boom would pass more easily than the previous designs, which forced the flow below the surface. The flow under the skimmer would cause a low pressure relative to the skimmer and would assist in drawing the excess water out the water drain.

Testing was conducted under the same conditions as described previously (see design No 7). During testing, oil was observed to be leaking from the skimmer area and was recovered by the filter behind the skimmer. No oil was observed to be leaking from under the booms or to be trapped in the filter paper behind the booms. The results of the test are given in Table 2.3.

Model speed (m/sec)	Volume of oil used for test (ml)	Volume of oil recovered (ml)	Percentage oil recovered
0,28	100	77	77%
0,35	100	57	57%
0,45	100	37	37%
0,51	100	27	27%

Table 2.3. Oil recovery - boom design No 8

The transposed results are given in Table 2.4.

Test speed (m/sec)	Transposed speed (m/sec)	Percentage oil recovered
0,28	1,31	77%
0,35	1,64	57%
0,45	2,1	37%
0,51	2,39	27%

Table 2.4. Transposed recovery results - boom design No 8

This configuration showed an improved oil recovery rate at lower velocities, but at velocities above 0,5 m/sec the recovery rate became equal to that of boom design No 7. It was concluded that oil was escaping under the boom and the flow in the inclined channel was turbulent, which prevented oil from separating from the water and rising to the suction pipe at the highest point of the skimmer. Therefore, oil was also escaping out of the water drain.

2.2.6 Boom design No 9

The purpose of this test was to ensure that the entire surface layer was recovered in order to determine whether oil was leaking under the boom or not. A simple rectangular shaped skimmer shown in Figure 2.12 was used for the test. It was held 20mm below the surface and had no excess water drain. The suction pipe was connected to a high volume pump. The results of the test are given in Table 2.5.

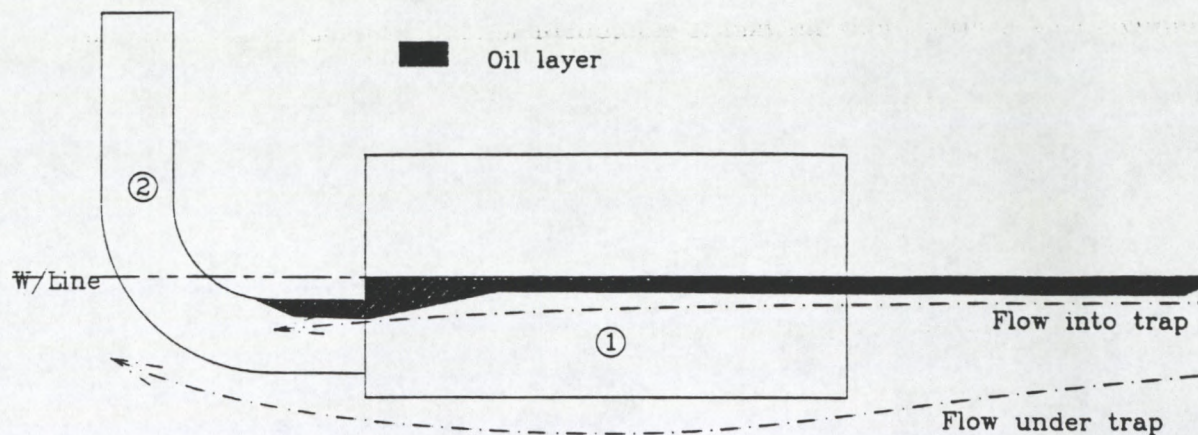


Figure 2.12. Principle of operation of skimmer used for boom design No 9

1. oil trap
2. suction

Test speed (m/sec)	Volume of oil used for test (ml)	Volume of oil recovered (ml)	Percentage oil recovered
0,48	450	370	92%
0,58	500	330	66%
0,76	500	170	34%

Table 2.5. Oil recovery - boom design No 9

The transposed results are given in Table 2.6.

Test speed (m/sec)	Transposed speed (m/sec)	Percentage oil recovered
0,48	2,25	92%
0,58	2,72	58%
0,76	3,56	34%

Table 2.6. Transposed recovery results - boom design No 9

During the test it was noted that the flow into the skimmer began to choke at the entry at a speed of 0,58 m/sec and then passed under it. The escaping oil became trapped in the filter behind the skimmer. No oil leakage occurred under the booms.

From the test results of boom design No 9, it was concluded that the booms were operating as required and were retaining the oil within the trap. A prototype would be effective at the target speed of 1,2 m/sec as the test result show that 92% of the oil spilt in the tank was recovered by the model operating at the equivalent full scale velocity of 2,25 m/sec.

The following was thus concluded:

1. a separate development for the skimmer must be instituted, and
2. from the model tests, the model booms were effective up to a transposed velocity of 2.25 m/sec and therefore were competitive with existing equipment. It was decided to build and test a prototype of the configuration.

2.3 Design of boom prototype

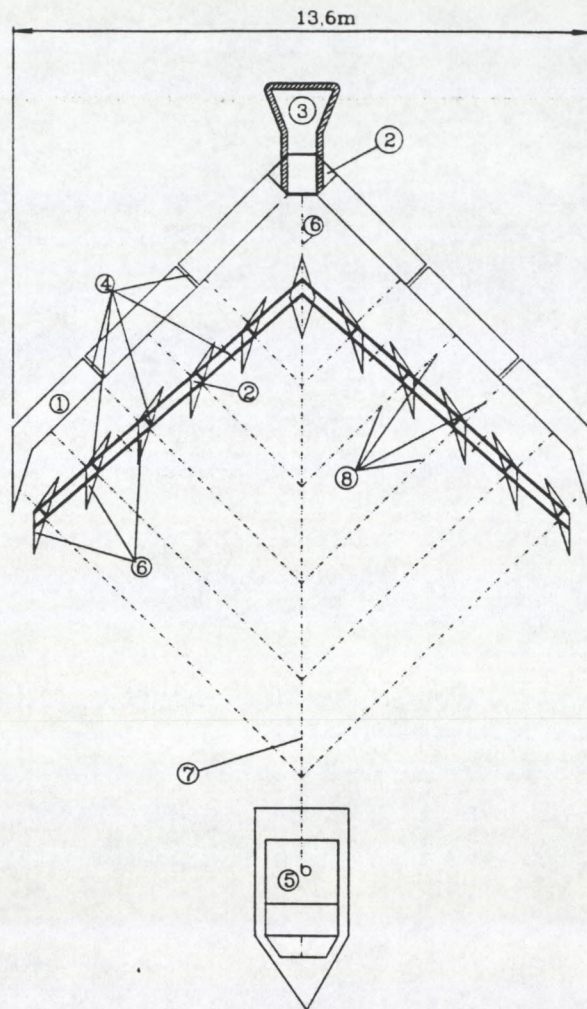


Figure 2.13. Layout of prototype boom configuration

1. booms
2. apex frame
3. straw oil bag
4. hinge points
5. launch
6. deflector floats
7. central tow line
8. towing stays

The design of the prototype boom configuration is based on the models tested in boom designs No 6 - 9 described previously. It comprised the following components (see Figure 2.3):

1. two semi - rigid booms,
2. ten deflector floats held in position by a semi - rigid frame,
3. an apex frame with an straw oil bag attached, and
4. a towing harness.

The configuration was made from fibreglass with mild steel inserts for additional strength. The harness was made from polypropylene rope.

It was decided after boom design No 9 that the skimmer positioned at the apex frame would be dealt with separately. Therefore, a straw oil bag was constructed to be positioned in place of the skimmer as an alternative method of oil recovery. The components of the boom configuration will be dealt with individually.

Semi - rigid booms

The prototype comprised two semi - rigid booms, each with a total length of 9,85m. The two booms were joined at right angles to each other at the apex frame and had a skimming width of 13,6m. Each boom comprised 3 sections, attached to each other by hinge brackets (see Figure 2.13) to allow flexing in the swell. The booms were ballasted until the draught on the leading face was 0,4m.

Deflectors were added to the ends of the outer-most booms. The sides of the deflectors

and the outer-most booms were designed to be in line with the flow, or at an angle of 135 degrees to the leading face of the booms. The inner side of the deflectors were constructed at an angle of 15 degrees to the flow. Towing brackets were attached to leading face of each boom section. The booms were adequately braced from inside.

Deflector floats

Two banks, each comprising five triangular deflector floats were positioned ahead of the semi-rigid booms. A diamond shaped float was positioned ahead of the straw oil bag located at the apex, where the two booms were joined.

The floats were held in position by a semi-rigid frame. The line of the floats was held at an angle of 49 degrees to the flow. This allowed for the width of the oil trap to taper outwards from the leading face of the booms, thereby increasing its surface area.

The semi-rigid frame assembly was divided into five rigid sections, which were linked together by hinges to allow flexibility. The centre frame section comprised two triangular floats positioned on either side of the diamond float. The remaining four rigid sections consisted of two deflector floats each. The floats were adequately braced from inside.

Towing brackets were attached on either sides of the floats. The rear brackets were linked to the brackets on the leading face of the boom by the polypropylene stays of the towing harness. Stays linked the front brackets to the central tow line of the harness.

Vertex frame and straw oil bag

The apex frame connected the two sets of booms at its vertex point. The frame provides a passage of 0,7m between the two booms to allow the surface oil layer to leave the trap and to enter the skimmer.

A large water - permeable straw bag, positioned in place of a skimmer, was used to recover the oil retained in the trap. This bag consisted of a steel frame with straw mat wrapped round the outside. Straw has oil absorbent properties and thus it was anticipated that oil would be absorbed by the mat while the flow of water permutates through it.

The straw bag was designed to be used for a single operation. The straw mat was 0,15m thick and had a total mass of 80kg. Straw can absorb a mass of oil equal to 15 times its own mass, and thus the bag theoretically had the potential to absorb 1,2 tons of oil. However, in view of the Port of Durban's strict pollution regulations, the bag was given a safety factor of 7 and during the test it would be used to collect 170kg or 214 litres of oil with a specific gravity of 0,8. The bag would be allowed to dry out after the test and then weighed to determined the mass of oil absorbed, which, when compared to the amount spilt, would be used to determined the percentage recovered.

Towing harness

The towing harness was made of polypropylene rope. The end of the central rope, which was 30mm in diameter, was attached to the towing bracket on the diamond deflector float. The towing brackets were positioned at 5 points along the central rope. Two towing

lines were strung from each side of every towing bracket to each of the triangular deflector floats. The upper tow line was shackled to the semi - rigid frame, while the lower line was shackled to the bottom of the base side of the float. A second set of stays were strung from the trap side of the floats to the leading face of the boom.

2.3.1 Prototype test

It was decided that the test would be conducted in the Silt Canal located in Durban harbour. A Portnet launch would be used to tow the prototype. Initially, no oil would be used, and the flow in through the configuration would be observed to determine if any problems existed. If the initial observations were satisfactory, a measured mass of oil would be pumped into the Silt Canal ahead of the prototype from the towing launch. The oil prototype would recover the oil in the bag.

On Wednesday 25 January 1995, the prototype was assembled in the Silt Canal in Durban Harbour as shown in Figures 2.14 - 2.19. A drum of oil containing 180kg

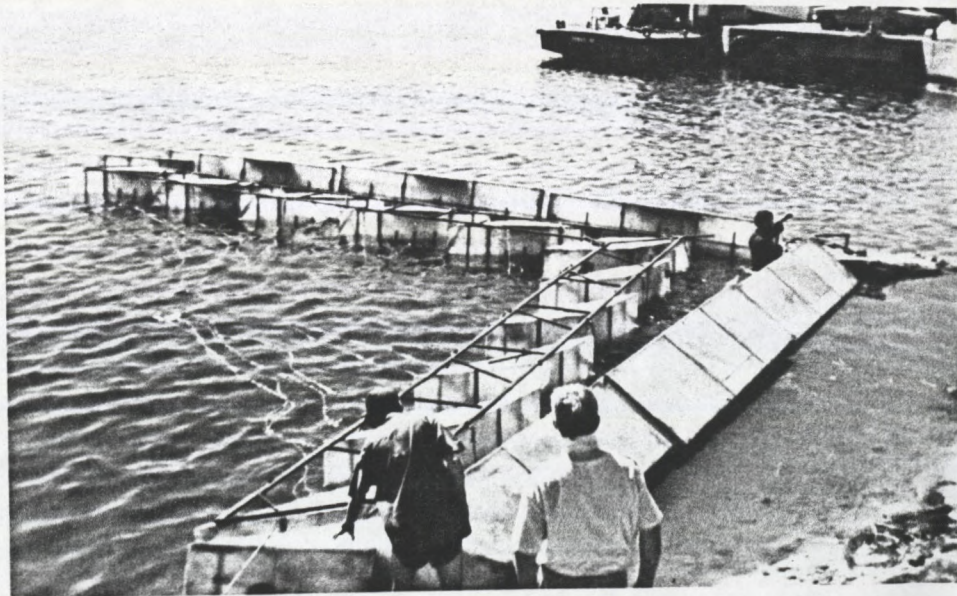


Figure 2.14. Side view of prototype boom

(220 litres) of oil was loaded aboard the towing launch.

A moderate North Easterly wind was blowing down the Silt Canal, which lay North - South. The test commenced with the prototype being towed due North (see Figure 2.15) down the canal at 1,0 m/sec against the wind. Immediately, a problem became evident. The prototype held form but short choppy surface waves were created in the trap area, caused by turbulence generated by the action of the deflector floats deflecting the flow. The turbulence generated wave action in the oil trap channel, causing water to be taken over the straw oil bag. The prototype was turned around and towed south at 1,0 m/sec down the canal with the wind from astern. This diminished the wave action slightly, but it was still unacceptable as the waves were breaking over the oil bag.

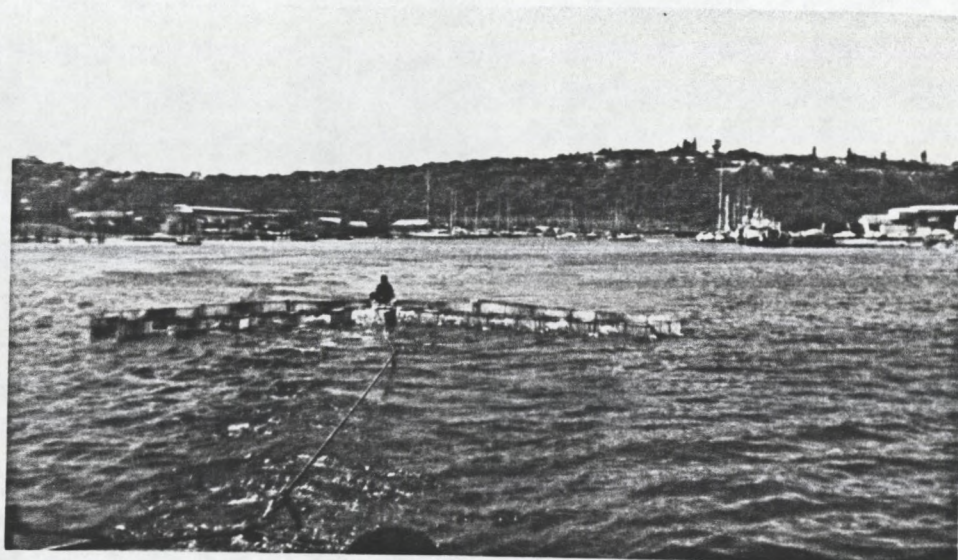


Figure 2.15. Prototype being towed North down Silt Canal

The prototype was again turned around and towed North up the Canal at a reduced speed of 0,5 m/sec. At this speed the wave action was reduced sufficiently. The prototype was turned around again and towed South and 20 litres of oil was pumped

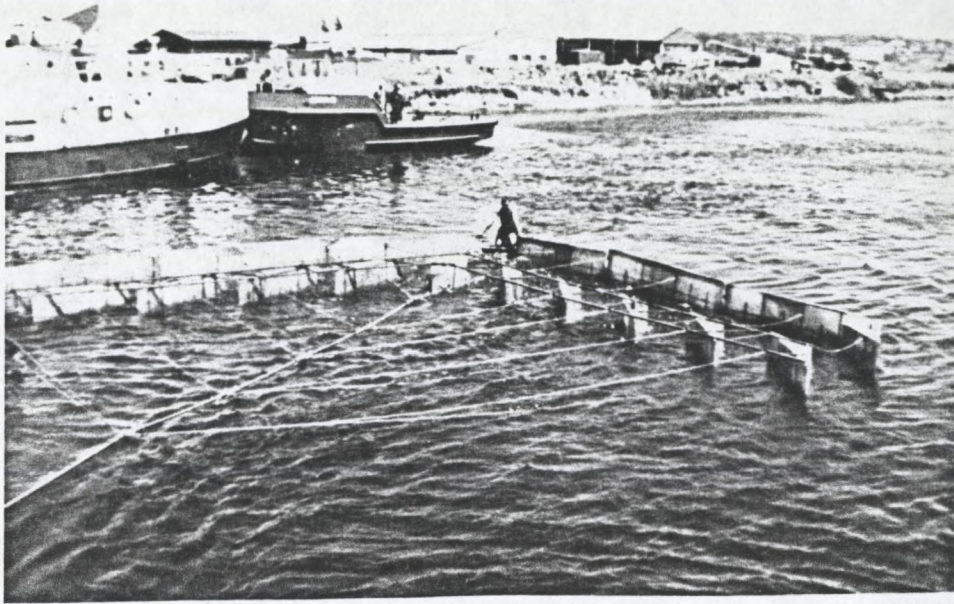


Figure 2.16. Prototype being towed South up Silt Canal



Figure 2.17. Oil being pumped from launch into bay ahead of prototype

into the canal ahead of the prototype. It was noted that oil was following the anticipated path down the trap and entering the bag.



Figure 2.18. Prototype seen from ahead.



Figure 2.19 Prototype seen from right hand side. Portnet launch seen behind

However, it was concluded that the turbulence generated in the trap was unacceptable and the prototype was not operating as required, and thus it was decided to abandoned the test for fear of polluting the bay. It was further concluded that, due to

the small scale, the model tests did not adequately display the small surface waves within the trap while being operated at the same Froude Number as the prototype.

Although the wave action rendered this design unsatisfactory, the concept of deflecting the flow ahead of the boom is sound and requires further investigation. A possible solution is to prevent the gravity wave from being created by the floats by positioning them below the water surface in the same location. They can be attached to the booms and deflect the lower flow layers entering the trap. This will in turn effect the surface flow and cause it to be deflected in the required direction without the creation of a gravity wave.

At this point of the study, the funds made available by Technikon Natal for this development were depleted. The Strategic Fuel Fund (SFF) of Johannesburg was approached and consequently made funds available to continue the project. The SFF operate the oil terminal at Saldanha Bay and required a manoeuvrable skimmer to recover oil spilt under the quay at the terminal. They showed interest in the skimmer which was planned to be positioned at the vertex of the booms. Therefore, at this point in the project, further development of the boom was halted and the development of the skimmer commenced.

2.4 Development and testing of a skimmer

A suitable skimmer was to replace the straw bag used to test the boom configuration described previously. It had to operate according to the requirements laid out in Section 2.1. The function of the skimmer is to concentrate the incoming oil from the boom in

an oil trap and dispatch it to storage. The oil to be recovered is limited to pumpable crude oil which has not weathered into a mousse.

2.4.1 Development of the prototype

Catamaran tests

Experiments to develop the prototype utilising the profile plate were initially carried out using a small catamaran shown in Figures 2.20. No oil recovery tests were conducted with it.



Figure 2.20. Catamaran in operation

The scales and dimensions of the oil trap were as follows:

- vertical scale - full scale (total vertical height - 0,4m)
- breadth scale - 1/2 scale (total width - 1m)
- length scale - 1/2 scale (total length - 1,5m)

The trap shown in Figure 2.21 - 2.23 was a short reach trap which was bolted to the catamaran. The oil/water mixture recovered by the trap passes through two stages, viz. entry and separation. During the entry stage, it was anticipated that the surface layer containing oil would be skimmed off by the lip weir positioned 50mm below the surface and which spanned the width of the trap. The oil/water mixture being recovered must be accelerated to the speed of the craft before entering the trap. During the second stage, oil in the trap separates from the water recovered with it and floats to the surface. It would normally be recovered at this point by a suitable skimmer floating in the trap. Water would leave the trap through the water drains after separation.

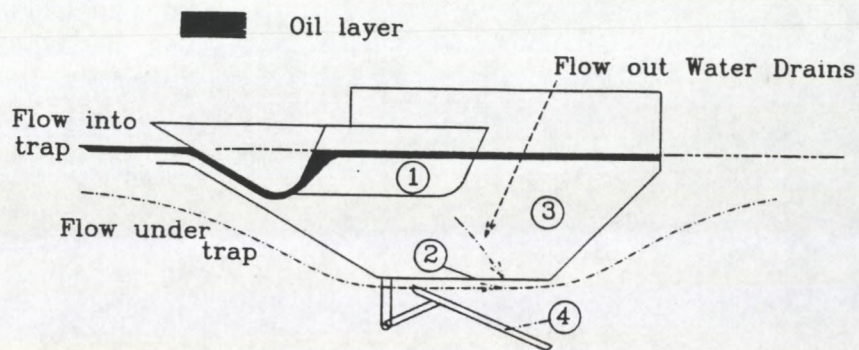


Figure 2.21 Principle of operation of oil trap

1. bow profile plate
2. trap entry
3. oil trap
4. water drain flaps

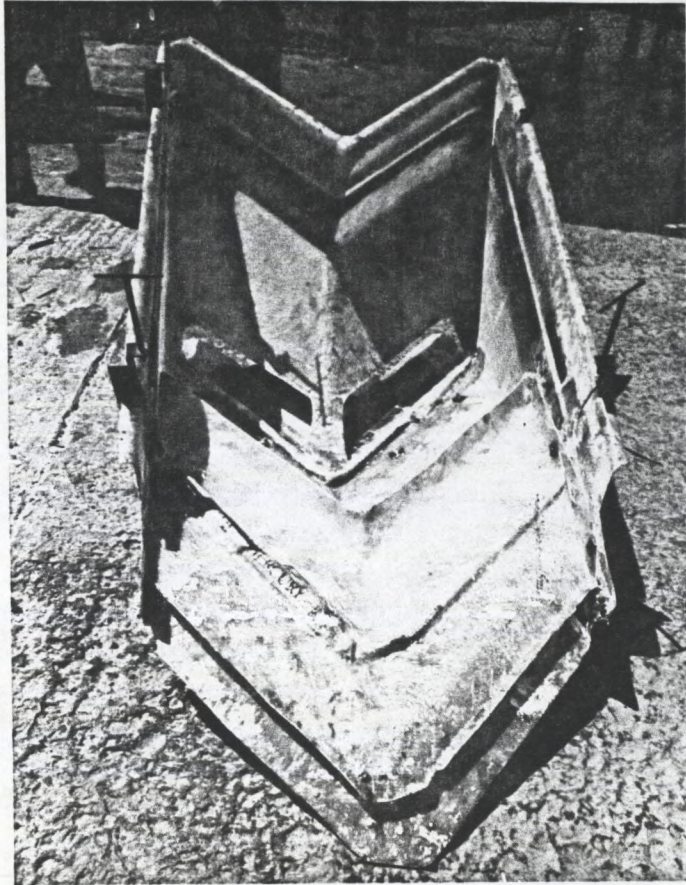


Figure 2.22. Oil trap seen from above



Figure 2.23. Trap seen from underneath; Note water drain flaps

The flow into the trap simulates open channel flow where, in relative terms, the trap is held stationery and a flow of water at a speed equal to the trap speed passes through it. Thus, the design calculations incorporate formula relating to open channel flow. The trap was designed to operate at a velocity of 1,6 m/sec, with the Froude Number equal to 2,28.

Without the inclusion of the bow profile plate shown Figure 2.21, the surface layer entering the trap would flow down the slope of the bow which is at an angle of 30 degrees to the horizontal, and during this stage the surface of the flow would be below the water surface datum (refer to Figure 2.24). This flow, being supercritical, merges with the subcritical flow in the trap, and causes hydraulic jump at the change over. This produces a change in depth from the supercritical flow y_2 (initial depth) down the bow to the subcritical flow y_3 (sequent depth) in the trap. The vertical distance by which the surface levels of the flows at y_1 and y_2 differ is equal to $y_3 - y_2$, which, using equation (29), is calculated as:

$$y_3 - y_2 = y_2 [0,5 [(1 + 8F^2)^{1/2} - 1] - 1] \quad (34)$$

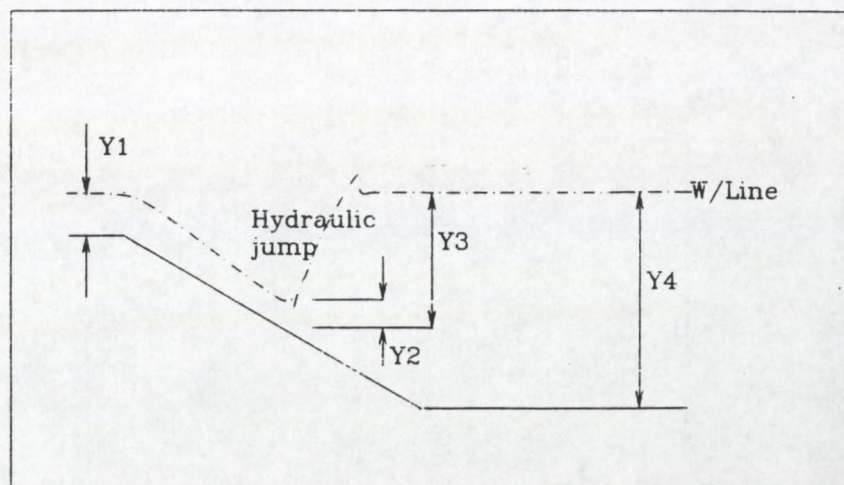


Figure 2.24. Hydraulic jump profile

Using the direct step method and equation (34), the profile of depth of the flow down the bow was plotted and the point at which hydraulic jump occurs was determined as 0,141m below the water surface datum (see D4 and D24 in Annexure D).

Hydraulic jump dissipates specific energy through turbulence, which, in the case of the prototype, causes the recovered oil entering the subcritical flow in the trap to be agitated and thoroughly mixed with the accompanying water. Thus, the profile plate shown in Figure 2.25 was constructed and attached as part of the bow to prevent hydraulic jump from occurring. The function of the profile plate was to cover the free surface of the flow entry, thus creating a siphon or pipeline. The profile plate is moulded to follow the water surface profile of the supercritical flow down the bow as calculated. At the points where hydraulic jump occurs, the profile plate allows a gradual enlargement of the flow area until the depth y_4 is reached. Thus, hydraulic jump is eliminated and the flow into the trap is smooth.

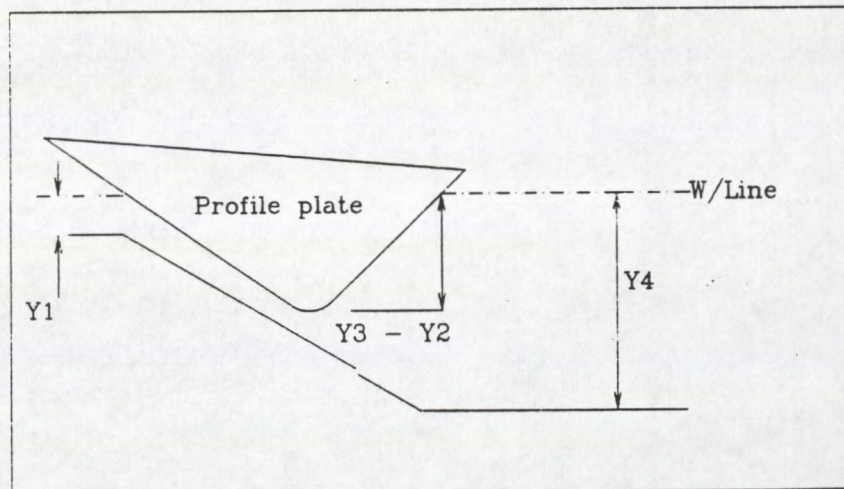


Figure 2.25. Action of profile plate

The depth of flow in the trap y_4 is kept level with the water surface datum by controlling the flow out the trap through the water drains. This is accomplished by opening or closing the water drain flaps.

After several unsuccessful attempts, a prototype was constructed which was able to recover the surface water layer through the bow without turbulence when the craft was being operated at 1,25 m/sec. However, turbulence was caused when the incoming flow merged with the flow out through the drains. Further, vortices formed on the free surface above the water drains and any debris in the trap was drawn out the drains.

It was concluded that the concept of the profile plate was successful. However, the prototype should be constructed with a longer trap to prevent the merger of flows. In addition, the design must be such that the water drains should have no free water surface above them to prevent the formation of vortices.

Quarter size model test

A quarter size scale model was constructed for testing. The recovery process of this concept was carried out in three phases, viz. recovery at trap entry, separation of oil and water in the trap, and the recovery of oil and exit of separated water at the end of the trap. Testing was carried out in the swimming pool at Technikon Natal and therefore no oil was used. The ability of the prototype to recover without creating turbulence was determined by observation.

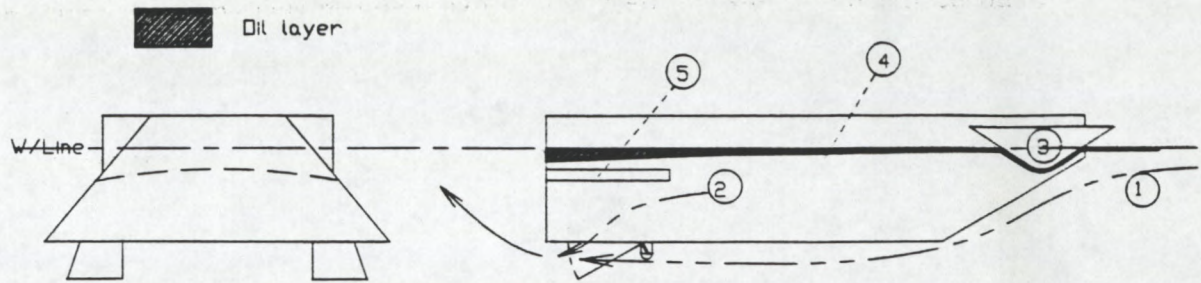


Figure 2.26. The principle of operation of quarter size model

1. flow under trap
2. flow out water drains
3. profile plate
4. trap
5. separation plate

The model was built with a length of 1m, a breadth of 0,5m and depth of 0,2m. The weir spanned the width of the trap and the lower lip of the weir was held 25mm below the water surface. The incoming flow passes through the bow at a velocity of 0,8 m/sec with a Froude Number of 1,6, and the depth of the profile plate below the surface was determined as 61 mm (see D25, Annexure D).

The velocity in the trap was reduced to 0,1 m/sec, thus allowing a period of 10 seconds for oil to separate from the water. Figure 2.26 shows the principle of operation. The surface layer, which would normally comprise recovered oil, is isolated from the water drains and the lower flow layers within the trap by the oil separation plates (see Figure 2.26 and 2.27). This prevents vortices forming and the surface layer from being drawn from the trap by the flow out the drains. The shape of the trap also prevents this from

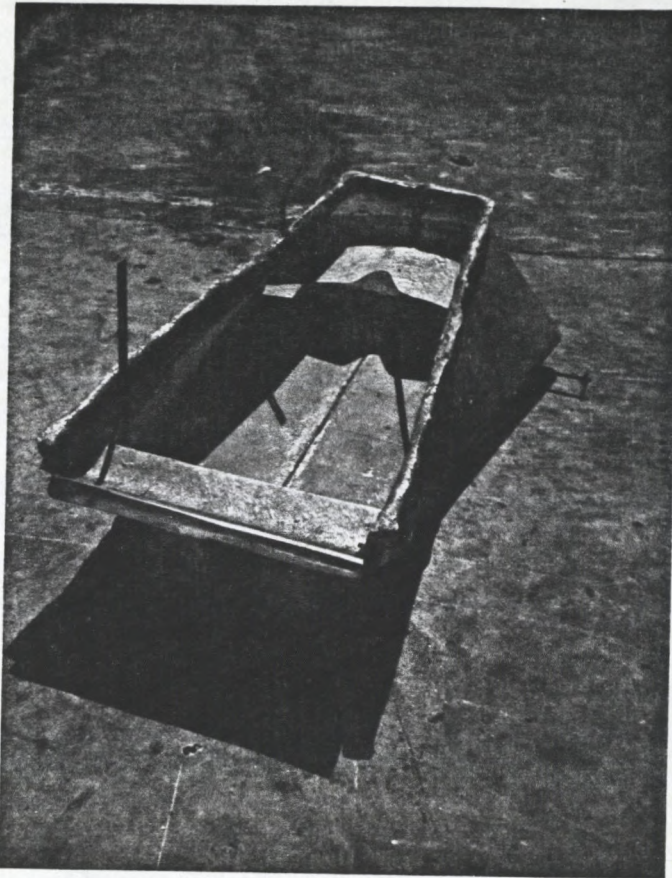


Figure 2.27. Quarter sized model (top view)

occurring. The sides of the trap are vertical at entry. Thereafter, the surface area tapers inwards towards the oil suction, and the trap bottom tapers outwards to the excess water drains. This ensures that there is no free water surface area above the water drains and thus no vortices can form. The separation plates also prevent vortices forming.

The model was attached to a wheeled cart as shown in Figures 2.28 and 2.29, which was pushed along the side of a swimming pool for a distance of 20m. This distance was covered in 21 seconds giving a speed of 0,95 m/sec, which is above the required velocity of 0,84 m/sec. The flow into the trap was observed to be smooth and debris drawn into the trap was held there and not drawn out through the water drains. No excessive turbulence was observed within the trap. Thus it was concluded that this model was

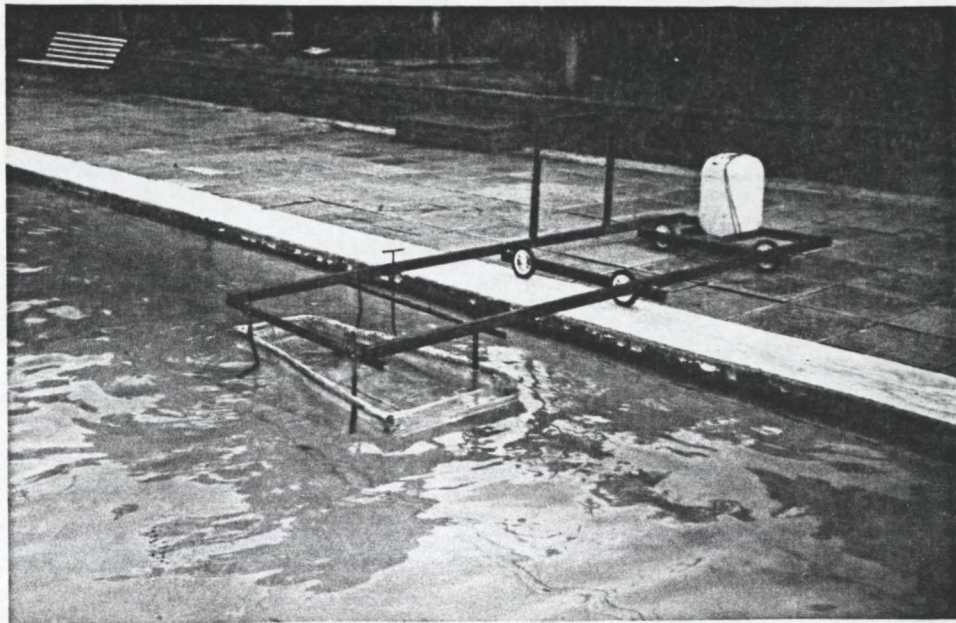


Figure 2.28. Model attached to trolley

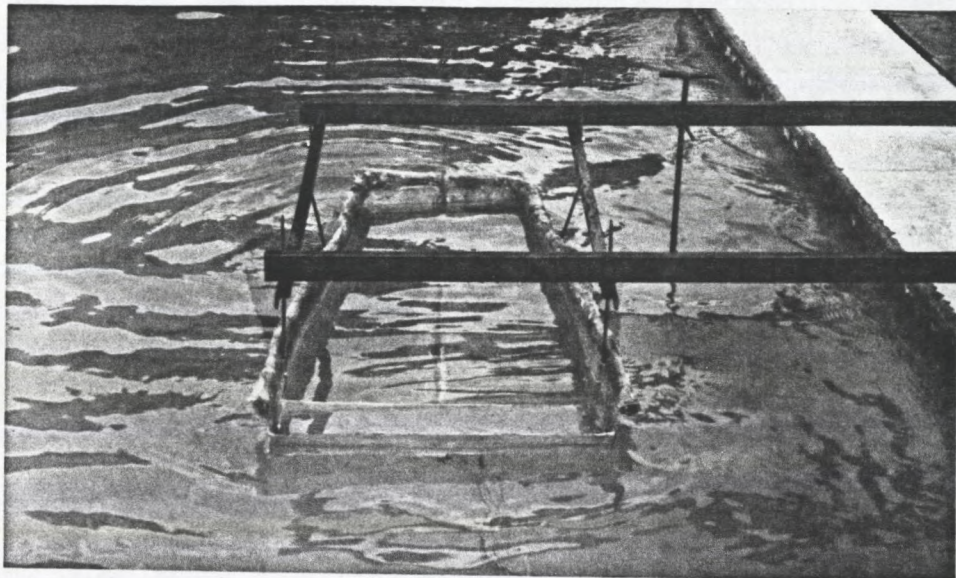


Figure 2.29. Quarter size model attached to trolley, seen from ahead

successful and the design of the full size skimmer prototype was based on this model.

2.4.2 Design and principle of operation of full size prototype

The full size prototype consists of a small craft, based on the quarter size model. As before, the oil/water mixture recovered by the craft passes through three stages, viz. entry, separation and recovery. The craft possesses little inertia (ie. light in weight),

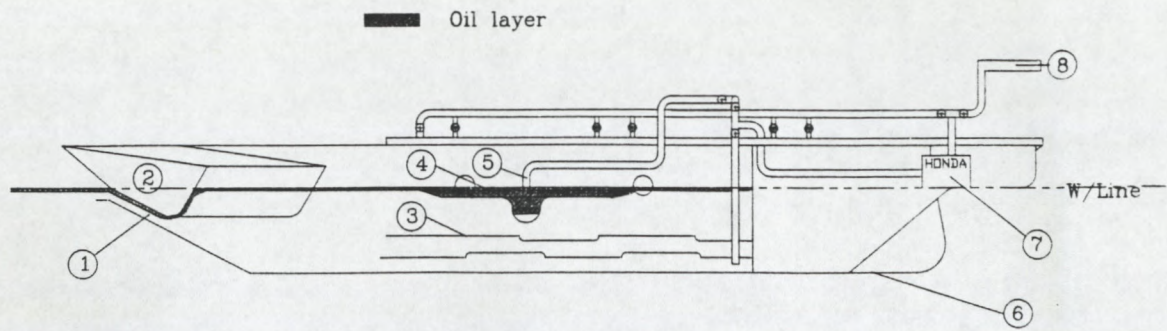


Figure 2.30. Principle of skimmer prototype

1. trap entry
2. bow profile plate
3. oil/water separation plates
4. skimmer disc
5. suction pipe
6. water drain
7. oil discharge pump
8. discharge pipe

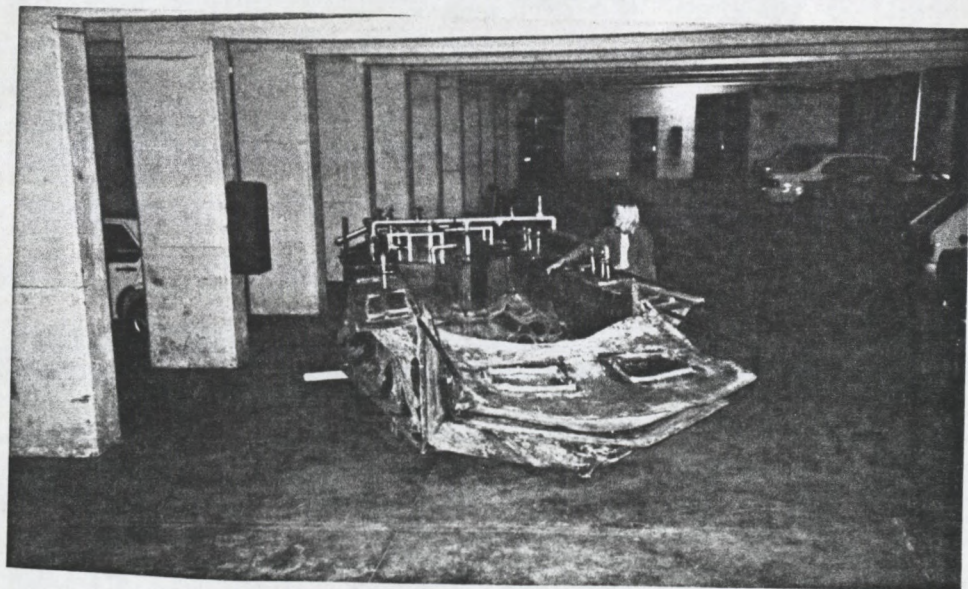


Figure 2.31. Bow view of prototype

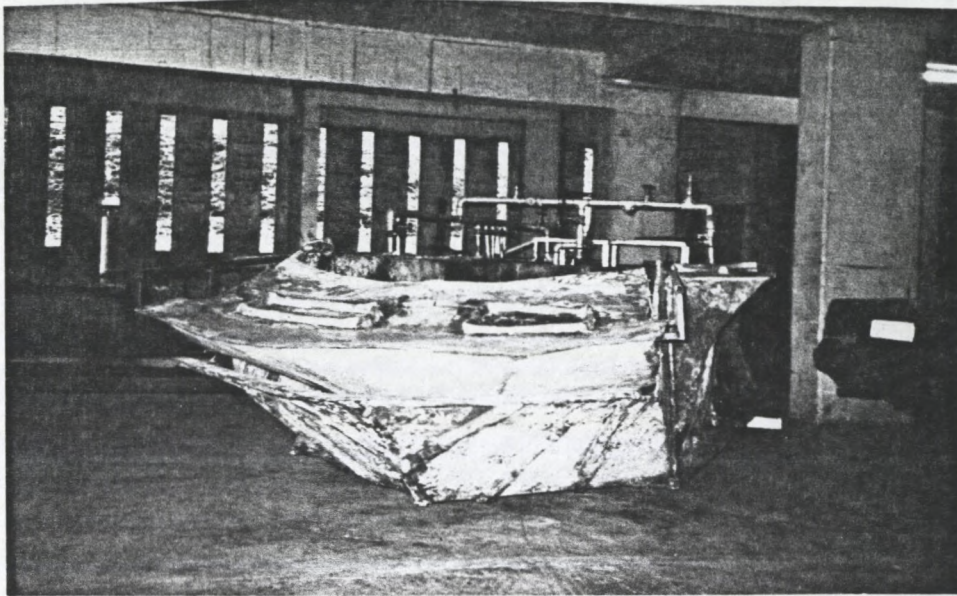


Figure 2.32. View of trap entry

which ensures that it rides with the waves to prevent the oil intake becoming submerged or breaking clear from the water surface. It was made from fibreglass, which has a relative density slightly greater than water, and therefore the craft is very buoyant in the swell.

The oil intake spanned the width of the bow with the lip of the weir positioned 80mm below the water surface (see Figures 2.30 - 2.32). The craft was designed to operate at 1,2 m/sec (Froude Number 1,69), and thus the depth of the profile plate was 0,161m (see D26, Annexure D)

After passing through the bow into the trap, the velocity of flow is reduced to 0,24 m/sec as the depth of flow increases to 0,4m. It travels down the 4,2m long trap and during this period (18 seconds) the oil and water separate due to the effect of gravity. The oil separation plate, as shown in Figure 2.33, channels the flow into horizontal

layers, thus preventing any large, slow eddies developing within the trap. The separation plate drain holes are there to allow vertical flow between flow layers. Oil trapped in the lower flow layers may rise through drain holes, and separated water flows out the trap through the water drains in the bottom of the trap.

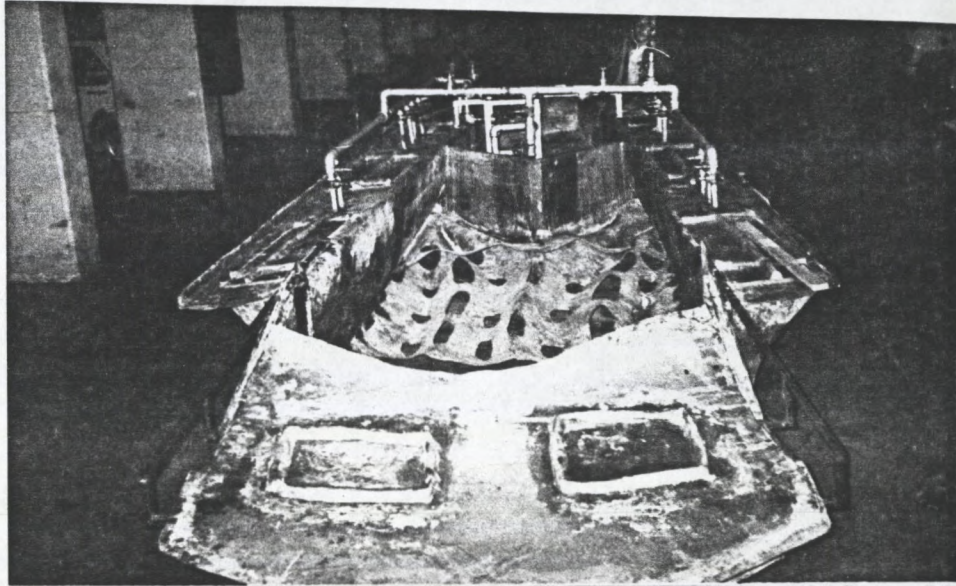


Figure 2.33. Trap seen from above; note oil separation plates

As with the quarter size model, the sides, which are vertical at entry, taper inwards at the rear of the trap at the point where the oil is recovered. This is to ensure that the water surface is isolated from the water drains. Thus, the drains are shrouded by the sides, having no free water surface above them to avoid the formation of vortices and to prevent oil escaping through the drains (see Figure 2.34 and 2.35).

Oil was recovered by a skimming dish (see Figure 2.30) positioned at the rear of the trap. This consisted of shallow saucer shaped disc with a diameter of 1m with a downward protrusion of 0,2m at the centre. The disc was kept floating at a depth of 15mm below the surface by 3 round floats. The pump only operates when the disc is

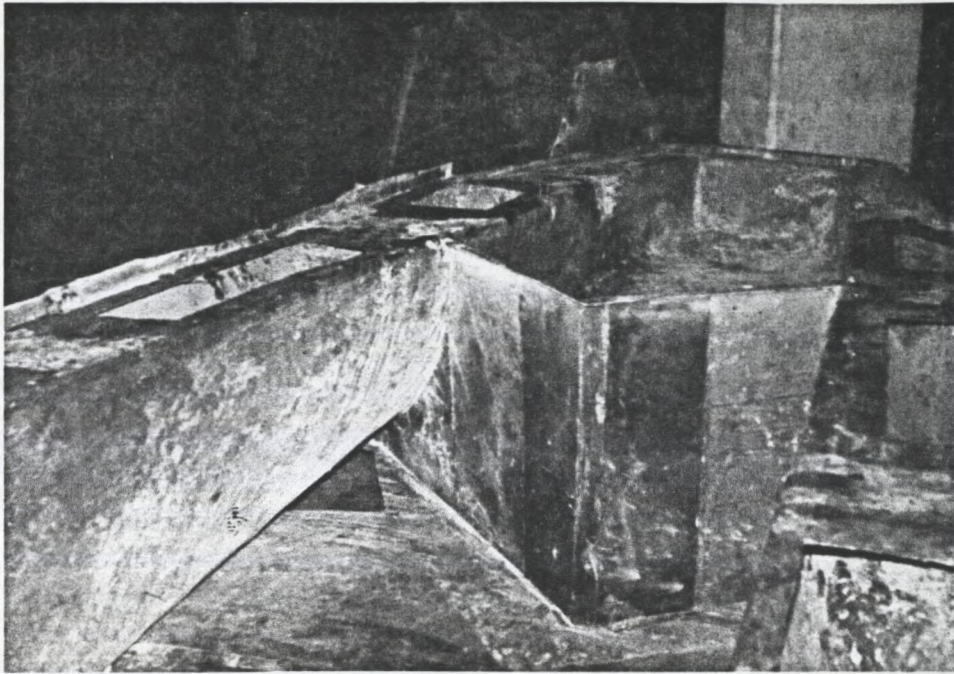


Figure 2.34. Water drain shrouded by trap side

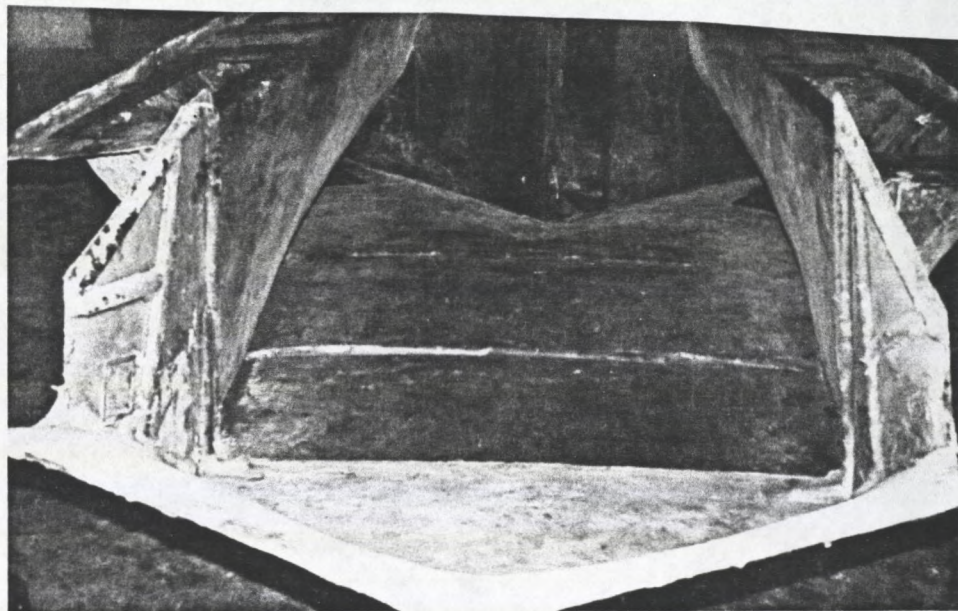


Figure 2.35. Trap seen from above

immersed in the oil layer. The suction line, the end of which was held 0,1m below the water surface, was positioned within the centre protrusion of the dish, thus allowing for vertical movement of the disc. Oil recovered by the disc was drawn into the oil suction, through the pump and out the oil discharge to oil storage facilities which may

consist of a support vessel with storage tanks accompanying the prototype or a Unitor oil bag (see Section 1.1.7). If the spill occurs within a boom encircled area at an oil terminal, the oil can be pumped to a tank ashore. Water, recovered with the surface layer, would leave the trap through the water drains after separation.

The prototype was effected by squat (see Section 1.2.5) since the surface area of the trap bottom acts as an aerofoil within the flow under the craft. To counter this, water can be pumped out of the buoyancy tanks, or the depth of the flow within the trap y_4 can be lowered by increasing the flow out the water drains to reduce the pressure head on the trap bottom.

2.4.3 Testing of the prototype

Initial tests using sawdust.

The initial prototype tests were carried out in the Silt Canal in Durban Harbour and sawdust was used to simulate oil for the tests. Wood has a similar density to oil and disperses on water in a similar manner to that of oil (as determined from the test described in Annexure A). Tests were also conducted to determine the ability of a floating layer of sawdust to remain buoyant after being shaken, when compared to a floating layer of oil. However from the test results, it was concluded that a substantial percentage of the floating sawdust becomes water saturated and sinks. Thus it provides a poor substitute for oil, for which experts in this field state that there is no substitute when testing oil recovery equipment (see letter of Dr.Wood - Annexure D). However, it can be concluded that if the prototype can successfully recover sawdust in a buoyant state, it must do so without shock and turbulence which would cause it to become

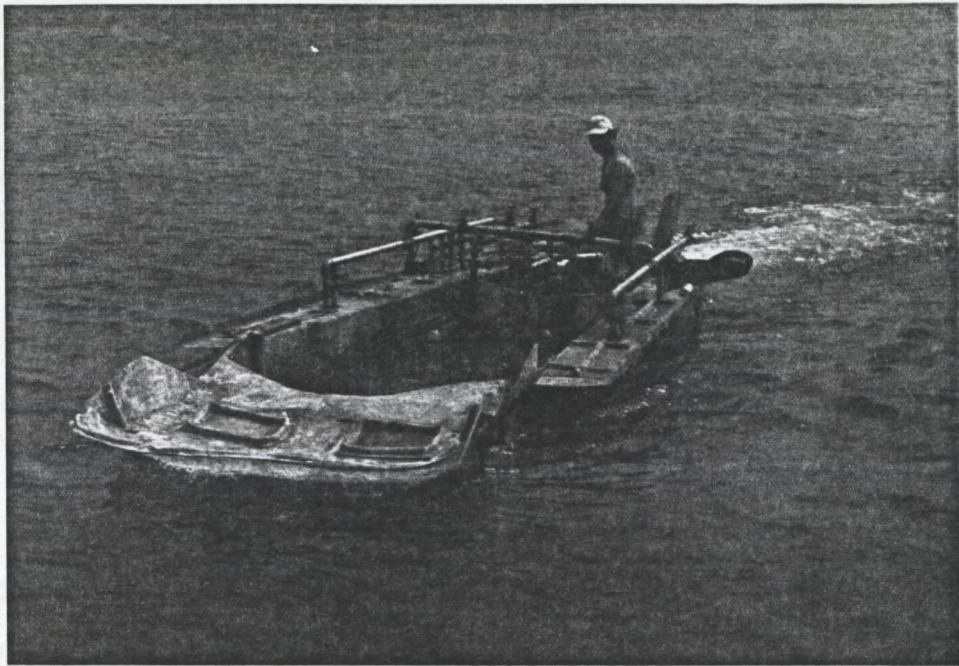


Figure 2.36. Prototype skimmer being tested in Silt Canal

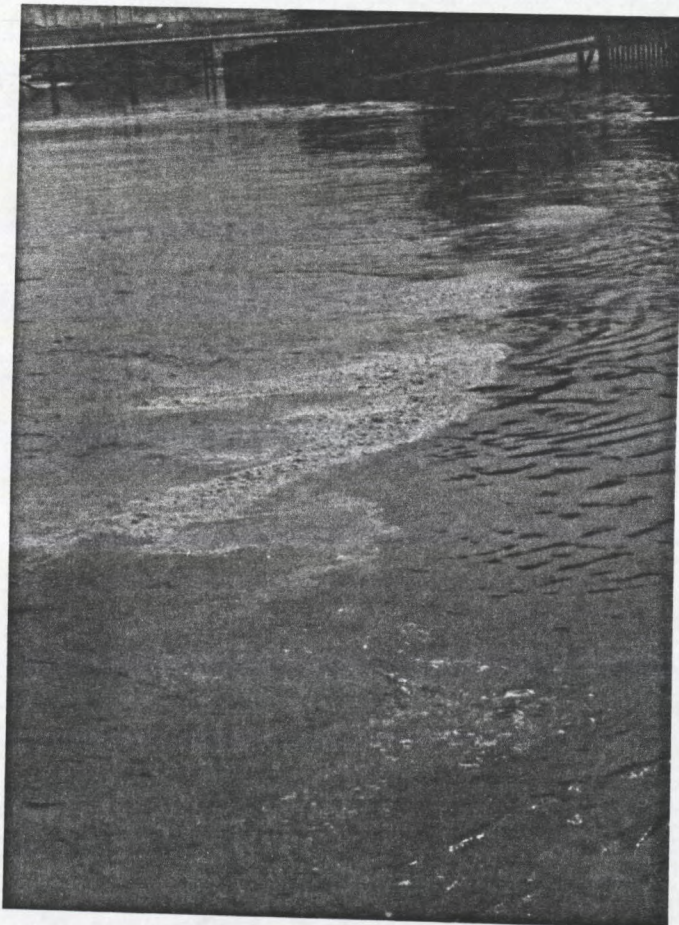


Figure 2.37. Saw-dust slick

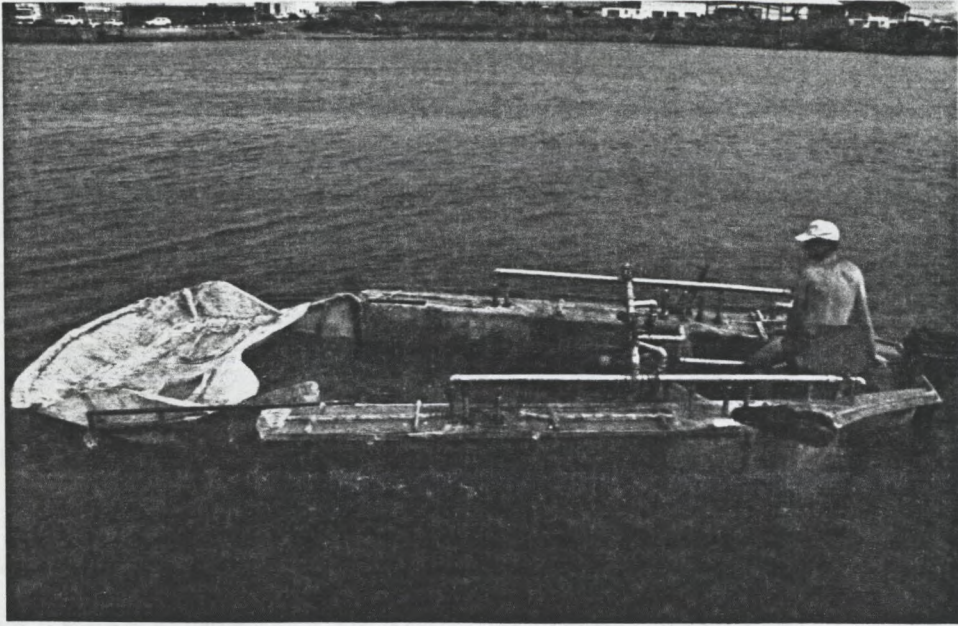


Figure 2.38. Prototype viewed from port side

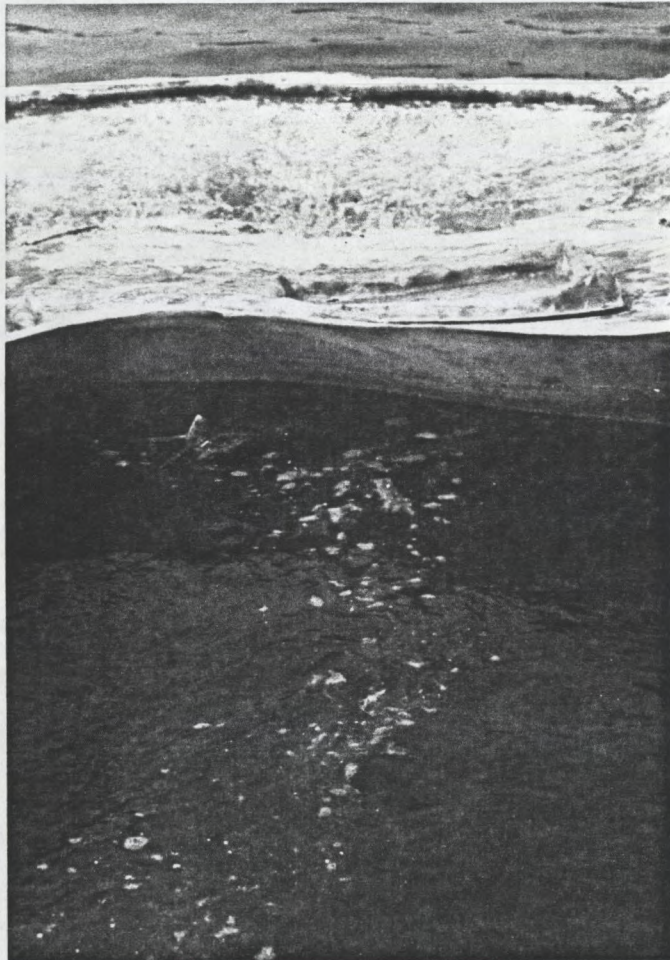


Figure 2.39. Saw-dust entering through bow

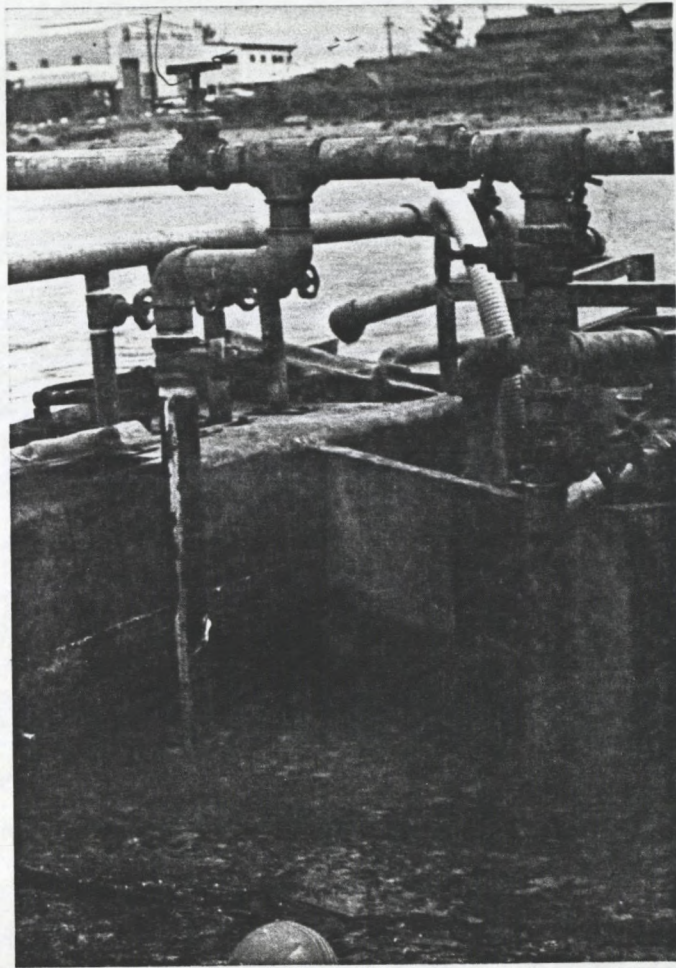


Figure 2.40. Saw-dust retained in trap

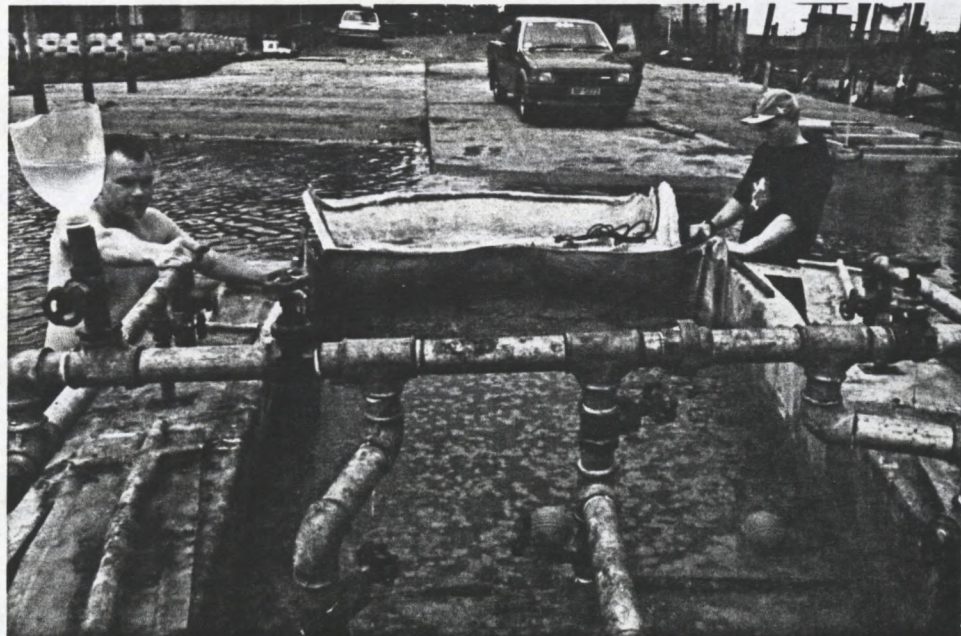


Figure 2.41. Saw-dust retained in trap, seen from stern

saturated and sink, and thus it will probably be successful when recovering oil.

Numerous tests were carried out using sawdust in the Silt Canal in Durban Harbour. Figure 2.36 and 2.38 show the prototype in operation. Figure 2.37 shows the sawdust slick on the water, and Figure 2.39 shows the sawdust passing into the trap without turbulence. Figure 2.40 and 2.41 show the trap holding sawdust. The final test would be the recovery of oil from a waterway. The sawdust tests were considered successful and it was decided to transport the prototype to the SFF Oil Terminal at Saldanha Bay for the final test using oil.

Before the final test, the prototype was tested using sawdust in moderate sea conditions at the SFF oil terminal at Saldanha Bay. The craft was set to work under the quay where the gap between the concrete supporting pillar is approximately 30m. A 1,5m swell was running during the test. Three bags containing 0.5m^3 of sawdust were emptied into the bay from a ski-boat. The prototype manoeuvred within the sawdust slick for 45 minutes recovering it from the water surface. When recovery was complete, the depth of the recovered sawdust retained in the trap was 75mm. With the surface area of the trap equal to $4,8\text{m}^2$, the recovered sawdust amounted to $0,32\text{m}^3$ or 64% of the original volume. The speed of the craft was held at 1,2 m/sec during testing except when turning or manoeuvring in a confined space close to the booms which were permanently in position at the oil terminal.

While operating on the swell, the recovery of the prototype was not adversely affected. However, when the prototype was operating into the wind, a pressure wave was

transmitted through the entry to the trap, causing a small surface wave in the trap. This did not adversely affect the sawdust retained in the trap as it remained on the surface. When the craft was operated with the wind on the beam, this effect was considerably reduced. After this test, the prototype was assessed as ready for a test using oil.

Oil recovery test using oil.

This final test was conducted in an oil overflow dam at the oil tank farm shown in Figure 2.42. On Wednesday 18 December 1996, a third of the area of the dam was boomed off on the upwind side for the test. Three hundred litres of crude oil was poured into the dam from a vacuum tank cart shown in Figure 2.43.

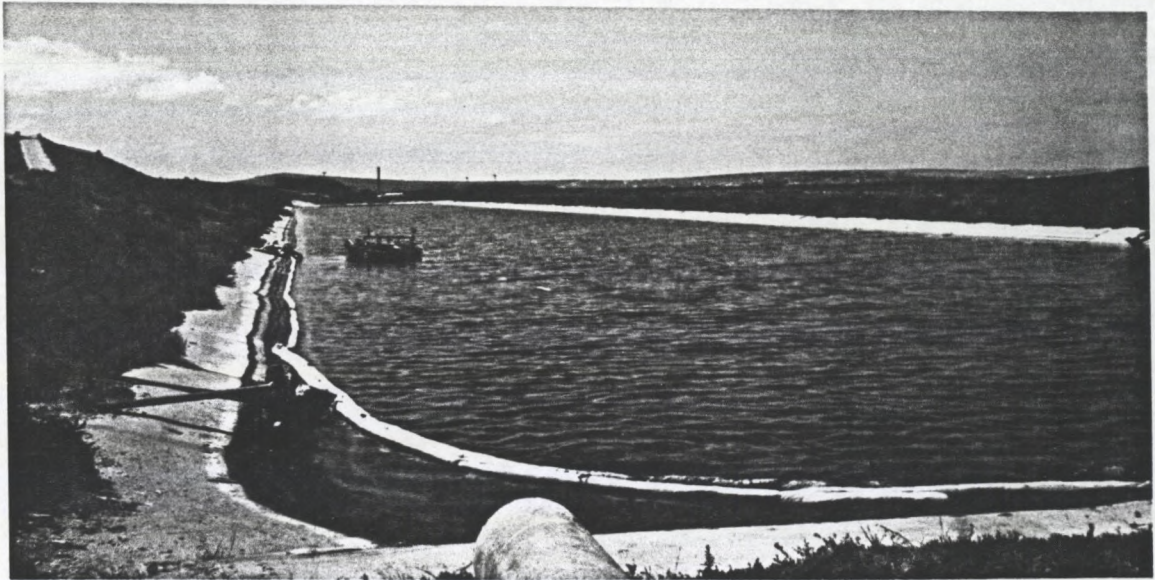


Figure 2.42. Evaporation tank at SFF tank farm

A flexible 75mm diameter pipe of 50 metres in length was attached to the oil discharge of the prototype and was used to pump the recovered oil back to the vacuum tank cart on the shore. To avoid twists developing in the pipe during turns, the prototype had to be manoeuvred in a "figure of eight", ie. one left turn followed by a right. The hose did

not affect the manoeuvrability of the prototype. The prototype collected oil successfully during the tests as shown in Figures 2.44 - 2.46. Oil entered smoothly through the trap without turbulence and settled on the surface.

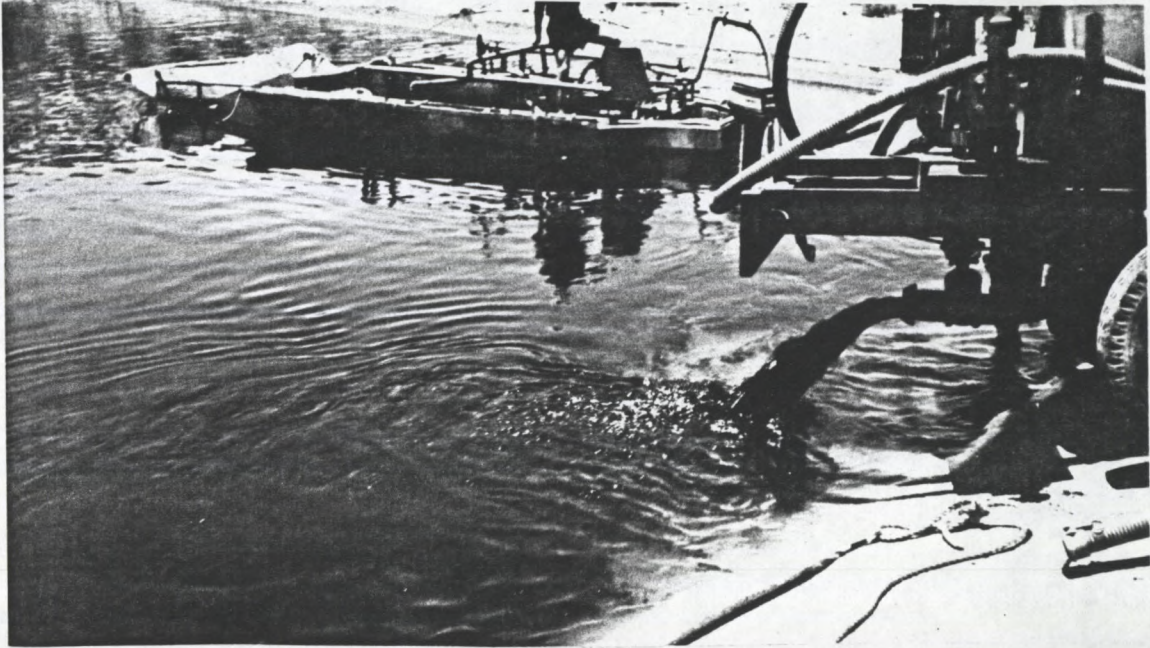


Figure 2.43. Oil being poured into evaporation tank from vacuum tank cart

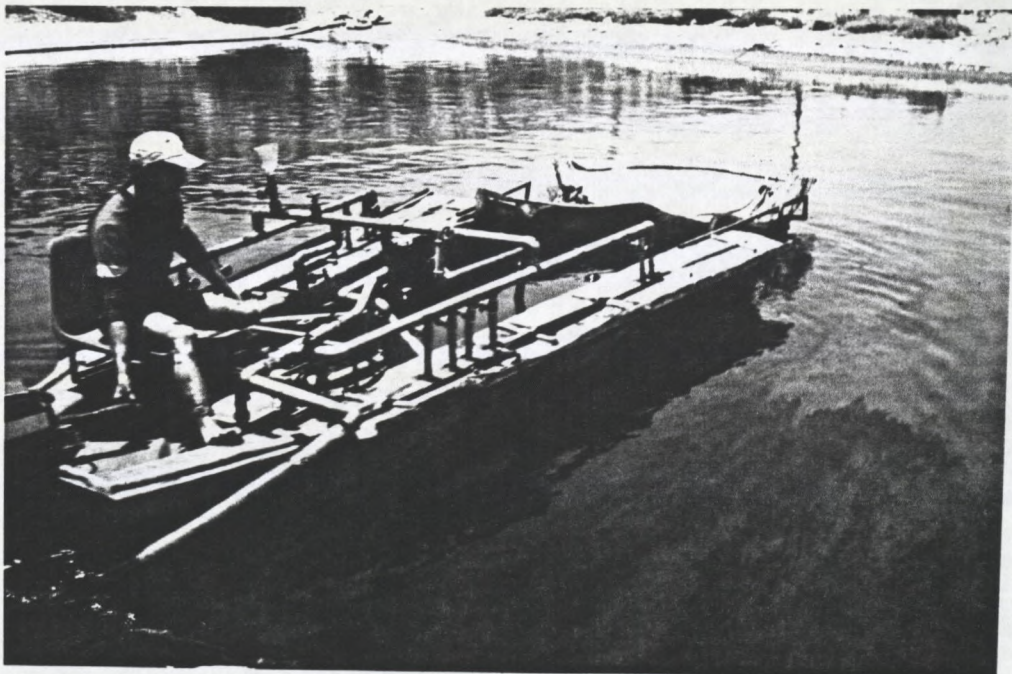


Figure 2.44. Prototype recovering oil from evaporation tank

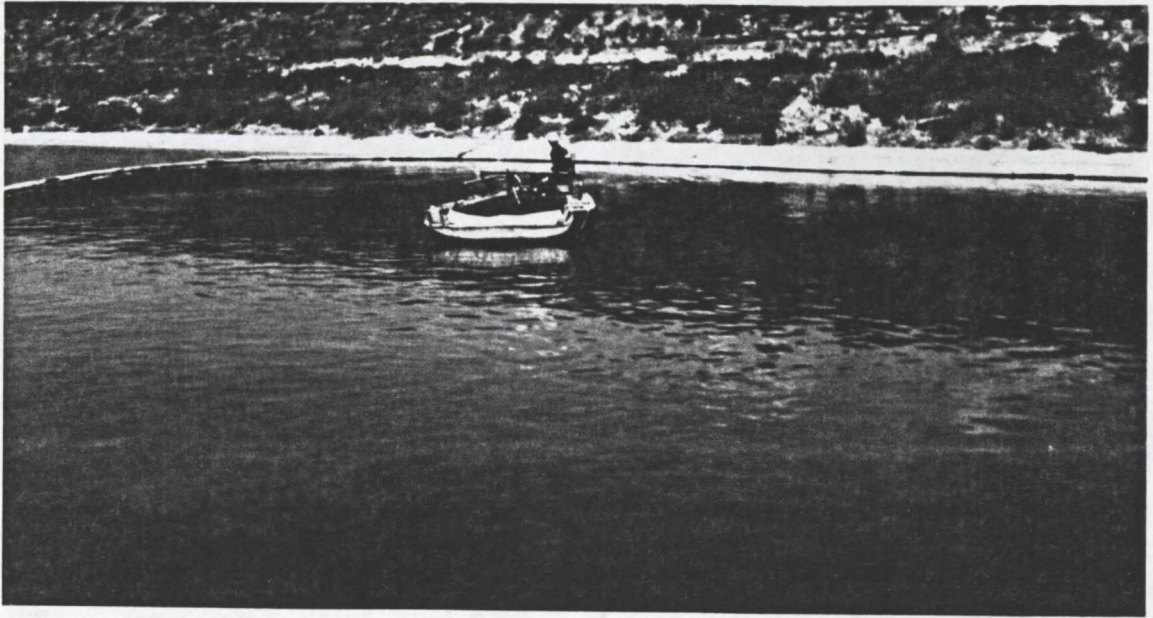


Figure 2.45. Prototype recovering oil from evaporation tank

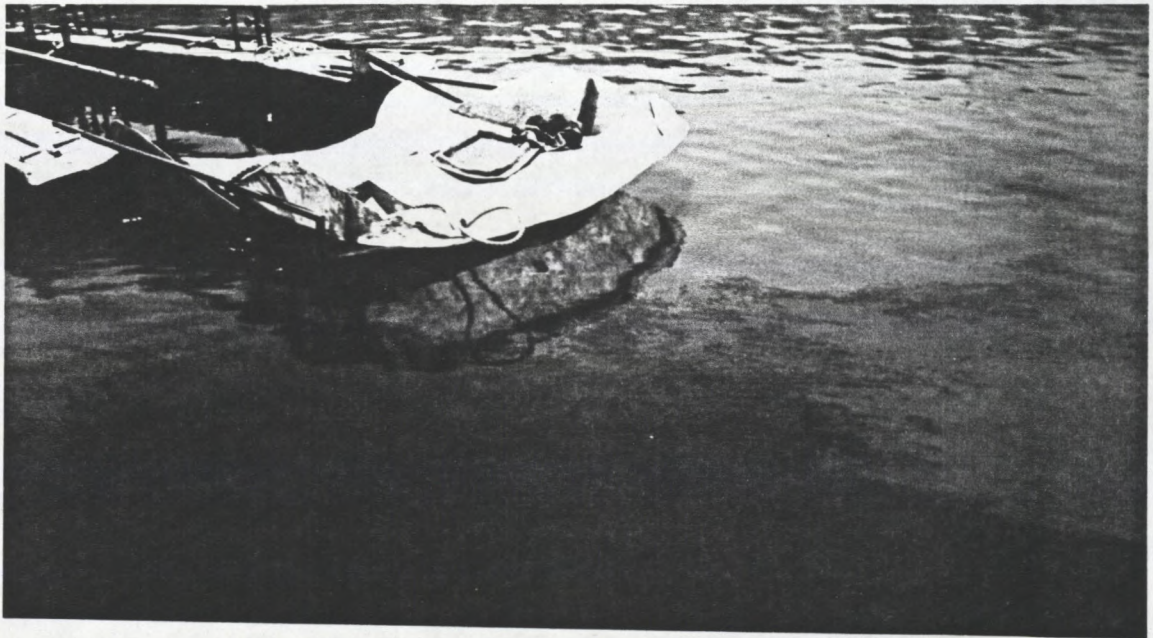


Figure 2.46. Slick passing through bow of prototype

Recovering the slick proved to be difficult. The biggest problem experienced was with the wind, which was blowing at 30 km/hr during the test (oil is blown across water at 3% of wind speed). Within 20 minutes the remaining slick had collected against the

barrier on the downwind side of the boomed area. When the prototype approached the barrier, the wash forced the oil under it. It must be noted that the barrier comprised of an oil absorbent material floating on the surface and not a conventional boom with skirt, which would have prevented this problem (see Figure 2.47).

The barrier was removed to allow the slick to spread across the dam and the prototype continued to recover it. After sufficient oil had been recovered by the prototype, the pump was started. The submerged discharge pipe contained approximately 0,275m³ of water, which had to be allowed to clear before it pumped oil. Oil is shown in Figure 2.48 being pumped into the tank and for a duration pure oil was observed being discharged.

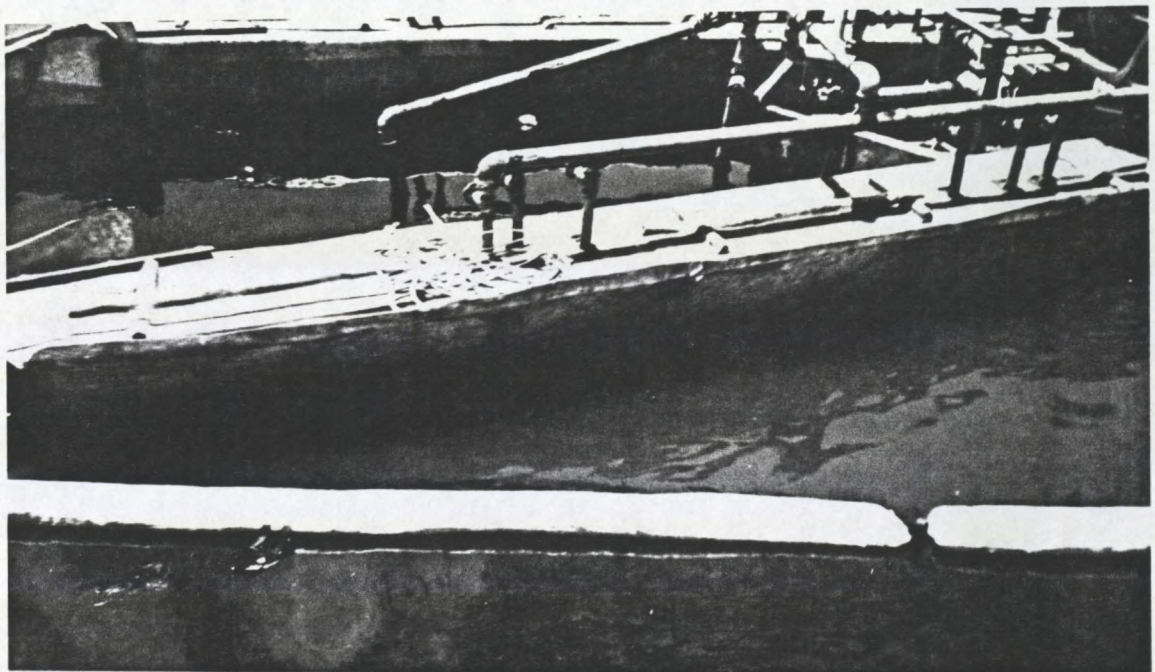


Figure 2.47. Oil forced under floating barrier. Note oil retained in trap

However, when the layer in the trap became thin, the oil recovery process experienced difficulties. The skimming dish contained oil, and was therefore lighter than the water it was displacing under it. The result was that the dish was forced out

of the water and suction was lost. The dish floats were re-adjusted to allow a higher flow rate into the dish, but this resulted in a high percentage of water being recovered with the oil. Eventually when the oil layer was 1 - 2 mm thick, it became impossible to remove any further oil from the trap, and in the end, 12 litres could not be recovered.



Figure 2.48. Pure oil being pumped from prototype into tank

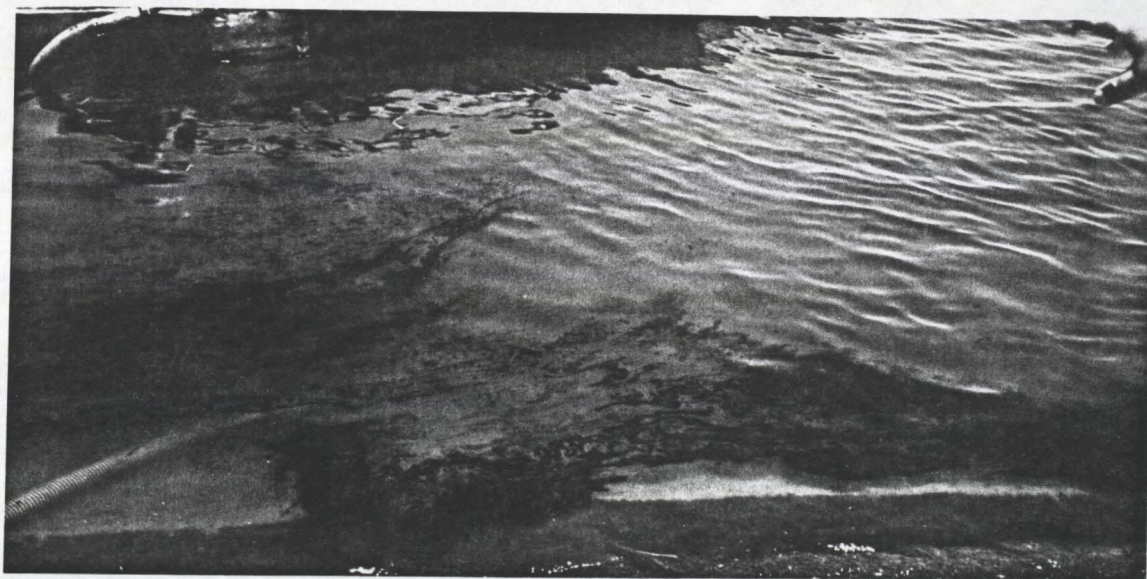


Figure 2.49. Fragmented slick blown to the shallow downwind edge of the evaporation dam.

The remaining oil had been blown across the dam and had settled on the downwind edge (see Figure 2.49) where it was too shallow to be approached and recovered by the prototype. This had to be recovered later by a pump.

The test was halted when the vacuum tank was full. The mixture was left to allow the oil to separate from the water, which was then drained off. The amount of recovered oil was measured and the results are shown in Table 2.7.

Total volume of oil poured in dam	0,275 m ³
Total volume of oil and water recovered	2,1 m ³
Total volume of oil recovered	0,130 m ³
Percentage oil recovered	47,3%

Table 2.7. Prototype oil recovery results

Discussion

The final oil test was the first of its kind for this study. The test made it easier to appreciate the complexities of cleaning up a real spill. There are many obvious differences between a controlled spill and an accidental one. This "spill" contained 0,275m³ which is considered very minor. With such a small spill, oil recovery is slow, as the oil layer is very thin and currents and wind can push it into areas where it is difficult to reach with mechanical equipment, as this test proved. During the initial sawdust test, the dust drifted into corners of the quay which were not accessible by the craft. In order to recover it, it was necessary to manoeuvre forward and astern which, in a spill situation, will churn up and mix the oil and water.

In the event of a larger spill, oil, pushed to the downwind side of a clean-up area, would spread over a greater area and therefore is more easily recovered by the prototype. As demonstrated during the test, oil recovery is easier when the slick is thick.

A further difference between this test and an actual spill was the absence of a swell on the dam. However, it was concluded that the prototype will effectively recover oil in a swell as it was effective during the previous sawdust test in Saldanha Bay. The oil test in the dam confirmed that the recovery process of sawdust is comparative to that of oil. During both tests, it was found that the recovered load in the trap remained isolated from the outside flow.

During this test, the skimmer recovered some weathered oil which had formed into sticky lumps. It was considered likely that such oil would stick to the trap entry as it was passing through. However, no difficulties were experienced but the lumps were difficult to recover because they were not fluid and remained bobbing on the surface. A problem is anticipated when recovering heavily weathered mousse, but specialised pumps such as the *GT* Series (Section 1.1.2) could be adapted for the prototype. As the prototype has not been tested on a mousse, such recovery is considered a limitation until properly tested.

Chapter 3: Conclusions

The objective of this study was to construct a boom/skimmer combination to meet the operational requirements of Section 2.0. During the study, the boom and skimmer were dealt with separately and were not tested together as problems were encountered with the boom prototype during testing. Further research on this project, which is described in Chapter 4, would involve the development of a boom and incorporated skimmer, thus eliminating the need for separate units. The successful principle of the skimmer operation will be utilised to achieve this.

3.1 The boom

The fundamental principle of the boom, viz. an oil trap shrouded from the flow by deflector floats positioned ahead of it, is sound. The major fault with the concept was the turbulence and gravity waves that were created in the trap by the deflector floats. By using a larger scale model (1/3 to 1/2) than was utilised in the development of our boom, the causes of this can be identified and eliminated. Already discussed is a solution where the deflector floats are attached to the boom and held below the water surface. In this position they serve their required function of shrouding the trap and deflecting the flow into line without creating turbulence.

3.2 The skimmer

During the oil recovery tests in the evaporation tank, oil entered through the trap of prototype without turbulence while operating at 1,2 m/sec. Pure oil was recovered from the trap when the oil layer was thick, but 12 litres of oil could not be recovered when the

layer became too thin. This problem can be rectified by using a specialised pump.

While operating in a moderate swell in Saldanha Bay, the prototype successfully recovered sawdust which was retained in the trap. In addition, the profile plate positioned across the bow successfully merged the fast and stationery water.

The following conclusions can be drawn:

- (i) the craft is smaller and more simple in design relative to most contemporary equipment. For example the smaller of the range of the Ro-Clean *Polcat* oil recovery boats (see Section 1.1.1) also has a skimming width of 2m, and the design includes oil storage tanks and the accompanying pumping layout, and thus implies a higher cost than the craft described here. The craft has a smaller wetted surface area, and is propelled by a small outboard motor and thus running and maintenance costs are lower than the larger in-board motor of the *Polcat*.
- (ii) although the craft has a 2m skimming width, further research (described in Chapter 4) would determine whether a craft with a wide skimming width could be operated efficiently,
- (iii) all tests carried out on the craft have shown that it should recover oil with a low water content efficiently while operating 1,2 m/sec in moderate sea conditions. This is comparable to the equipment such as Vikoma's *Weir Boom Rapide* and Allmaritim's *FOICS 800* (see Section 1.1.4). However the manufacturers claims do not

include the percentage water content in the recovered oil which could be high, as both configurations incorporate a boom towed by two or more support vessels. Thus, a fast body of water merges with a stationery one in the catenary and wave action can be expected in that location,

- (iv) the craft can be used to recover a wide range of oils which are not at zero buoyancy, viz. relative density of approximately 0.95 - 1, or have a high viscosity which will impede the flow through the trap entry. Any pump, which is required to recover the spilt oil, can be adapted and fitted to the craft, and
- (v) the oil storage facilities, which may consist of a oil bag being towed behind the craft, or a support vessel, can be changed when fill during clean-up operations. Thus the craft is not limited in oil storage space and can be utilized without any lengthy delays when the recovered oil is transferred to another storage facility. Also, when tanks are full, they increase the craft's inertia which adversely effects its manoeuvrability and its ability to conform to the floating oil layer on the water surface. Thus the concept of remote oil storage tanks enhances the crafts performance.

Thus, in conclusion, the prototype developed during this study constitutes a more efficient and effective skimmer than existing equipment.

Chapter 4: Further Research

In Chapter 3, it was concluded that the prototype was successful on the bases of the tests conducted. However, areas for improvement are as follows:

- (i) a wider skimming width is required and thus the concept will require the incorporation of a set of booms. The boom concept developed during this study requires modification, and it is anticipated that flow problems will be experienced in the areas where flow from the boom enters the skimmer. Further development in this area is required
- (ii) for the best results, it is necessary to operate the craft at right angles to the wind to prevent disturbances caused by waves being transmitted into the trap area. Although these disturbance did not cause the mixing of oil and water, they need to be minimised, and
- (iii) the craft developed does not have the advantage of a dual purpose function. Vessels such as Ro-Clean's *Polcat* can be used for general purpose activities when it is not required for oil recovery operations.

Future research will comprise the construction of another prototype with the aim of minimising the above-mentioned problem areas. This prototype, shown in Figure 4.1, will consist of a set of booms, each with an incorporated skimmer, linked to each other by a hinge joint to allow flexibility in a swell. Additional boom sections can be added

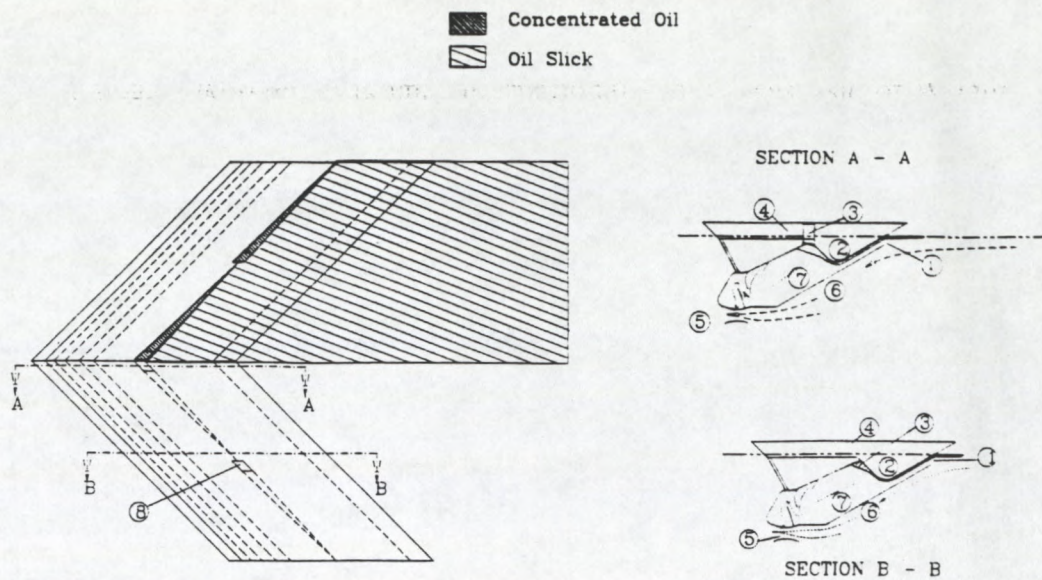


Figure 4.1. Principle of operation - proposed boom/skimmer

1. trap entry
2. bow profile plate
3. oil suction hatch
4. buoyancy chamber
5. venturi
6. flow under boom/skimmer
7. flow through trap - oil separates from water

to increase the skimming width. The booms should be positioned across the bow of a ski-boat or similar craft which can manoeuvre the booms through a slick. The booms are attached to the craft by a rigging arrangement in such a manner that its movement is independent of the boat (refer to Figure 4.2). This is achieved by attaching a bowsprit to the boat and towing the booms from the front. The rigid oil discharge pipes, which are located between the ends of the boom and sides of the boat, serve to stabilise the booms and prevent them from swinging out during manoeuvres.

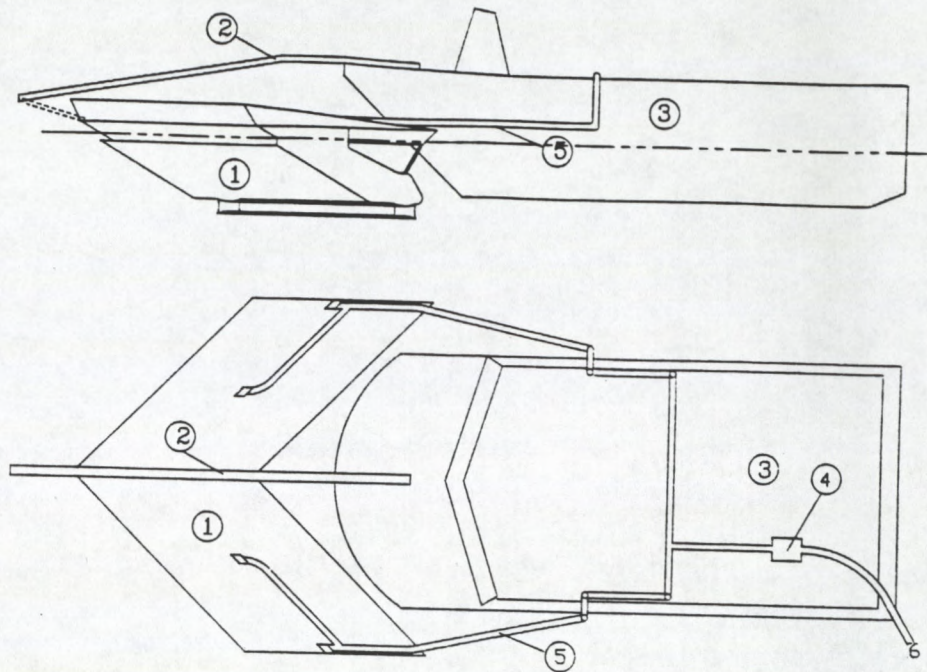


Figure 4.2. Layout of rigging - proposed boom/skimmer

1. boom/skimmer
2. bowsprit
3. ski - boat
4. pump
5. rigid oil suction pipes
6. oil discharge pipe

This craft has been designed to operate at 1,2 m/sec. The flow through the boom is similar to that already described for the skimmer. The surface layer containing oil passes into the skimmer through the trap entry. The presence of the bow profile plate reduces hydraulic jump. On entering the skimmer, oil rises to the highest point within the trap which is oil suction hatch. During the previous prototype tests, it was noted that the

recovered oil collected behind the bow profile plate on entry to the trap, and spread back from the bow as the volume of oil increased. Thus, the length of the proposed prototype will be shortened and the oil suction hatch located at the entry.

The trap is covered by the deck, thus eliminating any free surfaces which should prevent the surface wave from being transmitted into it. The deck incorporates the oil collection trap. The depth of this trap decreases down its length to allow oil to rise and concentrate around the highest point, which is the oil suction hatch. This will eliminate the problem experienced with the previous skimmer where the remaining thin layer of oil could not be recovered. Each boom section has two suction hatches

Oil from the suction hatches is recovered through the suction pipes by a pump located on the boat. As previously, it is pumped through a flexible discharge pipe to storage facilities which will either be a shore tank, a support boat, or a Unitor oil bag.

Water, separated from oil, passes the oil separation plates and exits the boom through the water drains. The venturi, located at the drains, will create a low pressure and thus enhance the flow through the trap.

It is anticipated that the proposed boom/skimmer will have the following advantages over the previous skimmer:

- (i) the boom/skimmer combination will be an attachment to a boat and thus allowing it a dual purpose function,
- (ii) the boom/skimmer combination will be smaller and simpler than the craft

- constructed during this study. Thus it can be constructed at a lower cost,
- (iii) it will be of low mass, and thus possess little inertia and thus be effective in recovering oil with a low water content,
 - (iv) the enclosed trap will eliminate disturbances being transmitted into the trap which were experienced when testing the skimmer craft, and
 - (v) the skimming width can be increased as required by the addition of more boom sections.

REFERENCES

- [1] Hodson, B., (1990), "Can the Wilderness Heal", *National Geographic*, January, Vol 177, No 1, pp. 5 - 43.

- [2] Anon, (1989), "Exxon Valdez Oil Spill Clean-Up - Hearing Before Subcommittee on "Coast Guard and Navigation of the Committee on Merchant Marine and Fisheries House of Representatives", U.S. Government printing office, Washington, USA, pp. 124 - 130, 165 - 190, 199.

- [3] Anon, (1990), "Dredge modifications: One Method of Oil Spill Response", *Surveyor* - Publication of American Bureau of Shipping, Paramus, USA, September, pp. 33.

- [4] Anon, (1991), "Right Boat", *Fairplay International Shipping Weekly*, Surrey, U.K., 11 July, pp. 33.

- [5] Anon, (1989), "Oil Pollution Abatement at Sea and in the Coastal Waters of the Federal Republic of Germany ", published by the Federal Minister of Transport, Bonn, Germany.

- [6] Anon, (1995), "Total Oil Response", *Fairplay International Shipping Weekly*, Surrey, U.K., 12 January, pp. 27.

- [7] Catalogue, "Polcat Anti Pollution Workboat", Ro-Clean, Tonbridge, U.K.
- [8] Anon, (1984), "Manual on Oil Pollution : Section IV", International Marine Organisation, London, pp. 10 - 27, 40 - 52, 60 - 64, 104 - 109.
- [9] Catalog, "*Seaskimmer 100K*", Vikoma International Ltd, Cowes, Isle of Wright.
- [10] Catalog, (1989), "Vikoma International Equipment Directory", Vikoma International Ltd, Cowes, Isle of Wright.
- [11] Catalog, "*Sea Devil Heavy Oil Skimmer*", Vikoma International Ltd, Cowes, Isle of Wright.
- [12] Catalog, (1992), "*Sea Devil Heavy Oil Skimmer Test Report*", Ref No. SD/1, Vikoma International Ltd, Cowes, Isle of Wright.
- [13] Chance, P. G., (1991), "Clean Ocean Vessels", *Seaways*, published by Nautical Institute, London, September, pp. 15.
- [14] Anon, (1991), "Oil Recovery: Technology that Tames Large Spills", *Mechanical Engineer*, May, pp. 44 - 49.
- [15] Catalog, (1993), "*Cascade LP 3000*", Ref No 1362TV 11/93, Vikoma International Ltd, Cowes, Isle of Wright.

- [16] Catalog, "*Vikoskim*", Vikoma International Ltd, Cowes, Isle of Wight.
- [17] Catalog, "*Ro-Skim*", Ro-Clean, Tonbridge, U.K.
- [18] Catalog, "Pharos Marine *G T* Series Skimmer/Pump Systems Technical Specifications", A. B. Pharos Marine Ltd., Brentford, U.K.
- [19] Catalog, "Desmi-Ocean Vertical Archimedes Screw Skimmer", Desmi Ltd., Tagholm, Denmark.
- [20] Catalog, "Oil Recovery", Frank Mohn Skimmers, Flatoy, Norway.
- [21] Anon, (1983), "Use of Skimmers in Combating Oil Pollution", Technical Paper No. 2, ITOPF Ltd, London.
- [22] Catalog, "*Seamop 4090* Skimmer", Ro-Clean, Tonbridge, U.K.
- [23] Catalog, "*Drizit 3000* Oil Skimmer", Drizit South Africa, Durban.
- [24] Catalog, (1992), "Slickbar: Pacesetters in Spill Control Technology... since 1960", Slickbar Products Corp., Seymour, Connecticut, USA.
- [25] Wolfe, D., (1978), "The *Amoco Cadiz* Oil Spill", *Marine Pollution Bulletin*, Vol. 9, 11 November, pp. 288 - 292.

- [26] Anon, (1981), "Use of Booms in Combatting Oil Pollution", Technical Paper No 2, ITOPF Ltd, London.
- [27] Breslin, M., (1978), "Boom Configuration Tests for Calm Water, Medium Current Oil Spill Diversion", Ref No. EPA-600/2-78-186, US Environmental Protection Agency, Cincinnati, USA.
- [28] Catalog, (1993), "*Shore Guardian Booms*", Ref No.1140 TV 3/93, Vikoma International Ltd, Cowes, Isle of Wight.
- [29] Catalog, (1993), "*Guardian Boom*", Ref No. 1135 TV 3/93, Vikoma International Ltd, Cowes, Isle of Wight.
- [30] Catalog, (1993), "*High Sprint Boom*", Ref No. 1100 TV 3/93, Vikoma International Ltd, Cowes, Isle of Wight.
- [31] Catalog, "*Floating Oil-Boom Boss-Covalca Patents*", Covalca *Floating Systems Division*, Rome, Italy.
- [32] Catalog, "*Anti Pollution Booms*", Aerazur, Issy-Les-Moulineaux, France.
- [33] Catalog, "*Oil Fence - The Oil Spill Containment Solution*", Ref No. 10M 2/87, Globe International, New York, USA.

- [34] Catalog, "*Fastflow Skimmer*", Ref No. 1345 TV, Vikoma International Ltd, Cowes, Isle of Wright.
- [35] Catalog, "*Weir Boom Rapide Systems*", Vikoma International Ltd, Cowes, Isle of Wright.
- [36] Catalog, "*Nofi Vee Sweeps*", Allmaritim A/S, Bergen, Norway.
- [37] Anon, (1982), "Use of Oil Spill Dispersants", Technical Paper No 4, ITOPF Ltd, London.
- [38] Kirby, S., (1993), "The Thin Black Line", *New Scientist*, London, 30 January, pp. 24 - 25.
- [39] Anon, (1982), "Aerial Application of Oil Spill Dispersants", Technical Paper No 3, ITOPF Ltd, London.
- [40] Anon, (1993), "Shelanders Roll out the Straw Carpet", *New Scientist*, London, 30 January, pp. 7.
- [41] Cogan, A., (1992), "Waxy Weeds sup on Oil Slicks", *New Scientist*, London, 16 May, pp. 20.

- [42] Anon, (1991), "Bugs Eat Oil", *Fairplay International Shipping Weekly*, Surrey, U.K., 11 July, pp. 33.
- [43] Anon, (1994), "Alaska Clean Seas Test In-Situ Burning on Emulsified Oil", *Oil Spill Intelligence Report*, Cutter Press, Arlington, USA, 15 September.
- [44] Tennyson, E. J., Wittaker, H., (1987), "The 1987 Newfoundland Oil Spill Experiment, an Overview", Published by Mineral Management Services, Reston, USA, and Environment Canada, Ottawa.
- [45] Ross, S. L., (1989), "Tank Testing of Skimmers with Waxy and Viscous Oils", Environmental Research Ltd., Ottawa, Canada.
- [46] Catalog, "Unitor Oil Bag", Unitor, Kolbotn, Norway.
- [47] Anon, (1991), "In the Bag", *Fairplay International Shipping Weekly*, Surrey, U.K., 11 July, pp. 33.
- [48] Wexham, B., "Shipwrecks of the Western Cape", Howard Timmins Publishers, U.K., pp. 98 - 102.
- [49] Sharp, J. J., (1981), "Hydraulic Modelling", Butterworth Press, London.

- [50] Dake, J. M. K., (1983), "Essentials of Engineering Hydraulics", Macmillian Press, London, pp. 95 - 125, 142 - 151.
- [51] Barrass, C. B., (1994), "Further Discussions on Squat", *Seaways*, published by Nautical Institute, London, March, pp. 4 - 6.
- [52] Ven Te Chow, (1959), "Open Channel Hydraulics", Mc Graw-Hill, Kogakusha, pp. 3 - 59, 93 - 111, 217 - 223, 262 - 265.
- [53] Prasuhn, A. L., (1987), "Fundamentals of Hydraulic Engineering", Dryden Press, Florida, USA, pp. 212 - 217, 221 - 235.
- [54] Swern, D., (Edited by), (1979), "Baileys Industrial Oils and Fats", Volume 1, 4th Edition, John Wiley and Son, Philadelphia, USA, pp. 178.
- [55] Cormack, D., (1980), "Response to Oil and Chemical Pollution", published by Warren Springs Laboratory, U.K., pp. 136 - 141.
- [56] Oudet, L., (1972), "In The Wake of the *Torrey Canyon*", The Royal Institute of Navigation, London, pp. 10 - 25, 64 - 69.
- [57] Anon, (1992), "Marine Pollution and Safer Ships", Drewry Ship Consultants, London, pp. 17, 22 - 25, 29 - 39, 50, 55, 57 - 70, 73, 79 - 99, 101 - 108.

- [58] Morgan, N., (1990), "Marine Technology Reference Book", Butterworths, London, pp. 3 (67), 13 (19 - 20).
- [59] Anon, (1990), "Guidelines for The Preparation of a Shipboard Oil Spill Contingency Plans", compiled by Oil Companies International Marine Forum and ITOPI Ltd., Witherby and Co., London.
- [60] Anon, (1996), "Germans Lay Oil Spill Trap", *Fairplay International Shipping Weekly*, Surrey, U.K., 25 July, pp. 7.
- [61] Vincenzini, E., (1992), "International Salvage Law", Lloyds of London.
- [62] Anon, (1981), "U K P&I Club", Thos R. Miller and Son, London.
- [63] Anon, (1989), "Tired of Talking", *Fairplay International Shipping Weekly*, Surrey, U.K., 22 June, pp. 2.
- [64] Anon, (1989), "Lack of Response", *Fairplay International Shipping Weekly*, Surrey, U.K., 6 April, pp. 2.
- [65] Anon, (1989), "Maritime Safety", *Seaways*, published by Nautical Institute, London, May, pp. 1.

- [66] Middleton, R., James, C., (1989), "Bosca and the Alaskan Oil Spill ", *Seaways*, published by Nautical Institute, London, November, pp. 12.
- [67] Anon, (1989), "Valdez", *Seaways*, published by Nautical Institute, London, August, pp. 32.
- [68] (1994), "Jury Orders Exxon to Pay \$ 5 Billion in Punitive Damages for 1989 Spill", *Oil Spill Intelligence Report*, Arlington, USA, 22 September.
- [69] Drahos, J., (1990), "U.S. News and Views" *Seaways*, published by Nautical Institute, London, January, pp. 20.
- [70] Shard, A., (1990), "Globe 90-Shipping and Pollution", *Seaways*, published by Nautical Institute, London, September, pp. 9.
- [71] Anon, (1996), "Exxon Seeks Alaskan Right", *Fairplay International Weekly*, Surrey, U.K., 18 April, pp. 9.
- [72] Luddeke, C., (1993), "Lloyds List : Practical Guides to Marine Claims", Lloyds of London Press Ltd., pp. 185 - 193.
- [73] Anon, (1991), "Protecting Our Waters", (Report to the Government of Canada), *Seaways*, published by Nautical Institute, London, September, pp. 9 - 13.

- [74] Montgomerie, A. J., (1993), "The *Braer* Sheland Disaster", *Seaways*, published by Nautical Institute, London, May, pp. 15 - 16.
- [75] Anon, (1994), "Mars Report No. 21", *Seaways*, published by Nautical Institute, London, July, pp. 19 - 21.
- [76] Anon, (1993), "Bad Weather Stops Oil Pollution Control", *Natal Mercury*, Durban, 9 January.
- [77] Anon, (1993), "On the Shetlands, Talk of a Miracle", *Natal Mercury*, Durban, 4 February.
- [78] Anon, (1993), "Health Fears after Oil Spillage", *Natal Mercury*, Durban, 11 January.
- [79] Anon, (1996), "Disaster on the Rocks", *Fairplay International Shipping Weekly*, Surrey, U.K., 29 February, pp. 21.
- [80] Anon, (1995), "OPAs and COFRs", *Fairplay International Weekly*, Surrey, U.K., 2 November, pp 6.
- [81] Anon, (1996), "*Sea Empress* Lightning nears Completion", *Fairplay International Shipping Weekly*, Surrey, U.K., 26 February, pp. 7.

- [82] Jernelov, A., Linden, O., (1981), "*Ixtoc I* : A Case Study of the World's Largest Oil Spill ", *Ambio*, Vol. 10 No. 6, pp. 299 - 306.
- [83] Anon, (1992), "*Katina P* Captain Denies Ship was on way to Scrap Yard", *Natal Mercury*, Durban, 1 June.
- [84] Anon, (1992) "Oil Stains Coast as Tanker Bleeds", *Daily News*, Durban, 22 April.
- [85] Anon, (1992), "High Drama as Crippled Oil Tanker Sinks", *Natal Mercury*, Durban, 27 April.
- [86] Anon, (1992), "*Katina-P* Owners turns a Blind Eye to Slick", *Natal Mercury*, Durban, 28 April.
- [87] Anon, (1992), "Sunken Ship no Threat to Environment", *Daily News*, Durban, 27 April.
- [88] Anon, (1992), "*Katina-P* Oil Pollutes Beach", *Natal Mercury*, Durban, 29 September.
- [89] Anon, (1992), "Bugs Used in Oil Spill Clean-Up", *Sunday Tribune*, Durban, 4 June.
- [90] Anon, (1992), "*Katina-P* Oil at Umdloti", *Natal Mercury*, 26 May.

- [91] Anon, (1992), "Oil Danger to SA Coast Exaggerated", *Natal Mercury*, 30 April.
- [92] Authors own observations
- [93] Anon, (1994), "Cape faces Worsening Catastrophe", *Natal Mercury*, Durban, 27 June.
- [94] Anon, (1994), "China Blamed for Oil Disaster", *Natal Mercury*, Durban, 29 June.
- [95] Anon, (1994), "Penguin Disaster", *Natal Mercury*, Durban, 4 July.
- [96] Anon, (1994), "2000 Penguins Suffocated", *Natal Mercury*, Durban, 8 November.
- [97] Anon, (1994), "2000 Oil-Free Penguins Released into Sea", *Daily News*, Durban, 27 July.
- [98] Anon, (1994), "Cape Oil Slick Clean-Up Operation Nearly Finished", *Natal Mercury*, Durban, 15 November.
- [99] Anon, (1994), "Beaches Hit by Oil Pollution", *Natal Mercury*, Durban, 7 December.
- [100] Anon, (1994), "Rig Drains Nazi Wreck", *Natal Mercury*, Durban, 17 October.

- [101] Anon, (1994), "Sunken Ship Leaking Oil", *Natal Mercury*, Durban, 30 August.
- [102] Anon, (1994), "Divers to Check Tanker Wreak for Oil", *Natal Mercury*, Durban, 20 October.
- [103] Anon, (1996), "ISU Reports Sharp Rise in Oil Pollution", *Fairplay International Shipping Weekly*, Surrey, U.K., pp. 19 - 21.
- [104] Drahos, J., (1990), "Tanker Safety Study Group", *Seaways*, published by Nautical Institute, London, October, pp. 24 - 26.
- [105] Anon, (1994), "Record Deficiencies ", *Seaways*, published by Nautical Institute, London, September, pp. 32.
- [106] Anon, (1991), "A Much Closer Shave for *Atlas Pride*", *South African Transport*, September, pp 30 - 31.
- [107] Anon, (1995), "Casualties Follow Familiar Patten", *Fairplay International Shipping Weekly*, Surrey, U.K., 9 March, pp. 21.
- [108] Parker, C.J., (1993), "Port and Shipping Management", supplement to *Seaways*, published by Nautical Institute, London, August, pp. 6 - 10.

- [109] Anon, (1994), "Ageing Ships Pose Risk to Cape Coast", *Sunday Times*, Johannesburg, 3 July.
- [110] Anon, (1996), "Boom or Bust ", *Fairplay International Shipping Weekly*, Surrey, U.K., 7 March, pp. 14 - 16.
- [111] Anon, (1995), "UK Detains 190 Ships in 1994 - 95", *Fairplay International Shipping Weekly*, Surrey, U.K., 6 July, pp. 6.
- [112] Anon, (1989), "What Price Life Extensions", *Fairplay International Shipping Weekly*, Surrey, U.K., 23 November, pp. 5.
- [113] Anon, (1989), "Anatomy of a Casualty", *Fairplay International Shipping Weekly*, Surrey, U.K., 14 December, pp. 17.
- [114] Rankin, P., (1993), "Tanker Inspection Jungle", *Seaways*, published by Nautical Institute, London, August 1993, pp. 6 - 10.
- [115] Beaumont, J. D., (1990), "Ship Construction and Safety - Tankers for the 1990s", *Seaways*, published by Nautical Institute, London, May, pp. 9 - 14.
- [116] Anon, (1995), "*Nicholas H* - Lords Uphold Class Society Immunity", *Fairplay International Shipping Weekly*, Surrey, U.K., 2 November, pp. 28 - 29.

- [117] Anon, (1989), "Steel or Paper", *Fairplay International Shipping Weekly*, Surrey, U.K., 14 September, pp. 34 - 36.
- [117] Staniland, H., (1994), "Marine Lepers and the Salvage Laws of South Africa", *S.A. Shipping and Fishing Industries Review*, Cape Town, July/August, pp. 14.
- [118] Anon, (1996), "Salvors Convention Raises Ludicrous Anomaly", *Fairplay International Shipping Weekly*, Surrey, U.K., 25 January, pp. 20.
- [119] Baptist, T., "Salvage Operations", Stanford Marine Ltd, London, pp. 98 - 102.
- [120] Anon, (1977), "The Fate and Effects of Oil in the Sea", published by *American Petroleum Institute Effluent and Water Treatment journal*, October, pp. 525 - 526.
- [121] White, I. C., "Major Oil Spills - There is no Miracle Cure", published by ITOPF, London.
- [122] Thingstad, T., Pengerud, B., (1983), "The Formation of Chocolate Mousse from Statfjord Crude Oil and Seawater", *Marine Pollution Bulletin*, Vol. 14, No. 6, June, pp. 214 - 216.

- [123] Anon, (1993), "Oil Pollution-Ecological Catastrophe or Short Term Problem", written by Baltic and International Marine Council, *Seaways*, published by Nautical Institute, London, March, pp. 10 - 12.
- [124] Bridie, A. L., Wanders H., and others, (1980), "Formation, Prevention and Breaking of Sea Water in Crude Oil Emulsions Chocolate Mousse", *Marine Pollution Bulletin*, Vol. 11, 12 December, pp. 343 - 348.
- [125] Groves, N., (1978), "Black Day for Brittany", *National Geographic*, Vol. 154, No. 1, July, pp. 124 - 135.
- [126] Hennig, H. F., Hennig, K. O., Fricke, A. H., (1980), "Recovery Potential and Chronic Oil Pollution on the South African Coast", *Marine Pollution Bulletin*, Vol. 11, pp. 301 - 302.
- [127] Anon, (1995), "Clifton to Mine Beach Oil", *Natal Mercury*, Durban, 11 August.

Annexure A

A.1 The Model Test Tank

The development of booms was implemented by the testing of models in a tank which was situated in the Fluids Mechanics laboratory at Technikon Natal. The models were held stationary in the tank, and water was circulated around it. This simulated conditions where the model was drawn through water.

A.1.1 The test tank

The six square metre tank, as shown in Figure A.1, was a welded construction, made from mild steel. It was divided into two channels, one used to test the models, which will be referred to as the test channel, and other served as the return channel for the flow of water. The depth of flow in the channels was 0,3m, except on one end where the depth was increased to 1,1 m for the development of another unrelated project. Figure A.2 and A.3 show the model in the test channel

The circulation of the flow was initiated by a waterwheel situated at the start of the test channel. The area of free surface outside the test channel was covered with a plate to prevent the build up of an excessive swell caused by waves rebounding off the tank sides.

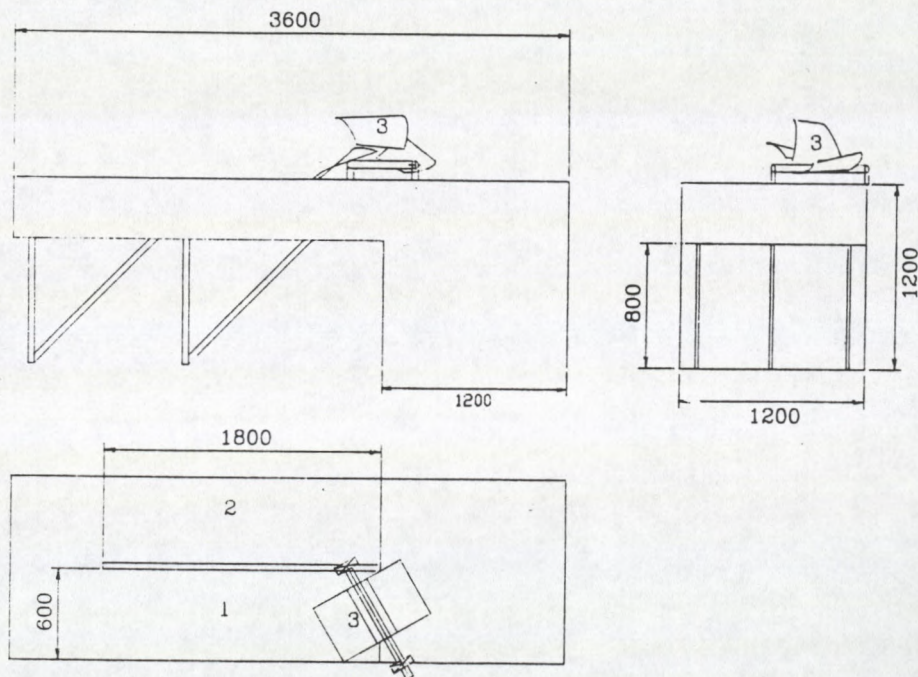


Figure A.1. Layout of test tank

1. test channel
2. return channel
3. water wheel

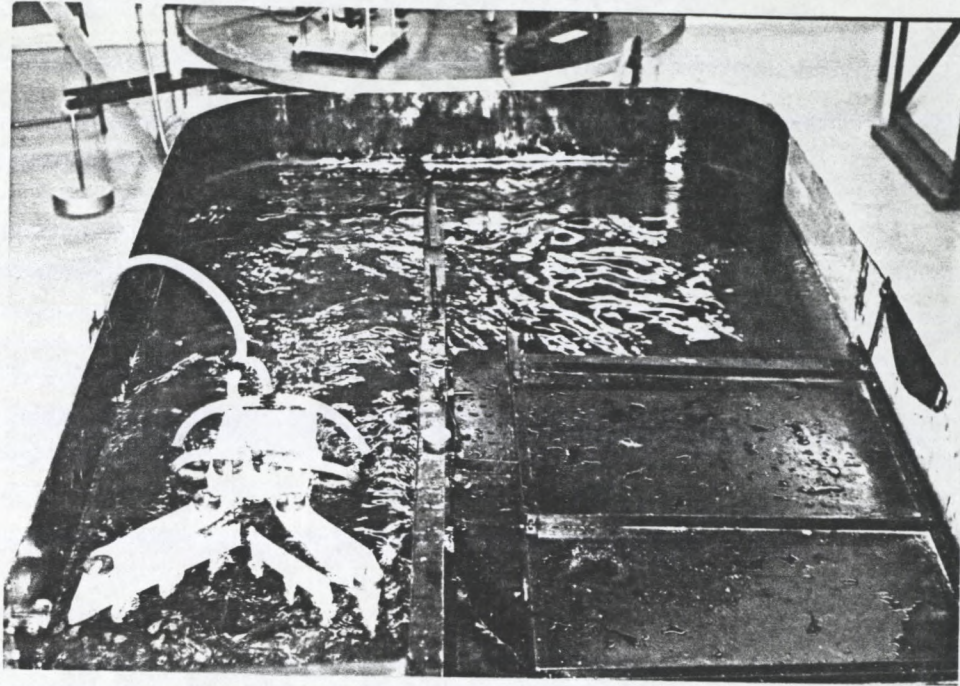


Figure A.2. Model in test channel

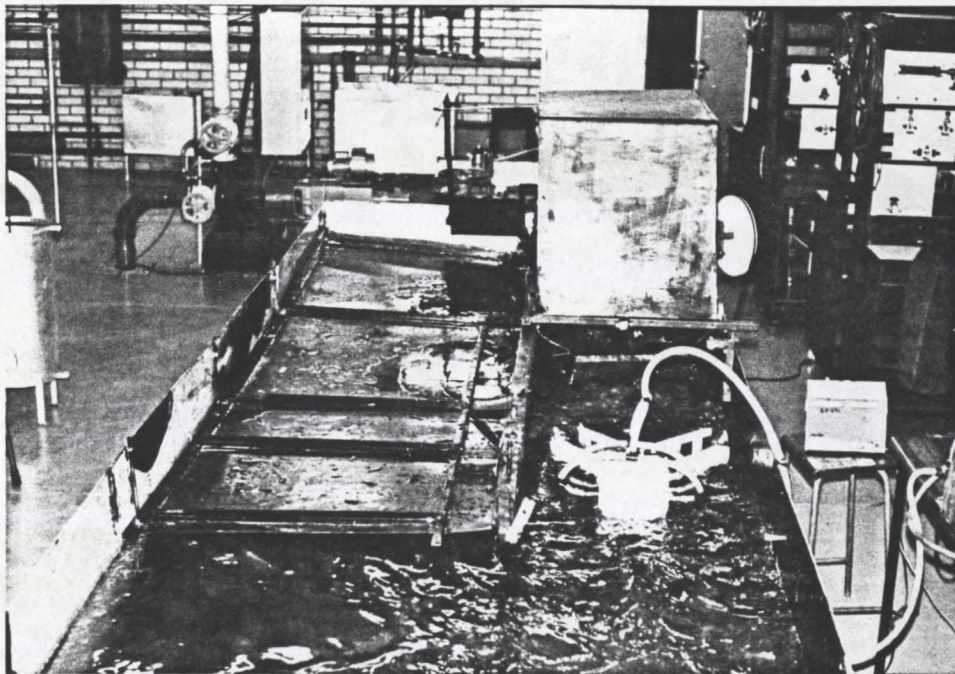


Figure A.3. Tank seen from behind with model prototype

A.1.2 The waterwheel

Kinetic energy, not pressure, was required to circulate the flow of water around the tank. Thus a centrifugal pump was not suitable for this application, and a water wheel, designed to produce a high

volume smooth flow, was selected.

The waterwheel, shown on Figure A.4 and A.5, was made from mild steel and rotated on two bearings. The five blades were set at an angle of 30 degrees to the axis of rotation. By this arrangement, the flow is perpendicular to the blade, and thus the axis of rotation of the wheel was set at 30 degrees to the test channel to ensure the flow was directed down it. This arrangement was necessary as a conventional waterwheel, with the blades positioned parallel with axis of rotation, would be subjected to a periodic sudden de-acceleration force when blade area makes contact with the water surface at entry. This would cause in an uneven flow and would eventually cause the electric motor to burn

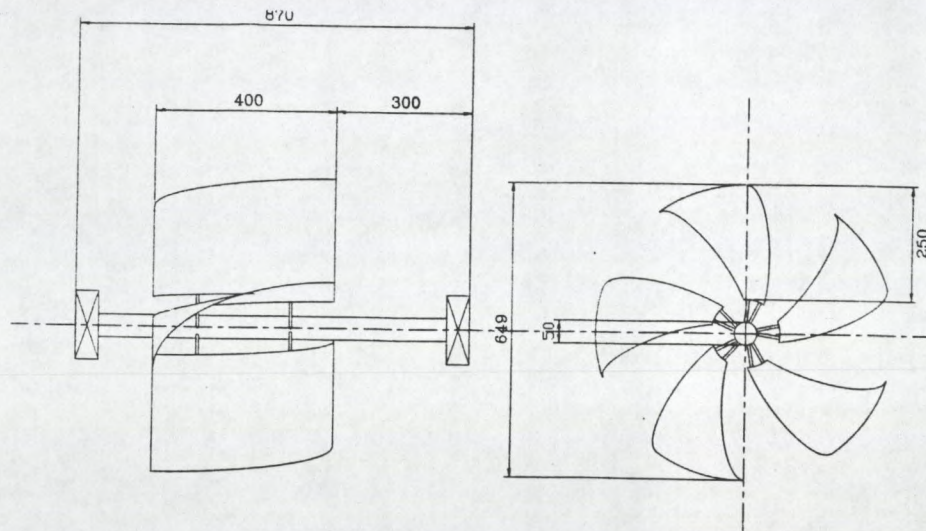


Figure A.4. Layout of water wheel

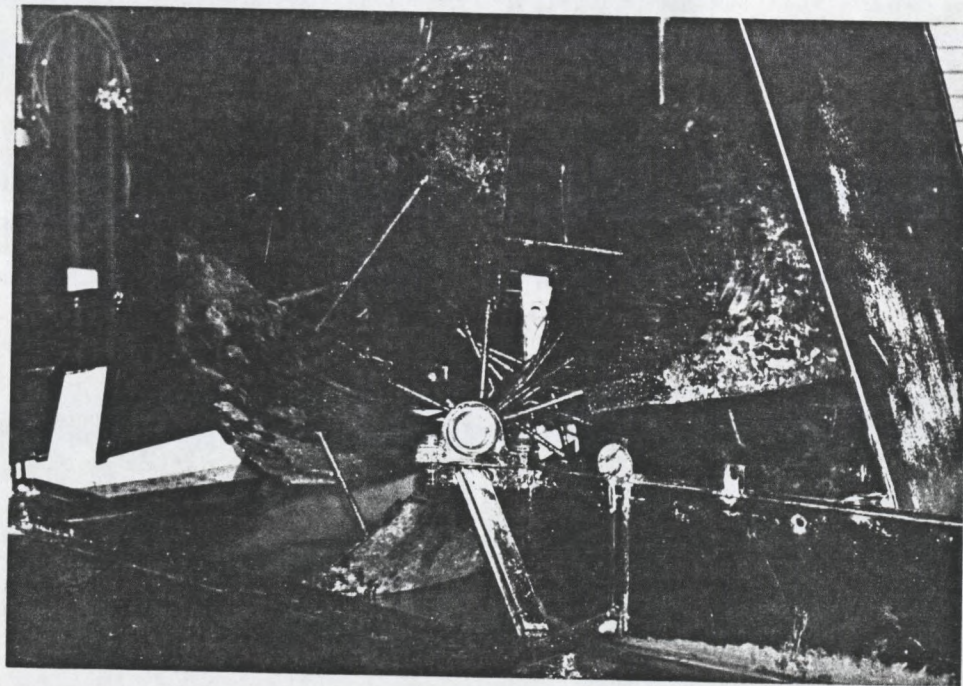


Figure A.5. The water wheel

out. With the blades set at an angle to axis of rotation, the blade entry into and exit from the water is gradual thus eliminating the sudden shocks and the uneven flow.

A D.C. motor, powered by a variable power supply, was used to drive the water wheel. The speed of flow was determined from the supply voltage and a flow metre was used to calibrate the supply voltage/flow velocity scale.

A.2 Scale

The Beaufort Wind Scale Force 4 condition is described as a moderate breeze having small waves becoming longer with the presence of fairly frequent white horses. The wind speed varies between 5.5 and 7.9 m/sec with a mean waves height of 1m. The maximum wave height is 1,5 m.

The wave height determined the scale of the models. The mean height of the waves in the tank was measured as 45 mm, and thus a scale of 22 : 1 is assumed.

A.3 Suitability of Sawdust as Substitute for Oil for Prototype Testing

Two test were conducted to determine the suitability of sawdust as a substitute for oil. The first was to compare the ability of a layer of sawdust to remain afloat on the water surface when a swell is running with that of an oil layer . The second test was to compare the speed at which a floating layer sawdust spreads after being spilt to that of a floating layer of oil.

A.3.1 Report on shaking test

For the first experiment, two 2 2000ml flasks were used. Both were filled with 1000 ml of water. One hundred millilitres of oil was added to the one flash and 100 ml of sawdust was added to the other. The relative density of the oil used for the test was 0,87 while the sawdust was 0.85. Both beakers were secured to a polystyrene holder which was placed on a shaker shown on Figure A.6 machine.

The first test was run at slow speed and the flasks were shaken for 10 seconds. It was found that the oil layer separated from the water immediately, but the sawdust acted differently. The surface layer became slightly damp and formed a thick "pancake". Fine particles remained in suspension in the water, some of which rose to the surface while the remainder settled out on the bottom of the flask in a thin film.

The second test was run at a more vigorous oscillation but for only 3 seconds. The results were the same as for the first test, except that more particles were found to be in suspension. Figure A.7 shows the two beakers before being shaken, and Figure A.8 shows the sawdust particles in suspension after the test.

It was concluded that sawdust rapidly becomes water saturated and loses its buoyancy properties. Sawdust collected from recently cut timber prove the best at withstanding becoming saturated as they still contain wood sap.

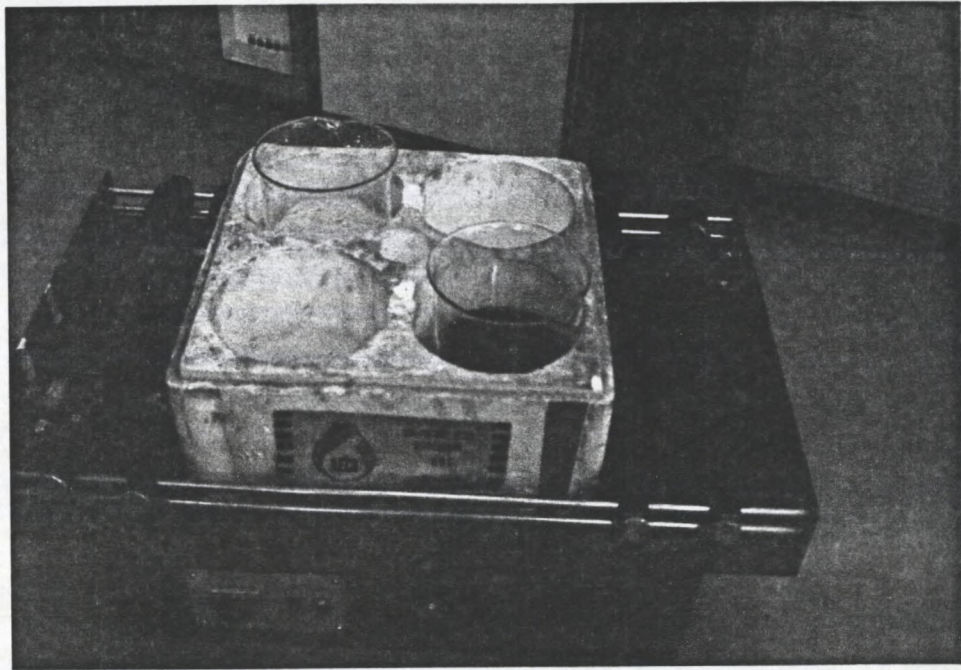


Figure A.6. Beakers containing floating oil and sawdust layers secured to shaker

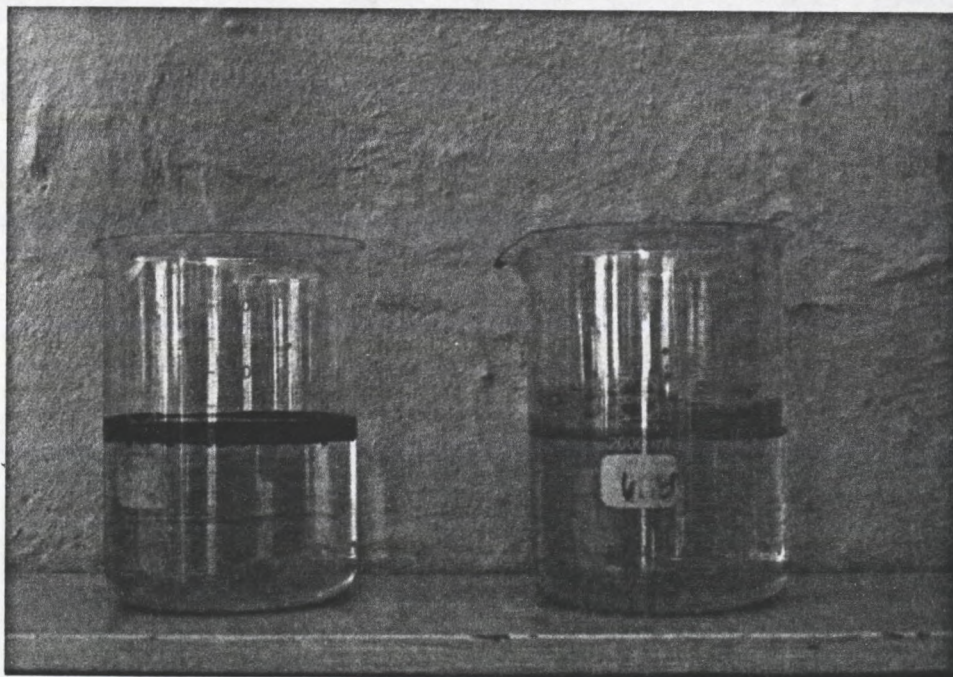


Figure A.7. Beakers containing layers of sawdust and oil floating on water before being shaken

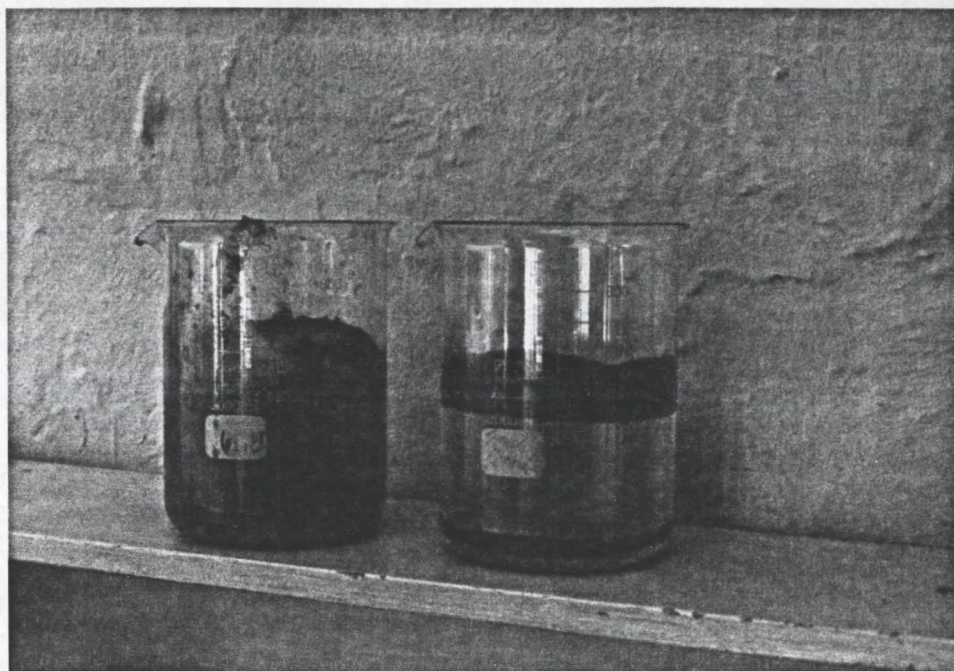


Figure A.8. Beakers containing layers of sawdust and oil floating on water after being shaken. Note suspended sawdust in water

A.3.2 The development of a sawdust slick

For this test, four bags containing 100kg of sawdust was floated out to a shallow area in Durban harbour. The bags were broken open in quick succession and the sawdust was poured onto the water surface as shown on Figure A.9. Thereafter the spread of sawdust was periodically monitored by placing markers on perimeter of the slick as shown on Figure A.10. Initially a North Easterly wind was blowing at average velocity of 5 m/sec and a low swell was running.

As shown on Figure A.11, the slick was thick after being spilled, and after 6 minutes, small "pancakes" had begun to form (Figure A.12). These "pan-cakes" appeared to have strong surface tension forces as small balls of sawdust lying on top of the slick were observed to being blown across it. After 8 minutes the wind dropped to light variable and the test was completed after 15 minutes. At this point a fine layer of sawdust remained on the surface (Figure A.13 - A.14). The progression of the slick was mapped and shown on Figure A.15. The surface area of the slick was determined as 277m^2 after 11 minutes.

During the period that the wind was blowing at a velocity of approximately 5 m/sec, the slick drifted 56m in that direction which equals a velocity of 3% of the wind speed. This compares with the drift of an oil slick.

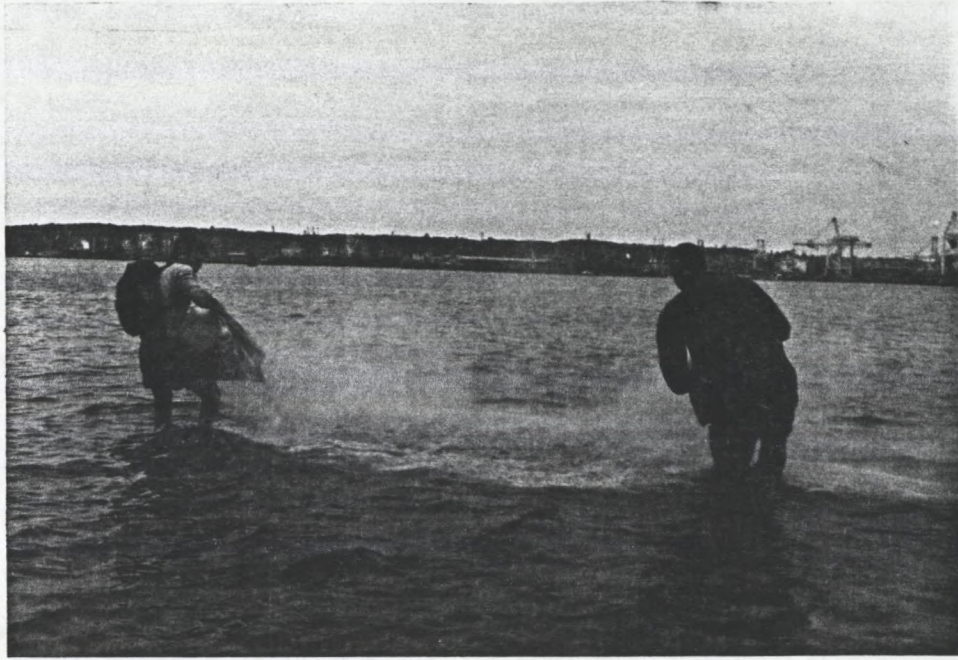


Figure A.9. Sawdust being spilt on water from bags



Figure A.10. Perimeter of slick being mapped out

A test was conducted in the United Kingdom where 1m^3 of oil was spilt on water and it was determined that a circle circumscribing an area of 1809 m^2 formed after 10 minutes. This test was unaffected by wind or current which was not the case during this test when a 10 knot wind blew during

the first 10 minutes. When these results are compared, it is be assumed that sawdust and oil slicks have similar densities (850 kg/m^3). As 100 kgs of sawdust was used during the test, the area circumscribed by that slick must be compared to an area equal with an area equal to 12 per cent of that covered by the 850 kgs of oil which was calculated as 217 m^2 . Therefore the oil slick covered an area equal to 20% smaller than the sawdust slick. The wind factors must be considered when comparing these results. However a percentage of sawdust was lost when it became saturated as, while mapping out the slick progression, pockets of sawdust were observed to be trapped in depressions in the sea bed. It was concluded that the cohesion properties of a sawdust slick are less than an oil slick and thus it will therefore spread quicker.

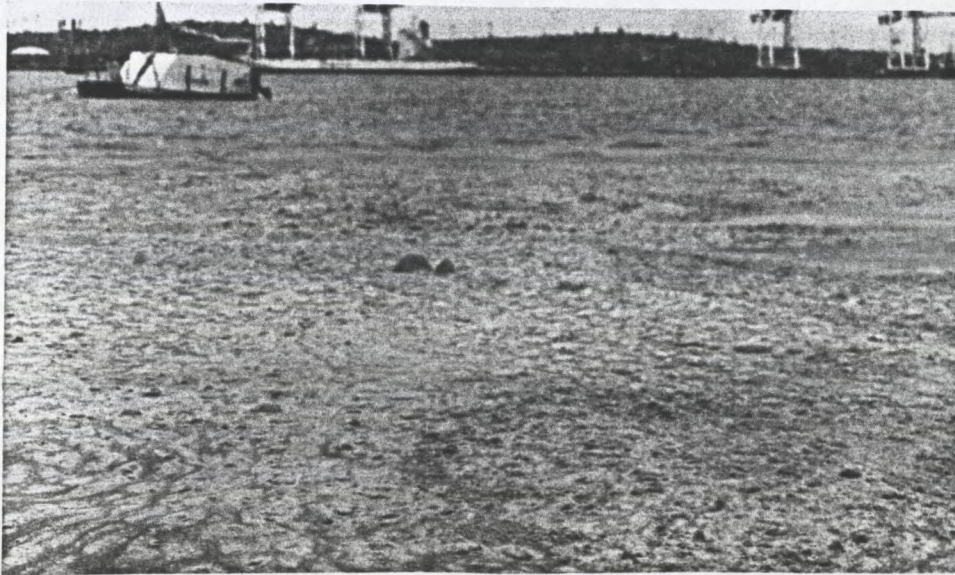


Figure A.11. Sawdust slick 3 minutes after being spilt



Figure A.12. "Pan-cakes" forming after 6 minutes



Figure A.13. Close up - sparse slick after 15 minutes



Figure A.14. Sparse slick after 15 minutes

A.3.3 Conclusion

From these test results, it is concluded that a sawdust slick is not as buoyant as sawdust and rapidly becomes water saturated. Sawdust spreads more rapidly than oil and thus provides a poor substitute. It can be compared to a slick of chocolate mousse which is approaching neutral buoyancy. In terms of recovery

assessment of a skimmer, it was concluded that a skimmer prototype operating on a weir principle, which is capable of recovering a sawdust slick, should have better capabilities of recovering an oil slick from the water surface. Sawdust was used despite being a poor substitute for oil as no better substitute could be found at the time of the tests (see letter Dr. Woods - D26).

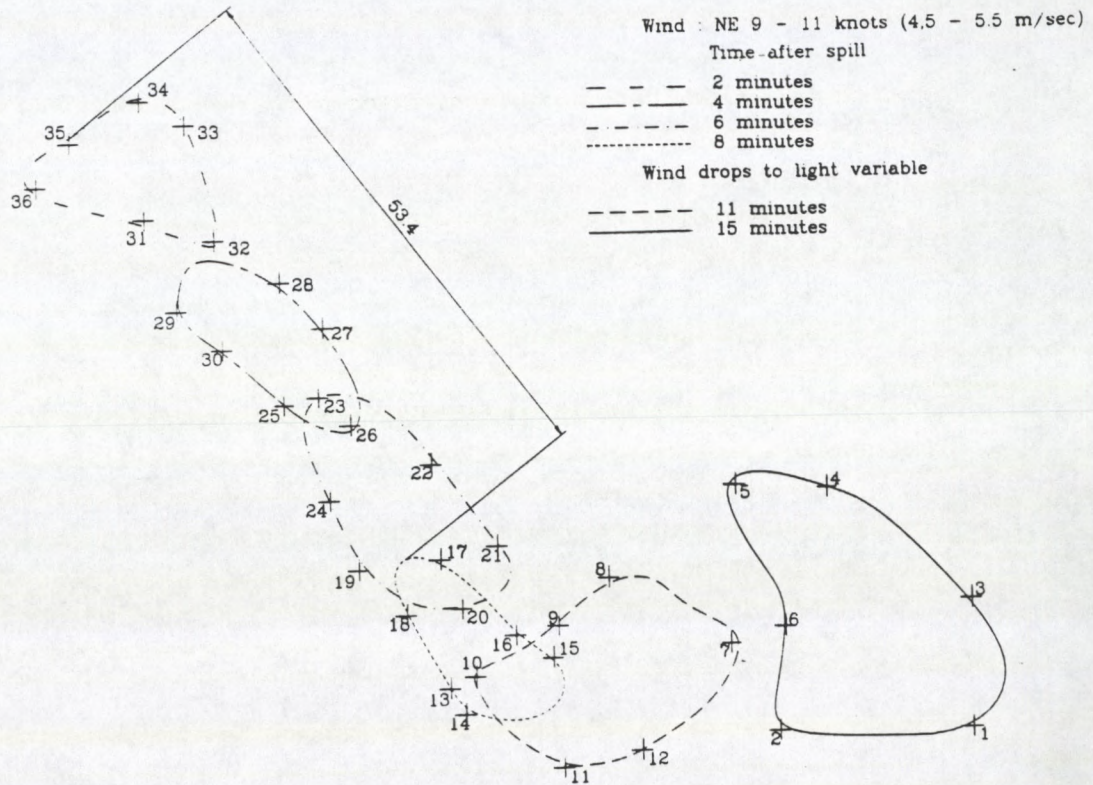


Figure A.15 Slick progression across water surface

Annexure B

Case Studies of Past Oil Spills and the Introduction of Marine Law Relating to Oil Spill

Prevention and Compensation

B.1 The *Torrey Canyon* spill: 18 March 1967

In 1967, the *Torrey Canyon* was a modern tanker of 120 000 DWT and at the time the 13th largest afloat in the world. The American - owned vessel was registered in Liberia to avoid taxation. [53]

The Master had considerable marine experience, with 40 years at sea. However, at the time of the incident, he had been continuously on board the vessel for one year and was very fatigued. His relations with the Chief Officer who was inclined to be insubordinate, were under strain.

On the 18 March 1967, as the *Torrey Canyon* approached her destination of Milford Haven, the Chief Officer made a course alteration without following the Master's expressed orders to consult with him first. This caused the Master to lose his temper and alter the vessel's course back to the original which took the *Torrey Canyon* between the Scilly Isles and Seven Stones reef, a route not recommended for large ships through an area of strong tidal currents. The current set the vessel down onto Seven Stone reef and when this was first realised, it was too late to take avoiding action and the vessel grounded on the reef [56].

A slick of 50 000 tons formed on the day of the stranding and was driven by westerly winds onto the Cornwall and Brittany coasts. It was mainly treated by detergents but the experience from this clean-up operation showed that they can be more harmful to marine life than the oil itself.

A second slick of 20 000 tons formed after the vessel broke up in rough weather, but it was blown offshore where it remained stationary for about 2 weeks. When it eventually reached land, there was hardly any left [56].

At the end of March, the vessel was bombed by the RAF and set on fire to release the approximately 20 000 tons remaining on board. After this operation there was no further leakage from the wreck.

At the time of the spill, there were no guidelines requiring an owner to bear the costs of damage resulting from pollution. To secure payment for clean up costs, the British and French Governments arrested the *Torrey Canyon's* sister ship, the *Lake Palourde* [56].

B.2 Marine law relating to Oil Spill Prevention

The *Torrey Canyon* spill led to the issue of oil pollution prevention and damage compensation becoming part of Marine Law.

Codes and guidelines relating to the carriage of oil cargoes have been compiled from international conventions on recommendations made by organisations such as the International Marine Organisation (IMO), the International Association of Classification Societies, and others. Most countries have incorporated such codes and guidelines into their Marine Law, and they are usually made a requirement in a commercial contract for the carriage of a cargo. Implementation of such is cited as good practice by courts and arbitrators [57].

The IMO is a specialized agency of the United Nations which is based in London. It has a governing body of 128 member states. It supplies technical information on safe practices at sea [58].

B.2.1 International conference relating to intervention on the high Seas in cases of oil pollution (1969)

The convention held in 1969 ruled that a coastal state is permitted to intervene on the high seas against the wishes of the ships or cargo owners to the extent necessary to prevent mitigate or eliminate grave or imminent danger to the coastline or related interests from pollution or threat of pollution following a marine casualty, viz. a state may bomb a vessel to prevent pollution. In this context, the phrase "related interests" refers to tourism, fishing or other marine resources and wildlife [59].

B.2.2 The International Convention on Marine Pollution (MARPOL)

Marpol which was compiled by the Marine Environment Protection Committee (MEPC) of the IMO, covers marine environment protection as far as ships are concerned. Under MARPOL, convention member nations bind themselves to prevent the discharge of harmful substances or effluent into the marine environment. Penalties are imposed in cases of violations. The convention lays down the requirements regarding overboard discharge equipment, the inspection thereof, and the issuing of certificates [57].

Most of the convention deals with the operational discharge of oil, such as tank cleaning. Some of the conditions are that oil cannot be discharged within 50 miles of land or within specially delineated areas. The discharge of oil cannot exceed 60 litres per nautical mile or 1/15 000 of the cargo. Tankers are required to be fitted with equipment which separates excess oil from the oily water discharges and monitors the discharge so that it does not exceed specification. Oil discharge is forbidden in certain regions such as the Mediterranean and North Sea.

Slick removal is a costly operation. In July 1996, a slick resulting from illegal tank washing operation in the North Sea was removed at a cost of \$1,3 million [60].

Marpol deals extensively with the layout of tanks in a tanker. Tankers of over 70 000 DWT which were ordered after 1975 are required to have segregated water ballast tanks. Ballast tanks are used to increase

the draught on a vessel to enable it to sail after it has discharged its cargo. Previously ballast was pumped into cargo tanks which caused pollution when ballast water, intermixed with the previous cargo slops, was pumped overboard prior to loading.

Cargo tanks are constructed to a limited size, and positioned to minimise oil pollution in the event of side or bottom damage [57].

B.2.3 Insurance and compensation for oil pollution damage

Two major international organisations have been established to cover the costs of oil clean-up operations and compensation for damage. The conventions which were developed under IMO, are the International Convention for Civil Liability for Oil Pollution damage (CLC) and the Convention on the Establishment of an International Fund for the Compensation for Oil Pollution Damage (Fund Convention) [56].

In addition to compensation issues, the Master of a ship causing oil pollution may face criminal proceedings leading to fines or imprisonment [59].

All vessels carrying more than 2000 tons of oil on entering the territorial waters of most countries, are required to produce a certificate of insurance covering pollution damage in the event of a spill. Under the convention, the owner of a vessel which spills oil is liable to pay a charge up to US \$200 for each ton of the vessels nett tonnage, with a maximum claim amount of US \$19 million. The oil loaded on any vessel must be covered by the CLC insurance fund to an amount covering the tonnage loaded. However if the incident occurs as a result of an actual fault or negligence on the part of the owner, he is not entitled to the limitation provided. States may seize any vessel or property belonging to the owner of a vessel which has caused oil pollution, if the owner has not provided a fund to meet the required amount for damages. Tanker owners are also responsible for the cost in preventing or minimizing pollution [61].

The Fund Convention provides pollution damage cover for a maximum amount of US \$81 million, which includes compensation by tanker owner under CLC [59].

B.3 Organisations Associated with Oil Spill Clean-up

B.3.1 International Tanker Owners Pollution Federation (ITOPF)

The ITOPF which has a membership of 3200 tanker owners and charters who operate 97% of the worlds tonnage, is actively involved in all aspects of combating oil spills in the marine environment. It provides technical advice on contingency planning, clean-up measures and environmental effects of oil pollution. It is also a comprehensive information source.

ITOPF has given advice at the scene of over 200 spills during the 1980s and has become one of the leading

authorities on all aspects of oil pollution. [59]

B.3.2 P&I Clubs

Oil pollution liabilities of a ship owner are usually insured through the Protection and Indemnity Association (P&I Clubs), which is a non-profit making organisation and has branches throughout the world. The P&I Clubs arrange for the issue of various certificates which are carried on board a tanker to provide evidence of insurance against oil pollution risks.

In the event of an oil spill, the Club acts on behalf of the organisations who cover pollution damage. The P&I Club surveyors are called immediately to the scene of a spill to establish the cause and extent of the pollution damage. They liaise with the authorities and technical experts to ensure that important decisions are made quickly and contracts concluded on the spot. In order to allow the vessel to leave port following the spill, the Clubs provide guarantees of payment of claims. It sets up a fund and processes claims made against the vessels [59, 62].

B.3.3 Classification Societies

The role of a classification society is to set the standards by which a vessel is constructed, and to ensure that they are maintained during construction. During the operational life of a vessel, classification societies carry out periodic surveys to ensure that these standards are maintained and that the vessel is in a seaworthy condition. The classification societies issue the statutory certificate of seaworthiness required in terms of marine law before a vessel can be registered by a state or before it can enter the territorial waters of one. Thus they act on behalf of a Government to ensure that a vessel registered under that States Flag is operated correctly in foreign waters [57, 58].

B.4 The Exxon Valdez Spill: 24 March 1989

The *Exxon Valdez* was a modern United States flagged and manned tanker, equipped with all the latest requirements. It was owned by one of the world's largest oil companies, Exxon Company. However one flaw which should not have been overlooked was that the Master had a drinking problem [63, 64].

At midnight on the 24 March 1989, the 214 861 DWT tanker loaded with 200 700 m³ of crude oil was steaming outward bound from Valdez in Prince William Sound. The Master, who should have been navigating the vessel in such confined waters, was intoxicated and had left his charge to the Third Officer who was under qualified for this responsibility [65].

The vessel altered course to avoid ice and departed from the navigation channel. The new course took the tanker over Bligh Reef and the tanker grounded at its full speed of 12 Knots. Eight of the eleven cargo

tanks were ruptured and by 05h30 that morning, 38000m³ had spilled causing a slick 8000m long by 300m wide. A total of 40 000 m³ eventually leaked into the Sound [2, 65].

In the first critical hours after the spill was reported, no oil spill clean-up equipment or personnel reached the scene. The barge carrying oil spill clean-up equipment reached the scene only in the mid afternoon of the 24 March [57].

The oil spill clean-up contingency plan at the Valdez terminal at the time of the spill allowed for a maximum spill of 31 800m³ of oil, and called for extensive use of in-situ burning (see Section 1.15) and dispersants as means of pollution combat. It was predicted that a considerable amount of oil would reach the shore, as that not even the best efforts would remove the spill entirely, and that the remaining oil would disperse naturally [2].

Damage to the Environment and Spill Clean Up: The reason for the delay in equipment reaching the scene after the stranding was that the barge carrying oil recovery equipment had been used to clean up a previous spill and had been unloaded for servicing. After the equipment reached the scene, the *Exxon Valdez* was not encircled by booms to contain the oil because tankers being used to lighten the remaining oil on board would require to breach the booms to come alongside, and most oil had already leaked from the tanks. This operation took eight days to complete, and thereafter the *Exxon Valdez* was re-floated and towed back to San Diego for repair [2, 66].

Diversions booms were deployed to protect the islands threatened by the spill, and to prepare for in-situ burning in accordance with the contingency plans [2].

Mechanical oil recovery was given highest priority and permission to burn was delayed. Three days after the stranding, a storm passed through the region and dispersed the oil over the Sound thus preventing any planned burning.

Experts from the UK were enlisted and specialised equipment was flown in. A total of 11 000 people, 1000 vessels of varying description and 70 aircraft were deployed during the clean-up [2].

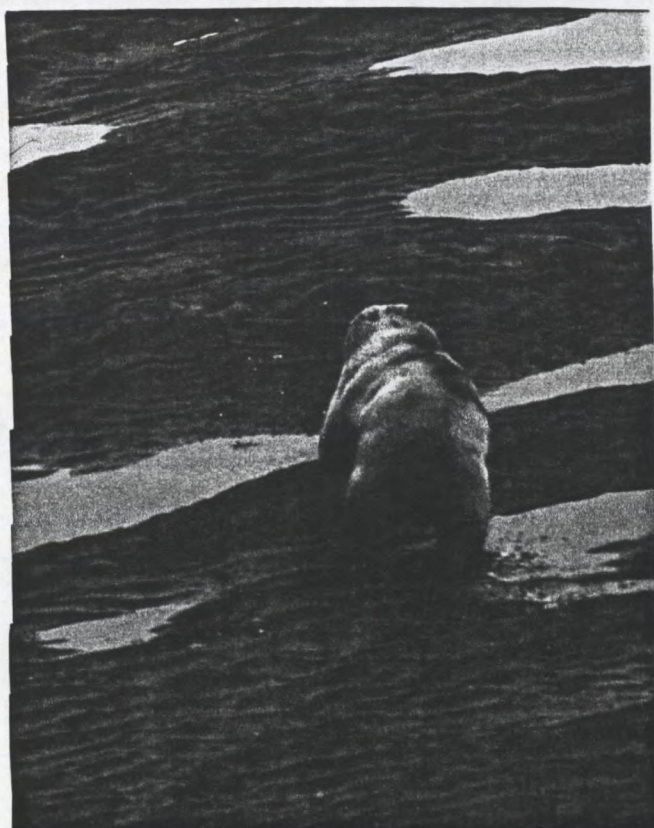
Skimmers were used to recover oil from the Sound. However debris and kelp floating with the oil caused many skimmers to become unserviceable. As the slick became dispersed, teams of two and three vessels towing booms were used to condense floating oil and thereafter recover it (see Figure 1.20 in Section 1.1.3). Fifty thousand tons of oil waste, oily water and debris had been collected by the end of June. It should be noted that oil can emulsify with water to form a mixture three times its original weight, and therefore the amount recovered may only represent one third of mass spilt (see section C.2) [2, 66].



Figure B.1 (Above) The Exxon Valdez on Bligh Reef shown during lightering operations

Figure B.2 (Right) A bear walks through oil on a beach in Prince William Sound

Figure B.3 (Below) A heavily oil impacted bay in Prince William Sound.



Within six weeks, the spill had become widely distributed, spreading up to 300km from the point of stranding. A total of 1170km of shoreline in Prince William Sound and the Gulf of Alaska had been polluted with oil, 8% of which had heavily impacted. By August, 1 120km of the shoreline had been treated. Difficulty was experienced on the heavily impacted beaches, as despite multiple washing, subsequent tidal action continued to draw some remaining oil to the surface and re-oil the beach [2, 66].

The clean-up took three summer seasons to complete. However in 1992, oil was still persistent in the Sound but, based on 25 scientific studies, Exxon company claimed that the Sound had largely recovered and was back to its pre-spill condition. [67]

The spill killed 905 sea otters or approximately 5% population, 123 bald eagles and 28 600 migratory birds comprising 10% of the bird life in the region. Only 211 sea otters, 25 Bald Eagles and 682 migratory birds were successfully treated and released [2].

The Cost to Exxon Company: The clean - up cost paid by Exxon Company was estimated at 2,5 billion dollars. In subsequent court action during 1994, punitive damages of 5 billion dollars were awarded against the company [68].

Although the 40 000 tons spilled amounted to less than 2% of the oil spilled during 1989, the Exxon Valdez will remain a major event in lists of tanker accidents. It happened in a region where oil exploration has always been a politically sensitive issue, and demonstrated how unprepared the oil industry was to deal with such a catastrophe. The American Petroleum Institute "Task Force Report on Oil Spillages" acknowledges that at the time of the reports release the oil industry did not have the "equipment or personnel ready in place to deal with catastrophic tanker spills [69, 70].

B.5 Revised Legislation regarding Tanker Design and Compensation for Oil Spill Clean-Up

B.5.1 1990 US Oil Pollution Act

The stranding of the *Exxon Valdez* in 1989, and other subsequent oil spills resulted in the US Oil Pollution Act (OPA 90) being passed by President Bush. The Act also applies to onshore and offshore facilities. [57]

The key points to the Act are:

1. all responsible parties, defined as "any person owning, operating or chartering a vessel which spills oil" are deemed jointly and severally, strictly liable for all costs for the removal of the oil. The costs also includes those incurred preventing or minimising oil pollution. They also have to meet any damages in relation to the incident, including damage to natural resources, and loss of profits. A limit amount of US \$200 per ton oil spilt or US \$10 million, which ever the greater, is to be paid by the shipowner. This applies to tankers of over 3 000 GT (Gross tonnage). Liability to pay

is unlimited if negligence or violation of regulations can be proved, and

2. all new vessels must be constructed with double hulls (see Section B.7), and all single hull vessel are to be phased out by 2015. No vessels which is over 30 000 tons and older than 28 years may enter the US waters [57].

A rider to this act is that any vessel causing an oil spill is banned from entering that State. This prevents the *Exxon Valdez*, now renamed *Exxon Mediterranean* from entering Alaskan waters for which trade it was built operate in. It is now losing money trading in the international market with a US crew. The act also applies to onshore and off shore facilities [71].

This act has caused controversy, as that statutorily recoverable amounts now include third party damages. This means that if P&I Clubs issues the required certificates, they could be sued directly for amounts which exceed the cover given by the organisations. The P&I Group is prepared to cover claims under the terms of the contracts, but it is not prepared to offer itself to the US courts as guarantor directly responsible for all claims made in consequence of an oil spill by its ship owner members. It would in effect become the property of the claimant under OPA 90 rather than the liability insurer for the ship owner [72].

B.5.2 Revised Marpol Regulations

The US Oil Pollution Act 1990 along with spills such as the *Haven* and *AGRIP Abruzzo* forced changes to IMO regulations. This has resulted in the Marpol regulation 13F and 13G being introduced as of March 1992.

Regulation 13F: stipulates that all tankers of 5000 DWT are to be fitted with a double hull, a mid deck structure or by any other design deemed an equivalent by IMO.

Regulation 13G: Applies to all existing tankers of over 20 000 DWT. Such tankers will go under more rigorous inspections. They must be upgraded to regulation 13F 30 years after delivery.

Amendments to Marpol require tankers to carry a oil spill contingency plan, to prepare to clean up an oil spillage [57].

B.5.3 Shipboard oil spill contingency plan

A contingency plan is required by Marpol to be carried on all tankers. Lack of planning can result in confusion, mistakes and key people being overlooked. This will result in time being wasted during which the situation can worsen. Effective planning will ensure that the necessary action is taken in a structured, logical and timely manner. Copies of the plan must be handed to relevant shore personnel such as terminal operators and P&I Club surveyors [59].

Theoretically the ship's operator/owner may be responsible for the clean-up, but in practice ships personnel will have little control over the way it is organised and conducted. The majority of spills are small operational spills, which generally occur at oil terminals and are usually handled by local response organisation. In these cases the terminals contingency plans take preference over the ships's plan. The prime role of the ship's personnel will be to supply as much information as necessary to assist response, and to cooperate fully with the authorities. Action must be taken to minimise the escape of oil [59].

In the case of a large spill, the safety of the ship and the crew take priority, and invariably the ships action will be limited to reducing leakage and reporting as much relevant information to the relevant authorities. One rule which must always be adhered to is that dispersants should never be poured on a spill without the consent of the proper authority. In most countries, dispersant cannot be used in less than 20 meters of water without the consent of a scientific authority, usually the fisheries [59, 73].

To minimise leakage, oil should be pumped out of a ruptured tank to reduce the head until hydrostatic balance is achieved. The stability and hull stress on the vessel should be taken into account before removing cargo [59].

B.6 The Braer Oil Spill: 4 January 1993

The 89 700 ton Liberian registered tanker was passing through Fair Isle Strait in the North Sea on the night of 4 January 1993. The weather conditions were adverse, and during the passage a pipe running along deck had broken loose, which destroyed an air vent to the fuel tank. This caused the fuel to become contaminated with water. During the night the vessels boilers were shut down for routine adjustments and could not be re-ignited because of the water contamination. The vessel lost power on-route to a safe anchorage to carry out repairs and began to drift down on Garth Ness, Shetland. A tug was dispatched to assist it, but arrived when the vessel was already too close to shore. Attempts to tow the vessel offshore failed and it ran aground under the cliffs at Garths Ness at 11 20 am [74, 75].

Oil began leaking from the vessel. Severe weather prevented salvors from boarding the vessel to pump the remaining oil aboard to a barge. The gale force winds continued, and the tanker eventually broke up on the 12 January releasing all the remaining oil aboard [76, 77].

A total of 85 000 tons of oil was spilt, making *Braer* the world's 12th largest oil tanker spill. Many islanders complained of illness resulting from oil becoming airborne in the gale force winds and spreading overland. A slick, 40 km long, spread from the wreck, causing a fishing ban to be imposed in water round the Shetlands. Environmentalists predicted thousands of sea birds and sea otters would be wiped out. Booms were used to protect the salmon farms on the island, but failed due to the winds. Dispersants were used on the slick. [57,76,78]

Then what can possibly be described as a miracle occurred. Within one month of the spill, the shore of the island were back to normal. The heavy seas had broken up the slick and dispersed it into the water column. [77]

The slick claimed two sea otters and a total of 1549 sea birds as compared to 905 and 28 700 respectively in the case of the *Exxon Valdez* spill. [77]

B.7 Revised Tanker Design

Both the OPA (90) and March 1992 amendments to Marpol 73/78 have lead to change of tanker design. There are two designs to tankers, the double hull and mid deck concept. Both have been approved by IMO, but the latter has not been accepted in the USA. [57]

B.7.1 Double hulled tankers

All new tankers of 5 000 DWT and above must be built with double hulls. Oil tanks separated from the ship side by an oil free space of up to 2 metres. Most tankers are built with a space larger than required for construction and inspection purposes. According to a study conducted by the UK National Academy of Science, double hulls should prevent 3000 to 5000 tons. See figure B.4. [57]

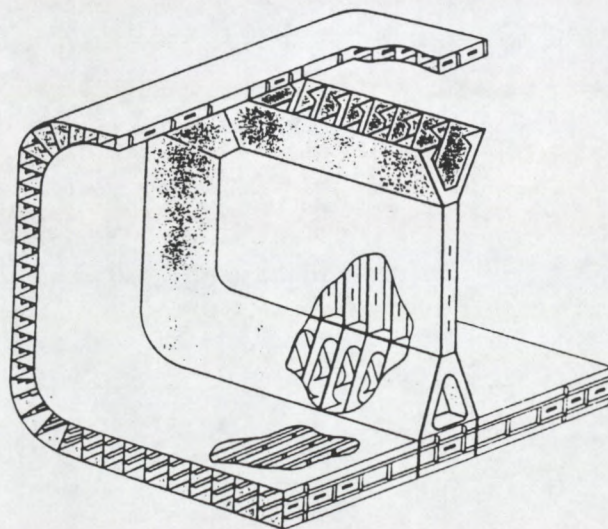


Figure B.4 Layout of a double-hulled tanker

A number of studies have exposed a number of weaknesses with the concept which are:

1. the majority of collisions and groundings involving tankers are low energy accidents, where the inner hull is unlikely to be penetrated. However many critics have concluded that in event of a high energy accident such as the *Exxon Valdez* where rocks penetrated 8 metres into the hull, the inner hull would be breached and would result in the void space being flooded with oil. This would exacerbate the extent of the pollution. The US National Research Council acknowledges the problem to a degree, but it can be overcome with hydrostatic balancing.

Hydrostatic Balance refers to when the pressure head in the tank equals the pressure head outside the tank. If the pressure head of oil in a breached tank is higher than the pressure head of the water line, oil would flow out of the tank until hydrostatic balance was reached. If the pressure head of the tank is lower than the water line, water would flow into the tank until hydrostatic balance is reached (see Figure B.5) [57].

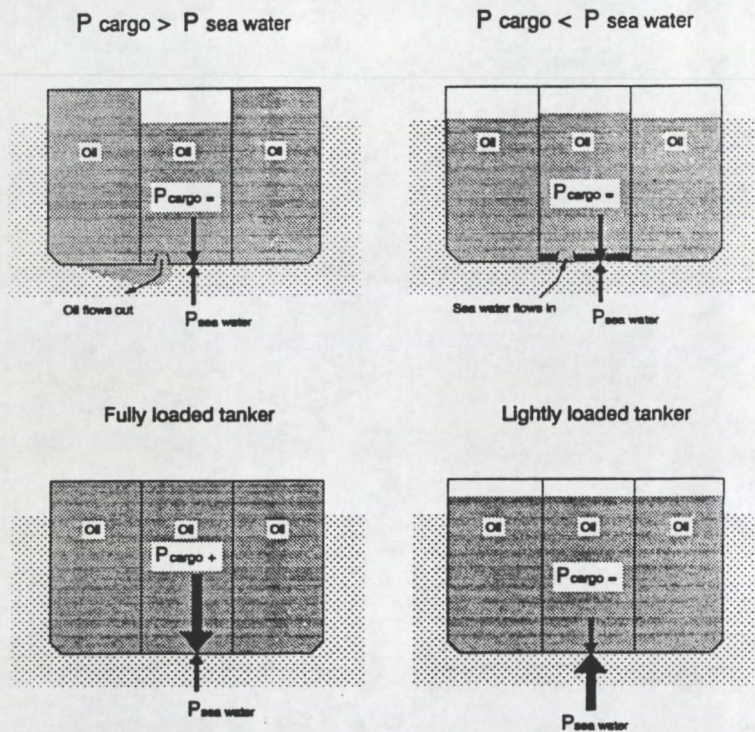


Figure B.5. The principle of hydrostatic balance

In event of both skins of a double-hulled tanker being breached, oil from the tank would flood the void space, which would require to be pumped out, causing salvage operation to become more complicated..

2. The oil remaining in a breached tank of a grounded vessel after hydrostatic balance has been reached is also subject to tidal discharge. When the water level outside the tanks drops with the tide, the oil will leak out until hydrostatic pressure is reached. This occurred during the *Exxon Valdez* spill. [57]
3. There is a possibility of a build up of explosive gases in the sealed double skin area which can result in an explosion. Sealed areas such as ballast tanks are notoriously difficult and dangerous areas to inspect, and therefore an increase in area to be inspected will jeopardise the safety of the surveyors involved. The build up of gasses in void spacing was the cause of the explosion aboard the double - hulled tanker *Aegean Sea* after it ran aground while entering La Coruna, Spain in December 1992. [57, 79]
4. The double skin area will require constant maintenance to prevent corrosion and therefore maintenance costs are increased. With substandard operators, this can lead to major problems. [57]

A case when a spill was averted due to the double - hulled construction occurred in October 1995 when the tanker *Borga* ran aground while entering Milford Haven. The outer skin, not the inner, was ruptured and therefore no oil was spilt. This contrasted considerably with the events at the same port during February 1996 when the single hulled tanker *Sea Empress* ran aground while under pilotage and spilt 82,000 tons of crude. Adverse weather conditions prevented the vessel from being re-floated soon after it ran aground. [80, 81]

B.7.2 Mid-deck design

This concept is believed to be both less costly and more effective than the double hull concept. The design incorporates a continuous deck at mid-deck level through all the cargo tanks and a continuous water ballast tank extending down either side of them [57].

The side ballast tank make the design double sided. The tanks, being wider than those on the double hulled design, have the advantage of offering more protection in the event of a collision and are safer to inspect. [57]

The continuous deck at mid height level divides each cargo tank into a upper and lower tank. The pressure head in the lower cargo tanks when loaded are lower than that the sea water pressure at that depth. Therefore, in the event of lower tanks being breached, water will flow into the tank until hydrostatic balance is reached thus preventing any oil leakage. The disadvantages of this design when compared to the double hulled design is that a small amount of leakage may occur and if the sea current under the hull

was strong enough oil could be drawn through the rupture [57].

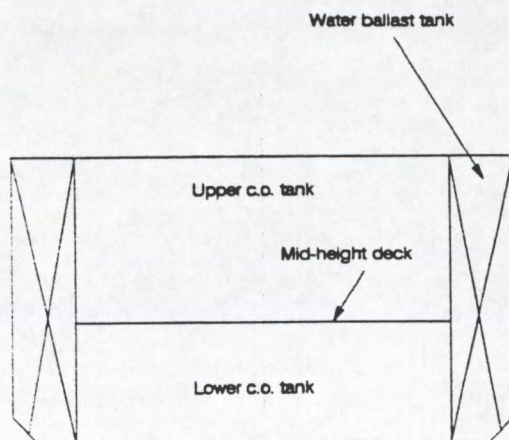


Figure B.6. Section through the tank of a mid-deck tanker

B.8 Other oil spills

B.8.1 The world's largest oil spill - *Ixtoc I*: 3 June 1979

Oil spillages need not necessarily be from tankers. The world's largest spill occurred when the *Ixtoc I* exploratory oil well blew out, spilling 475 000 tons of crude oil into the Gulf of Mexico. [82]

The well had reached a depth of 3625 meters when problems with the drilling operation developed. As the well seemed stable, it was decided to withdraw the drill and seal it by inserting a plug. During the attempts to seal it, an extremely high pressure caused the well to blow out and this was followed by an explosion which sank the drilling platform. Oil and gas began leaking out from the damaged stack and rose to the surface.

Initially the well was estimated to be losing 4500 tons per day and by August it had lost 225000 tons. A relief well was drilled near the blow out well to relieve the pressure and the well was finally capped 290 days after the blow out. [82]

B.8.2 South African coast - *Katina-P*: April 1992.

During April 1992, the Greek tanker *Katina-P* was on route from Venezuela to the United Arab Emirate carrying 66 000 tons of heavy furnace oil. After discharge, the 28 year old vessel was to be sent for scrapping [83].

While rounding the Cape in a heavy sea, cracks developed in the hull. The master decided to continue to calmer waters off Mozambique where he anchored the vessel on a sandbank 30 kilometres off shore. A

25 by 12 metre hole had developed in the hull of the vessel. Oil leaking from the vessel began polluting the beaches and mangrove swamps around Maputo. The worst hit area was the Macaneta Peninsula, a large sand spit which forms a natural barrier for the harbour. About 3000 tons washed onto the spit killing all inter-tidal life [84].

On Wednesday 22 April 1992, the tanker was towed stern first away from the coast in preparation to transfer the cargo to another vessel. On 26 April after being towed 80 kilometres off shore, the vessel broke her back and began to sag amidships. The *Katina-P* broke in two and sank in 2740 metres of water. It was estimated that 12 000 tons escaped from the tanks which ruptured when the vessel broke, causing a slick of initially 3 square km. The remaining 52 000 tons sank with the vessel [85, 86, 87].

The furnace oil was very thick and unlike crude oil it did not break up and mix with the sea water easily. By the 30 April the slick measured 33 miles long by one mile wide. By 11 May the slick, which was no longer toxic, began washing up on the beaches at Kosi Bay, and booms were erected to seal the estuary mouth. Oil continued to be sighted and wash up on various beaches down the coast of Kwa-Natal till 27 September. The washed up oil was removed from beaches by municipal workers, and buried after being mixed with fertilizer which forms bacteria to dissolve the oil [87, 89, 90, 91].

The oil from the *Katina-P* can still be seen stuck on rocks at various Natal beaches. It is completely solid, and shows little sign of deteriorating [92].

In the subsequent enquiry into the sinking, it was found that the vessel initially left Brazil in ballast heading for the ship breaker. However the owners ordered the vessel back to load in Venezuela. The vessel was issued a Certificate of Sea Worthiness in Brazil in 1991 which was valid for 5 years. However the salvors who towed the vessel out to sea described it to be in a terrible state [83, 86].

B.8.3 Off Saldanha Bay - *Castillo De Bellver*: August 1983

On 6 August 1983, the fully laden 271 540 ton VLCC *Castillo De Bellver* after sustaining structural damage to its deck, caught fire off 70 Km off Saldanha Bay. The vessel became totally engulfed in flames and was constantly being buffeted by a strong swell. Eventually the vessel broke its back, sending thousands of tons of oil into the sea, and the resulting fire sent a column of smoke 450 metres up into the atmosphere. The fire burnt itself out, and a while later, an explosion ripped through the stern section causing it to break away and sink. All the oil contained in the stern section was released. The bow section, which was floating vertical to the water surface, was towed 120 miles offshore, where it was sunk. The bow still contains 60 000 tons of oil. [48]

A large black cloud appeared above the town of Riebeeck Kasteel and it began to rain oil. The buildings

in the town were black with oil, the fleeces of sheep were tainted, and the dams in the area were covered with oil films.

Meanwhile the slick which covered 120 sq.miles was a threat to the penguin colony on Dassen Island where half the world's population of Jackass penguins live along with other bird species. A South Easterly wind continued to blow keeping the slick away from land, and finally the rough weather caused it to break up. However thousands of sea birds were killed by the slick. [48]

The *Castillo De Bellver* is reported as the largest oil tanker disaster, and third largest oil spill in the world. [57]

B.8.4 The Appollo Sea: June 1994

In June 1994, a large oil slick appeared off the Cape west coast. Initially the slick was thought to be bubbling from the wreck of the *Castillo de Bellver* which sank in the same vicinity. However later it was confirmed that the oil was emanating from a 19 year old Panamian ore carrier *Appollo Sea* which disappeared after leaving Saldanha Bay. All 36 crew members were missing. [93, 94]

The vessel was loaded with 2000 tons of fuel oil which began washing up on Dassen Island and Robin Island which are important breeding places for the Jackass penguin. A total of 10 0000 penguin chicks died and 4000 to 5000 of breeding pairs were unaccounted for. Of the 9600 oil covered penguins rescued, 54% of them subsequently died [95, 96, 97].

Most of the beaches around the Cape Peninsula were affected by the spill. The cost of the clean up was between R15 million and R20 million. All beaches were cleaned of the oil and were back to an acceptable condition by November 1994. Unfortunately more oil from the wreck washed up on Cape Town's Clifton beach early in December, but was quickly mopped up [98, 99].

B.8.5 Sunken Wrecks

Oil can remain in tanks of a vessel for many years until the tank corrodes through allowing it to leak. Recently, a US cargo ship *Park Victory* which sank off the coast of Finland during World War II began leaking oil in September 1994. The vessel, which was estimated to contain 600 - 900 tons aboard, started leaking about 3 tons per day.

Also in Oslo fjord in the Baltic sea, an oil rig started to pump oil from a sunken Nazi warship, *Bluecher* which was sunk during the invasion of Norway. Approximately one ton of fuel, which had leaked into the fjord, was recovered [100, 101].

In October 1994, oil began leaking from the wreck of the *Produce*, which sank off the Kwa Natal coast in 1974 after running aground on Aliwal shoal. Light patches of diesel had washed up on the nearby beaches [102].

The sunken *Katina-P* is believed to still contain approximately 53 000 tons of furnace oil, and the sunken bow of the *Castillo De Bellver* still contains some 60 000 tons of crude oil. These wrecks are still pollution threats [87].

B.9 Causes of Oil Spills at Sea

In 1988, oil comprised about 38 per cent of the world's energy consumption and 45% of it (1,356 Millions tons) was moved by more than 3,000 tankers over an average distance of 4 700 nautical miles. In 1989, 600 000 tons or 0,004% of the 1 500 million tons of oil transported was spilt into the sea [70].

Operational discharges such as from tank cleaning are responsible for 30% of the oil entering the sea each year. Approximately 500 oil slicks caused by operational discharge are spotted each year off the Dutch coast and as a result some 30 000 dead sea birds are washed up on the North Sea shores [70].

The total amount of oil spilt through accidents, such as the *Exxon Valdez*, make up only 12% of total marine pollution. However such accidents usually spill large volumes of oil in a short period of time which can cause catastrophic environmental damage. The media coverage of such incidents raises public awareness of oil pollution while showing the world's unreadiness to deal with them [70].

During 1995, members of the International Salvage Union recovered 2.1 million tons of oil from stricken vessels, up from the 1994 figure of 1,4 million tons. They responded to 140 calls for assistance which included 21 tankers, 7 of them being VLCCs and ULCCs. Twenty one ship-to-ship oil transfers took place during this period [103].

It is difficult to develop a standard strategy for spill combat following from tanker accidents, as the conditions and circumstances under which they occur are diverse, as can be observed from the accidents already described. The major cause of casualties is attributed to human error, causing 90% of groundings/collisions viz. the *Exxon Valdez*, *Torrey Canyon* and *Braer* - the latter being the failure to secure the broken pipe on deck). Human error accounts for 75% of explosions. Tanker deterioration is a further cause and is on the increase because laws and regulations designed to ensure the seaworthiness of vessels are not enforced. This is illustrated in the case of the *Katina-P* which, having been issued a certificate of seaworthiness, broke up after encountering heavy weather. In 1993, 82% of tonnage lost consisted of vessels over 15 years old. [104, 105]

B.9.1 Human error

At present, heavy emphasis is placed on technological solutions to prevent accidents, but human error has been found to be the major cause of accidents, many as a result of fatigue. Manning requirements of a vessel are sufficient for sea operations, but are insufficient for port operations and recently ship owners have cut crew sizes to save running costs [56, 104].

A number of experts are claiming that work practices aboard some vessels have become substandard as ship owners are reluctant to pay higher salaries to ensure a quality crew. The crews of certain vessels are recruited in countries where they can be found cheaply and with minimum checks on their experience and qualification. There is a brisk trade in forged certificates of competency and no established means of identifying them. In some countries they can be obtained without any serious examination [57, 104].

Further, Masters are pressured to meet deadlines: which leads them to choose dangerous vessel routes viz. *Braer*. Tankers are frequently driven too hard in heavy weather. Large ships do not give adequate notice when labouring in heavy weather, unlike smaller vessels which shudder and vibrate in a heavy swell. Some masters may not be familiar with the signs of a large vessel labouring, and may not reduce speed, an error which can result in structural damage. In recent years, the South African coast has witnessed several tankers sustaining damage in adverse weather conditions. The *Atlas Pride* and *Tochnal* lost bows and the *Minosa* developed cracks in its hull [104, 106].

B.9.2 Tanker Deterioration

The age of the tanker fleet has steadily increased over the years. During 1991, there was a sharp upturn in total losses of all classes of vessels, including twenty tankers of 501663 GT. The total tanker tonnage lost during 1994 was 421 000 GT and age was the most significant factor in the casualty statistics. In all likelihood corrosion and poor maintenance were major contributing factors in the losses [57].

During 1994, there was a 57% increase in the number of vessels detained in Europe for deficiencies threatening their seaworthiness. A number of bulk carriers were detained because of corrosion defects. More than three quarters were over 15 years old [63, 105, 107].

The Institute of London Underwriters notes that half the world's Capesize fleet, viz. vessels which are too large to enter the Suez canal and therefore must navigate round the Cape, are approaching the end of their economic life and that loss statistics are expected to increase over the next few years. In 1993, over 50% of all VLCC (Very Large Crude Carriers) were over 15 years old. [106]

Freight rates for the transporting of oil have, until recently, been half the amount a tanker owner requires to operate a vessel correctly and cover the cost of investing in new ships. Freight rates have not changed

much since 1975 and as of August 1993, there was a 15-20% over capacity of tankers. Consequently maintenance is often neglected allowing the tanker to deteriorate. During the mid-80s when freight rates were very low, expenditure on maintenance was reduced leaving much of the world's VLCC fleet with corrosion problems, particularly in the cargo tank bottoms and permanent ballast tanks. Originally owners planned a life expectancy of a tanker to be 15 to 20 years, but now this is stretched to 20 to 25 years [59, 108, 109].

Freight rates have now improved but not enough. Presently a 1974 built VLCC, which costs \$16-17 000 per day to operate, is being charter at \$21 000. However a modern VLCC, which requires to be chartered out at \$40 000 per day to justify the investment, are currently earning near \$30 000 per day making an acquisition of a new build a unprofitable venture [110].

Lord Goschen, the UK minister of shipping in 1995, blamed the unsatisfactory state of shipping on "Poor standards of maintenance and management coupled in many cases with dubious standards of surveying and inadequate flag state control" [111].

B.9.3 Classification Societies

Questions have been raised recently on the thoroughness of surveys carried out by some classification societies. An example is the case of the *Pacificos*. The 270 000 DWT Cypriot flag tanker underwent a full safety construction survey in May 1989 and was issued with Certification valid for 5 years. In October 1989, 300m² of plate fell off the port side of the vessel near Durban while fully loaded en route to Brazil. While being repaired in Durban, it was found that the frames in the undamaged tank on the starboard side were described as being "like lace curtain" [112, 113].

Another famous case of suspect surveying was that of the *Kirki* which despite having passed all necessary inspections (flag, class, charter and oil company) lost its bow while approaching Australia. The vessel was found to be badly corroded [114].

There are factors which have contributed to the dubious standards which have been applied lately. A proper survey requires all the plating and welds in the tanks and compartments of a vessel to be checked for corrosion. To carry out a through inspection of tanks and compartments on a VLCC, this will entail the inspection of 300 000m² of steel and 1 200 kilometres of welded seam, which will require a total height of 10 600m to be climbed by ladders. In the experience of the author, surveys are not carried out in such detail as surveyors are pressurised to complete surveys quickly to enable vessels to commence loading. Corrosion assessment of a tank is complicated by the fact that corrosion rates vary between a vertical and horizontal surface. There is also variance in corrosion rate at different locations in same tank. In addition, areas of high stress concentration corrode faster than others [114, 115].

Classification Societies are private companies which compete against each other for clients. This enables ship owners to class shop amongst the societies in order to get the best deals and exemptions for their vessels, a process contributing to a slide in standards. The high number of classification societies and the competitive environment in which they operate have resulted in a high proportion of substandard ships being able to receive certification from some source [57, 114].

Recently a cargo was lost after being loaded on a unseaworthy vessel which subsequently sank. The vessel had developed cracks in the hull on the sea passage and diverted to a port for repairs. Initially the class surveyor recommended permanent repairs but after objections for the ship owners, the vessel was allowed to continue to the port of discharge after temporary repairs had been undertaken. Shortly after leaving port, the vessel sank. The cargo owner received a limited pay out from the owner, and subsequently sued the classification society for neglect. However the court ruled in favour of the classification society on the grounds that it had no duty to the owner of the cargo, but to the ship owner to whom it was contracted to. The court ruled that the purpose of the classification society certificate was not to guarantee safety, but to permit the ship owner to take advantage of insurance rates available to a classed vessel [116].

B.9.4 Flag of Convenience

Originally international law gave States complete discretion as to the conditions under which they granted their nationality to ships. This has resulted in the national laws of different nations concerning shipping varying enormously. Some states lay down strict conditions for the grant of nationality, whereas others are prepared to grant their nationality to virtually any vessel. Such states are known as Flag of Convenience (FOG) or open registry states. The principal states in this category are Cyprus, Panama and Liberia, whose ships account for 30% of world shipping. Ship owners are encouraged to register their ships under FOG by lower fees, taxation and crew costs (certification is not properly monitored) thus giving them a competitive advantage over owners registered under other flags. Some FOG states do not exercise proper control over their registered vessels. Standards regarding manning, safety and anti pollution measures are not adequately enforced [61].

The record number of vessels detained in Europe indicates a decline in the standards of the world fleet. This is attributed to the increasing age of the world fleet and the register of vessels under FOG which allow substandard vessels to be operated by substandard crews [105].

B.9.5. Cost Cutting of Newbuild Ships

During the 80s, the price of new tankers was determined by what the owner was willing to pay rather than by the builder's cost. This has resulted in the cutting of costs in two areas, labour and steel. Scantling has been reduced to the minimum size acceptable to classification societies and smaller high tensile steel sections are used more extensively in place of larger mild steel sections. A major concern is that high

tensile steel does not exhibit a major gain in fatigue performance over mild steel. A lighter HTS structure will flex more than a thicker mild steel construction resulting in higher stress levels and causing the protective coatings in tanks to break down: leading to higher maintenance costs or corrosion problems. Corrosion occurs at an absolute rate, therefore a light high tensile steel plate will use up its percentage margin for corrosion earlier than a thicker mild steel plate corroding at the same rate [117, 118].

B.9.6. The Inadequacy of Marine Law.

At present, laws regarding salvage need to be revised if the dangers of pollution are to be prevented. Listed are some inadequacies:

1. Awards to prevent or minimise pollution: In terms of LOF 1990 (the Lloyds Standard Form of Salvage Agreement) the salvor is now awarded services to prevent or minimize pollution. But no South African judgement has so far been awarded for service made in this regard (as of August 1994). In 1992, a salvage company was involved in an 84 day operation to salvage the *Nagasaki Spirit* after it had collided with another vessel. During the subsequent arbitration, it was ruled that the fair rate in the special compensation provision for prevention of environmental damage should not include an element of profit. By the removal of the profit element from the definition of a fair rate, salvors could earn more from participating in clean-up operations than preventing the pollution [114, 115].
2. Need to preserve Salvage industry: Salvors are the first line of defence against pollution and provide the most cost-effective service by, in the majority of cases, preventing the spill in the first place. However, the International Salvage Union which operated about 150 salvage tugs in 1975 presently operates 65. Salvors complain that awards are generally too low to cover the cost of operating tugs, and frequently a tug with a salvaged vessel in tow is denied entry into a harbour [119].
3. "No cure - no pay" maxim: The time honoured maxim provides for awards to be made only when a vessel is successfully salvaged. If a State owned tug makes an unsuccessful salvage attempt, the taxpayer bears the cost, but there are no state owned tugs powerful enough to render assistance to a VLCC which is threatening the South African coast. Under the "no cure - no pay" maxim, a private salvor is unlikely to attempt the salvage of a tanker if there are no reasonable prospects of success. The risks of fire and explosions are too obvious, and if the tanker is towed, the State may order her to be sunk, thus denying the salvor his reward. If the tow reaches port, the authorities may deny her entry. During the attempt to salvage the *Torrey Canyon*, the salvage company lost a

substantial amount of their salvage equipment which was aboard the vessel when it broke up. Under the terms of Lloyd's Open form "no cure, no pay", there was no means of recovering the cost of the equipment or the expenses of the salvage (for example the charter of aircraft and helicopters) [119, 120].

4. The vessel is handed back to the owners after the award for salvage is made. If the owner does not accept delivery of the vessel at the port of safety, the salvor can expect a lengthy delay before receiving his award.

South Africa, being situated next to one of the main tanker routes of the world, is continually threatened by pollution, but there is no incentive for the private salvor under the present laws to attempt to salvage a vessel or minimize the effects of pollution if there is little prospect of success [119].

Annexure C

The Fate and Effects of Oil at Sea

When dealing with oil spills, the individual properties of oil, the sea condition and climate will affect the spread and removal of oil from the sea.

C.1 The chemical make up of crude oil

Crude oils are a complex mixture of hydrocarbons of varying molecular weight and structure comprising three main chemical groups, paraffinic, naphthenic and aromatic. These hydrocarbons range from simple, highly volatile substances, to complex waxes and asphaltic compounds which cannot be distilled. A relatively small amount of oxygen, nitrogen, sulphur, vanadium, nickel and mineral salts may also be present [8].

C.2 The spread and dispersion of oil on water

Oil spilt on water spreads very rapidly. Under (ideal) conditions which are unaffected by wind, current or swell, a cubic metre of Middle East crude will spread to a circle with a diameter of 48m and average thickness of 0.5 mm in 10 minutes. After 100 minutes, the diameter will increase to 100 metres and will have an average thickness of 0,1 mm. Light oils spread rapidly over the surface to cover a large area with thin oil, while heavier oils tend to thicken to form "pancakes" up to several centimetres thick. As the natural degrading processes are related to surface area, light oils disperse more rapidly than heavy oils [8].

When oil is spilled on the sea in large quantities, the slick will not spread as described, because it is buffeted by the winds and waves. The slick becomes patchy, particularly round the edges [121].

Immediately after the spill has occurred, the lighter hydrocarbons such as gasolines and kerosene begin to evaporate off, which results in between 25 to 50% of the spilled oil being disposed of. Rough seas may remove some of the slick in the form of sea spray. Droplets may be blown 50 miles from the spill to re-enter the sea or to evaporate into the atmosphere. During the *Braer* spill, oil blown off the sea coated pastures on the Shetland Islands [8, 121].

Within a few hours, only the heavy elements of the slick will remain which will begin to break up into windrows: viz. narrow bands lying parallel to the wind direction. In the majority of cases, a water-in-oil emulsion called "Chocolate Mousse" will form. In these cases, oil can absorb up to four times its volume of water, resulting in a very stable, highly viscous emulsion. Recent research has suggested that an emulsion will form only if there is sufficient wave motion. A mousse is more stable than oil which results in the natural dispersion becoming retarded and this increases the possibility of the slick

reaching land. The slick becomes more difficult to deal with as its volume and viscosity will increase until it becomes nearly impossible to recover. Water-in-oil emulsions are usually thixotropic: viz. they become thinner when stirred by waves but revert to high viscosity when the sea becomes [8, 57, 122].

As the majority of a mousse consists of seawater, it will therefore have a near equal density to seawater. As the mousse ages and becomes more stable, the outer layer may eventually form a skin. As the mousse deteriorates, it absorbs solids suspended in the sea water and eventually sinks after it becomes heavier than seawater [8, 122, 123].

The oil is further degraded by biological action. Numerous organisms, which exist in the seawater, use hydrocarbons as food, and convert it via enzyme-catalysed reactions into more soluble alcohols, organic acids, carbon dioxide and water. Normal sea water contains 10 hydrocarbon decomposing bacteria per litre but, after an oil spill, this can increase to 50 million per litre. Although the rate of breakdown of oil through biological action is small when compared to evaporation, it is the last of the natural dispersion processes [8, 124].

Predicting the movement of a slick is difficult. It will move at the same speed and direction as the regional current and is blown across the surface at a speed equal to 3 - 4% of the wind speed. However the speed and direction of local currents and winds are seldom exactly known, and therefore predictions are difficult. Tidal currents are cyclic, and therefore the resultant movement is slight. Modelling techniques are available to predict slick movement, but they are as good as the available environmental data on local conditions. There is no better substitute for actual observation [8].

C.3. Characteristics of a mousse

Numerous tests have been carried out to determine the characteristics of a mousse. During tests carried out in the Netherlands, the effect of the boiling point and the wax and asphaltenes content of an oil on the formation of a mousse were demonstrated. The formation of mousse was simulated in the laboratory by adding 200 ml of oil to 500 ml of water which was stirred with a propeller for between 1 and 2 hours until a stable mousse was formed with a 70% water content. A mousse was considered stable if no spontaneous separation of water occurred when stirring was discontinued [125].

C.3.1 Boiling point of oil

It was demonstrated that the heavier and more viscous crude oils, which have higher boiling points, produced more stable emulsions [125].

C.3.2 The presence of wax in oil

As a crude oil is cooled, the paraffin wax present starts to crystallize out, causing an increase the viscosity.

If the wax content of the oil is over approximately 2%, the temperature is reached at which sufficient wax crystals are present to form a rigid layer, which considerably reduces the ability to pump the oil. At this temperature the oil cannot be poured and is at its pour point. It was found that such oils could not form a stable emulsion if it was at or above the pour point temperature [125].

C.3.3 The presence of asphaltenes.

It was found that asphaltenes did not effect the formation of mousse, but tests demonstrated that only mousses with low asphaltene content became unstable if the temperature was increased over the pour point where the wax redissolved. It was concluded that asphaltenes act in the oil/water interface to preserve the mousses' stability. Some mousses remained stable at temperatures up to 100 °C [125].

C.3.4 The effect of light

In a similar experiment carried out in Norway, a mixture of crude and water formed a stable mousse if shaken in light. If the light intensity was lowered, the mousse had a lower water content and its formation was retarded. If the mixture was shaken in darkness, an unstable mousse was formed. Other tests showed that if a substance B-carotene (Beta), which retards photo-oxidation, is added to a mixture before it was shaken in light, an unstable mousse is produced similar to that formed in darkness. When tetradecanal, a model product of a slightly oxidized hydrocarbon, was added to the mixture before being shaken, a stable mousse was formed irrespective of whether the mixture was exposed to light or not. Therefore it was concluded that photo-oxidation changes the properties of crude oil, causing water droplets to be retained in oil during physical mixing. It was further found that a stable emulsion became unstable when the temperature was increased [123].

C.4 Environment damage caused by oil spills

Environmental damage studies carried out on oil spills impacted areas have shown that no long term damage is caused. However the short term effects can be serious. A specialist in marine and earth science, Dr. Mielke, concluded that 10 years is the longest period of spilled oil resident in marine and coastal environment. The majority of the damage occurs within the first 4 months. Five month after the *Exxon Valdez* spill, beaches along Prince William Sound which had been choked with oil were returning back to normal. Bacteria had eaten much of the oil [1, 124].

Short-term impacts on marine life are dramatic, but recovery of species populations in most cases has been swift as in the case of the *Amoco Cadiz* tanker disaster. The tanker ran aground on the Brittany coast in May 1978 after its steering gear failed and approximately 233 000 tons of crude oil was spilled into the sea. Ninety per cent of the cargo was spilt in the first 11 days after the grounding and about 250 miles of coastline along the Brittany peninsula was polluted over a period of 4 weeks. Some of the oil was buried in sediments or trapped in low energy salt marshes and estuaries. The clean-up lasted for several months,

with some operations continuing into 1979 and beyond. The immediate effects were serious, with 4 500 dead sea birds recovered, and bottom feeding fish affected. Oil drowns some 2000 areas of oyster beds in the rich Brittany fishing grounds which are the source of a third of France's fishing industry [124, 126].

Three years after the spill, a survey concluded that the bird population had recovered and fish were being affected only in the vicinity of the wreck. There had been no visible signs of recovery in the heavily oiled marshes. After 5 years the marshes had largely recovered through natural processes, and after 8 years only a measurable amount of residue of the oil was found at isolated spots [124].

Biological effects from oil spills vary. Damage to plants such as phytoplankton, some algae and flowering plants can occur during the acute stage following a spill, but nature replaces them relatively quickly. Some plants are relatively resistant to toxicity from oil and recover. After a spill in San Francisco bay, organisms such as barnacles, mussels periwinkles and limpets reproduced at an accelerated rate; some doubled in intensity [121].

There is a strong correlation between the exposure of an area to wave action and the longevity or persistence of oil within an area. For example, during the *Braer* where the affected coastline was subjected to severe wave action, the oil dispersed in a month. [77]

C.5 Damage to wild life following a spill

Fish are less affected by spills than expected, partly because oil floats on the surface and by remaining at a depth below this, they can remain unaffected. Tests for hydrocarbon contamination were conducted on fish and shell fish in Prince William Sound six months after the *Exxon Valdez* spill. With the exception of traces of oil found in pink salmon, the fish tested showed no signs of hydrocarbon and are therefore efficient at converting digested hydrocarbons into metabolites. Tests were extended to fish eggs and no substantial oil related damage was detected. Shell fish were found to be inefficient at digesting oil and only traces of hydrocarbon were found during laboratory tests. [1]

Seals are killed by spills, although the exact affect on the population is not known as seals sink when they die. Further, seal numbers in Prince William Sounds had been decreasing before the spill [1].

All types of seabirds are effected by oil. It destroys the insulation property of their feathers and hypothermia sets in. They digest the oil when cleaning themselves which can be fatal. Dead birds are scavenged by Bald Eagles, bears and other animals and fatal effect of oil passed down the food chain. Two thirds of the Bald Eagle nest failed after the spill. Although populations increase with time, some rare species can be wiped out. Penguins breeding colonies at Dassen and Robben Island were devastated after

the *Apollo Sea* spill. [1,73].

Many sea otters, which have no thick blubber, succumb to oil when their thick coats become oil saturated and insulation is lost. Also the toxic effect of oil weakens the membranes in their lungs. Others suffer from liver and kidney damage from digesting oil possibly when cleaning their coats. One third of the sea population in the effected areas of Prince William Sound were wiped out during the spill [1].

C.6 Methods of combating oil spills

After an oil spill, the two combat options open for the clean up are either to contain and collect the oil, or to use dispersants [122].

A number of problems are encountered with oil recovery using mechanical means (skimmers). Spills tend to spread and fragment over a large water surface, which must be swept over by the oil recovery equipment to remove it, a lengthy operation. In order to contain this spread, the booms must be rapidly deployed to encircle the spill. In reality this is only possible if the spill occurs near a terminal or other facility where oil recovery equipment is on permanent standby. Thereafter all support vessels, oil storage facilities, and other vital support must be brought to the spill scene before oil recovery can begin; which results in an inevitable delay [122].

A clean-up operation can also be hindered by wind, waves and current, which will cause oil to splash over the top of booms or be drawn under the skirt of the boom, thus reducing their effectiveness. If and when the spill is encircled by the booms, it must be recovered by a skimmer suitable to recover the viscosity range of the spilt oil. The difficulties are further increased by the formation of a mousse. Because of the major difficulties associated with combating major instantaneous releases of oil in open waters, such as from a tanker casualty, it is rare for as much as 10% of the original amount spilled is recovered through mechanically means [122].

Dispersants are also used to dispose of oil slicks. Dispersants break the slick into tiny droplets which disperse into the water column. However, they can be toxic to the environment and cannot be used to disperse a mousse (see Section 1.5.1) [37].

C.7 Response to oil spills

During the first hours after a spill, a slicks will spread, fragment and form an emulsion and thus it will become difficult to clean-up. Therefore for clean up operations to be successful, it should commence within the first few hours [57].

Presently, the most oil spill responses are defensive in protecting sensitive coastal resources such as fish

farms, power stations, marine reserves and ecological sites and to allow the spread of spilt oil to occur and disperse naturally at sea. When selecting equipment to be allocated to a potential spill site, one must take into account the priority given to a site and the local conditions such as currents and accessibility [122].

C.7.1 Beach clean-up

If a slick reaches a shoreline, it is inevitable that oil will bypass the booms if in place and the beaches will be polluted. Beaches can be cleaned without specialised equipment. Skimmers and vacuum trucks, used for sewage removal, may be utilised to clean beaches and rocky bays where access may be gained. During the *Amoco Cadiz* spill a 4,5 m³ vacuum truck, which could be drawn across the beach by a tractor, proved most effective for beach clean-up. Suction equipment was used to pump oil and mousse from natural depressions and specially dug trenches on the beaches. There was a large amount of seaweed floating in the slick, and this blocked the pumps during the oil recovery operation and this proved a major problem [25].

Mousse when it lands on a beach will move back and forth with the tide. It will ultimately become stranded, usually at high tide mark as its specific gravity is increased through oxidation and entrapment of sand. The stranded mousse can be removed by well organised teams of labourers or by bulldozers [25, 122].

Beaches undergo deposit and erosion cycles depending on the stage of the neap cycle. If oil is not removed, it will become covered by sand during the deposit cycle. During the erosion cycle, the buried oil is exposed and the concentrations reduced [127].

After the *Apollo Sea* spill, pools of oil with depths of 0,5m at Clifton beach, Cape Town were covered in a deposit cycle during a storm. Heavy earth moving equipment had to be airlifted to the beach to mine the oil which had been covered by 3m. of sand. [128]

During the *Amoco Cadiz* spill mousse, which had landed in rocky areas where machinery could not reach it, had to be gathered and removed in plastic bags. Unitor oil bags can further be used to store oil recovered under these conditions (see Section 1.7.2) [123].

Problems are caused when the oil penetrates into shorelines consisting of boulders, cobbles or gravels. It is rarely practical to do more than remove the surface accumulations of oil to prevent any further spread. If amenity or wildlife concerns dictate a more thorough clean-up, the covering boulders must be removed and cleaned with hot water or steam before being replaced. This technique stimulates microbiological activity or natural biodegradation, especially in cold climates. However tests carried out after some of the hot water washing showed large scale mortality in beach organisms. Also after washing a beach, 10 times the amount of oil can be found in the inter-tidal zone than found just after the spill. By applying fertilizer to the

shore (bioremediation), the natural process is accelerated (see section 1.6.3). During the *Exxon Valdez* clean-up, heavily oiled beaches which had been cleaned became reoiled as buried oil resurfaced. The clean-up became further complicated as there are several different types of shorelines around the Sand and thus no single strategy could be applied. [1, 25, 38, 127]

It is recommended that oil polluting sensitive shoreline such as salt marshes and mangroves be left to be cleaned by natural processes. Cases have shown that physical disturbance caused by clean-up crews and vehicles have caused more damage than the oil itself. After the *Amoco Cadiz* clean-up, it was found that the artificially cleaned marshes took up to two years longer to recover than those where nature was permitted to run its course [25, 122].

A major problem associated with clean-up is the temporary storage and disposal of recovered material. The volume is considerable and usually contains a small percentage of oil. The mousse is further mixed with sand, seaweed and other debris. It can be incinerated but this will result in the atmosphere becoming polluted, or it can be treated at considerable expense. It can also be buried in landfills to allow bacteria to break it down into carbon and water. After the *Pentingo* spill off Richards Bay, 550 tons of oil mixed with thousands of tons of sand was buried behind the dunes. The mixture was spread out and fertilizer to enhance the bacteria growth was added. It was found that vegetation soon re-established itself and that the region was on the way to recovery. A disadvantage of this method is that the ground water may become polluted [8, 89].

C.8 Case study: *Ixtoc I* oil spill

Oil was injected into the sea from the blowout at *Ixtoc 1* well at an initial pressure of 350 bar and at a depth of 51 m. The oil was saturated with gas and formed an emulsion of gas bubbles and water droplets in oil while rising to the surface. The emulsion had a water content of 50%. Most of the gas burned off as it reached the surface, causing a small percentage of the emulsified oil to be incinerated with it. It was estimated that 50% of the spill evaporated into the atmosphere and that 1% burnt off with the gas [82].

The spill occurred over a period of nine months, and was estimated to lose 4 500 tons per day during the first 2 months, which dwindled to 60 tons per day before being capped. Approximately 5% or 23 000 tons were recovered mechanically from the sea surface above the well. The theoretical recovery capacity of the mechanical equipment used during the recovery operation the spill was equal to about 20% of the total oil spilled. However the low actual figure was attributed to following factors:

- (i) weather conditions: which caused a 3-4 meter swell at which level the equipment could not operate,
- (ii) night time: it was not considered feasible to operate the equipment at night. As result there was a loss of clean up time,

- (iii) equipment adjustment: the equipment required constant re-arranging when the wind and currents changed direction causing the oil location to shift,
- (iv) equipment reliability: the equipment broke down on a number of occasions.

Recovery operations commenced at the end of June and ended during the early part of October [82].

A slick of 60 km in length, between 0.7 and 5 km in width and 1 - 4 cm thick formed during the first part of the blowout. Micro-organisms, which attached themselves to the oil droplets, were disposed of by zooplankton filter feeders and in this way 12% of the spill was removed. The oil formed a mousse which gradually increased in density through oxidation and became weighed down by particle matter, causing 25 % to sink to the bottom. The remaining 7% landed on beaches around Mexico and Texas [82].

Damage to the environment: The shrimp population, which is economically important in the region, was particularly affected by the spill. Shrimps, particularly their eggs and larvae, are sensitive to the toxicity of hydrocarbons. The oil from *Ixtoc I* is very toxic, and approximately 120 000 tons sank, landing on the sediment. Shrimps burrow into the sediment and become tainted as a result.

The region has a number of shallow lagoons entering the sea. Oil was prevented from entering them by the river water flowing out as result of heavy rains inland.

Nine months after the spill, it was found that the crab population on the impacted beaches had been eliminated. Dense mats of green algae were observed to be covering corals and other rock formations. Booms of plankton, which are normally observed in the area, were no longer sighted indicating that they had been damaged [82].

Annexure D

D.1 Boom design No. 1

The first boom was constructed from plastic, with a wire frame for rigidity. It was not constructed to float and was held in position by brackets attached to the sides of the test channel (refer to Figure D1).

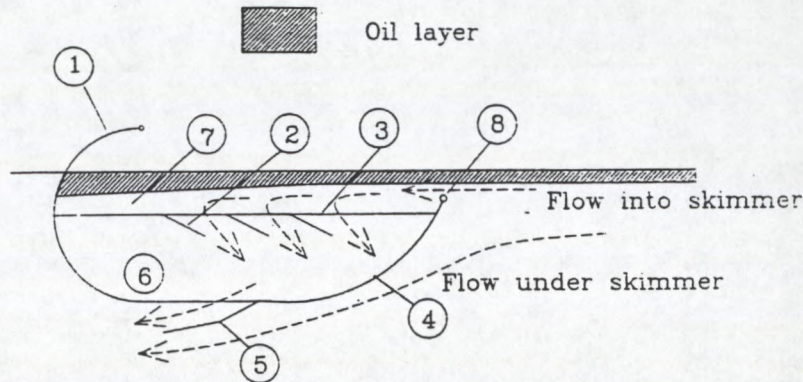


Figure D.1. Flow through boom design No.1

1. splash cover
2. water drains - centre skin
3. centre skin
4. outer skin
5. water drains
6. lower section - separated water chamber
7. upper section - oil trap
8. lower lip

The function of the boom is to accelerate the incoming surface layer up to the tow velocity before it enters into the trap. The position of the lower lip below the water surface determines the depth of the layer to be skimmed. Once in the trap, the oil layer should separate from the water and float on the surface. The water recovered with the oil layer leaves the trap through the drains positioned through the trap bottom.

The trap is divided into two chambers by a centre skin. The upper chamber serves as the oil trap where the recovered oil collects and the water recovered with it, separates and passes into the lower chamber before exiting the boom through the water drains. The drains through the centre skin comprise of three rows of holes which are angled back against the flow to force a change direction, thereby assisting the oil to separate.

The boom, which was held at 45 degree to the direction of flow, deflects the flow down to a collection point where a skimmer would normally be positioned.

During the test, no turbulence was observed within the trap and the surface layer flowed down the trap as required. However, model was too flimsy and it began to bulge at the water drains which were not coping with the flow.

The following conclusions were drawn:

- (i) the model had insufficient water drains and therefore the next model must disperse the excess water more effectively,
- (ii) the next model must float independently to observe the presence of any downward forces,
- (iii) the following model must be stronger.

D.2 Boom design No. 2

The second boom, which floated independently, was constructed from thin plastic sheeting with floats made from polystyrene. The boom was attached to a harness, which held it in position at an angle of 45 degrees to the flow. The stays were made from fishing line.

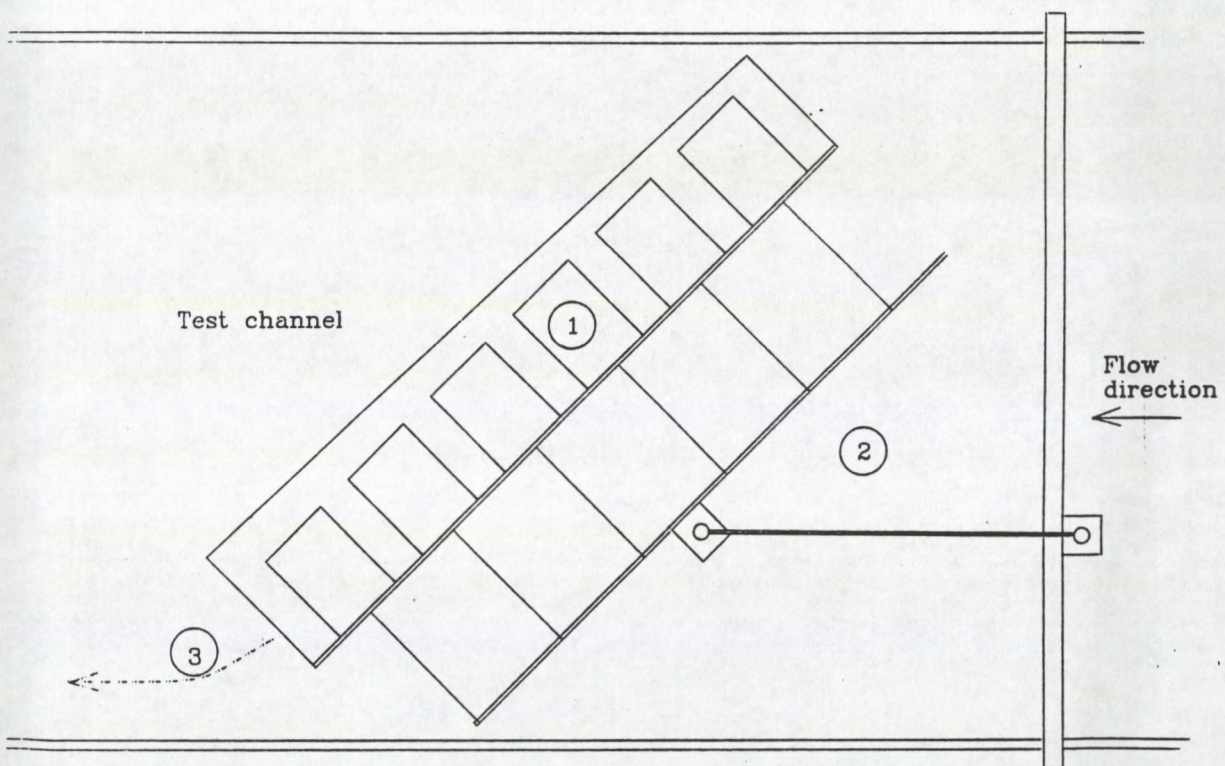


Figure D.2. Layout of Boom Design No.2 in test channel (top view)

- 1. boom
- 2. harness
- 3. flow out of boom

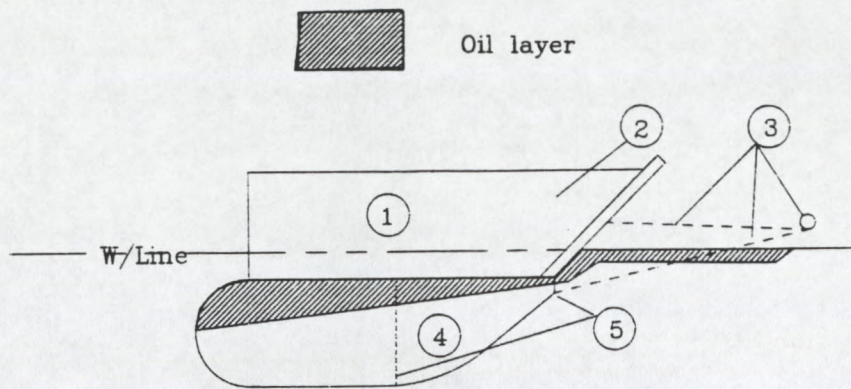


Figure D.3. Principle of boom design No. 2

1. floats
2. leading face
3. towing harness
4. oil trap
5. tow stays

Boom design No 2 consisted of an enclosed oil trap area, which was held below the water surface, thus eliminating any free water surface within the trap. The floats positioned at intervals down the trap top, held it at the required level.

It was anticipated that the surface layer containing oil would be forced into the trap when it made contact with the leading face of the boom, which was held at an angle of 45 degrees to the vertical to assist the flow through the trap entry. Thereafter it would pass into the trap and the lower flow layers would pass below the trap.

Once in the trap, the surface oil layer would be forced down the length to the where normally oil collection point would be located

The trap entry extended down the full length of the boom, and the stays connecting the lower lip to the trap top, set the width of the trap entry at 3mm.

When the test was initiated, it was observed that the flow through the trap was insufficient, and the surface flow layer failed to enter the trap. The model construction was still too flimsy as the pressure difference across the trap bottom caused it to bulge and consequently the size of the trap entry increased. As the flow

speed was increased, the entire boom became submerged below the water surface.

It was concluded that the flow into the trap was insufficient due to the following reasons:

- (i) there was no means to dispose of the excess water within the trap causing a build. The next model must include an excess water disposal method, and
- (ii) the trap top, which was in contact with the flow into trap, created drag and resisted it. The next boom must have a free water surface within the trap area.

D.3 Boom Design No 3.

Boom design No. 3 (refer to figure D.4) was built of the same materials and operated to a similar layout as boom design No. 2 described.

This model had of an oil trap running down its length with the trap entry positioned below the water surface. It was anticipated that the surface layer would be forced under the leading face, and enter the trap through the entry. Stays connecting the upper and lower lip of the trap entry held the size of the trap entry at 5mm. The trap top was now raised above the water surface to allow a free water surface within the trap.

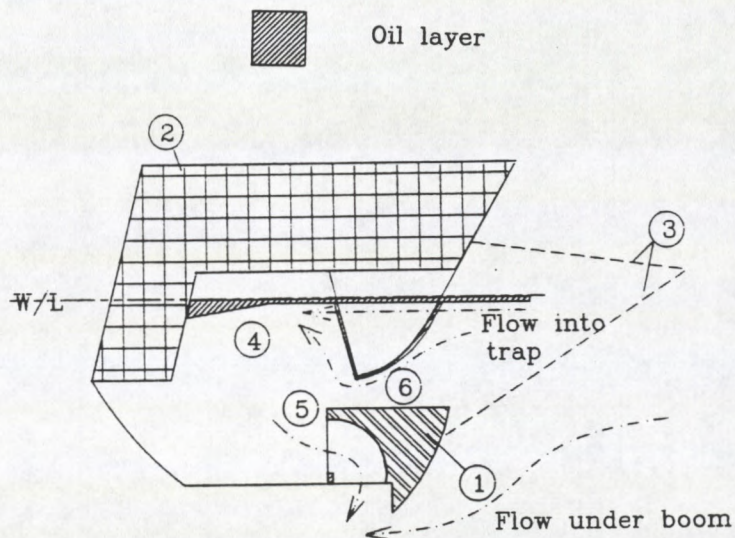


Figure D.4. Principle of boom design No.3

1. water drain
2. float
3. harness
4. oil trap
5. oil passage
6. trap entry

The leading face was angled at 45 degrees to the vertical and floats were positioned at 40mm intervals down its length of the boom. To enhance the flow into the trap, 50mm wide passages cut through each float linking the trap to the incoming flow. These passages were cut in line with the incoming flow, which was at an angle of 45 degrees to the leading face.

The plastic insert housing the excess water drain formed the lower lip of the boom and was curved to ensure a smooth flow under boom. The drain consisted of a passage extending along the length of the boom which linked the trap to the flow passing under the boom. It was anticipated that oil, separated out from the incoming flow, would settle on the surface in the trap. The location of the excess water drain, being at the foremost and lowest level of the trap, would ensure that the outgoing flow would not draw any oil out with it.

Applying Bernoulli's theorem between trap and flow under boom, and assuming a 10% increase in flow velocity under boom, the area of the drains can be calculated as follows:

$$Z_1 + \frac{P_1}{\delta g} + \frac{V_1^2}{2g} = Z_2 + \frac{P_2}{(\delta g)} + \frac{(1.1 V_1)^2}{(2g)} \quad [37]$$

where v_1 = velocity of flow in trap = 0 (assumed to be stationary), and $Z_1 = Z_2$, v_2 = velocity of flow, P_1 and P_2 = static pressure in trap and under boom respectively. Substituting in eqn (37):

Substituting:

$$\frac{P_1 - P_2}{\delta g} = \frac{1.1^2 v_1^2}{2g} \quad (38)$$

$$\Delta H = \frac{1.1^2 v_1^2}{2g} \quad (39)$$

where ΔH is the pressure head difference between trap and the flow under the boom. Now flow volume into boom equals flow volume out boom.

$$v_2 \cdot A_2 = v_3 \cdot A_3 \quad (40)$$

where A_2 and A_3 are area of flow at entry and exit respectively, and V_1 and V_3 are velocities through entry and exit respectively of the trap. Now:

$$v_3 = C_d (2g \cdot \Delta H)^{1/2} \quad (41)$$

where C_d is the coefficient of discharge through the drain holes. Substituting eqn (41) into eqn (40):

$$v_2 A_2 = C_d A_3 (2g \Delta H)^{1/2} \quad (42)$$

Substituting eqn (39) into eqn (42):

$$v_2 \cdot A_2 = C_d A_3 \cdot [2g(\frac{1,2 v_2^2}{2g})]^{1/2} \quad (43)$$

$$= C_d 1,1 v_2 A_3$$

$$A_2 = C_d 1,1 A_3 \quad (44)$$

Assume $C_d = 0,8$

$$A_3 = 1,14 A_2 \quad (45)$$

$$= 1,14 [(0,005 \cdot 0,20) + (2 \cdot 0,05 \cdot 0,015)]$$

$$= 0,00285$$

$$= 15 \times 190 \text{ mm}$$

The boom operated successfully at low flow rates, but became submerged at the flow rate was increased. This was due to inadequate drainage through water drains.

Further, it was noted that the trap entry was acting as a drain as the flow was in the opposite direction to that anticipated.

The following was concluded from this test:

- (i) The method of drainage required modification as the anticipated pressure difference between trap and flow under boom was not developing.
- (ii) The trap entry was having no effect on the flow into trap, and therefore should be excluded from the next model.

Continued in section 2.5

D.4 Method of Determination of Depth of Bow Profile Plate using Direct Step Method

Given the following:

- (i) depth of flow at entry to skimmer $y_1 = 80\text{mm}$,
- (ii) area of flow through trap entry $A_1 = 0,16\text{m}^2$,
- (iii) velocity of craft = velocity of flow at entry $v_1 = 1,2\text{m/sec}$,
- (iv) hydraulic radius at entry $R_1 = 4,16\text{m}$,
- (v) specific energy at entry $E_1 = 0,153\text{m}$
- (vi) $S_{f1} = 5,88 \times 10^{-7}$
- (vii) $X_1 = 0$

The commutation of the profile of the bow plate is as follows. Nominate any value for the new depth of flow and determine the distance down the slope of the channel that this depth occurs.

$$(i) \quad Y_2 = \text{Nominate Value}$$

$$(ii) \quad A_2 = 2 \cdot Y_2 \quad [46]$$

where A is the area of flow

$$(iii) \quad [R_2]^{0,75} = \left[\frac{A_2}{4 + (2 \cdot A_2)} \right]^{0,75} \quad [13]$$

$$(iv) \quad V_2 = \frac{Q}{A_2} \quad [47]$$

where Q is flow rate through skimmer

$$(v) \quad E_2 = Y_2 + \frac{V_2^2}{2 \cdot g} \quad [17]$$

$$(vi) \quad S_{f2} = \frac{(V_2 \cdot n)}{R_2} \quad [31]$$

$$(vii) \quad S_{f \text{ average } 1-2} = \frac{S_{f1} + S_{f2}}{2} \quad [48]$$

$$(viii) \quad \Delta x_2 = \frac{E_2 - E_1}{S_o - S_{f \text{ average } 1-2}} \quad [34]$$

$$(ix) \quad x_2 = \Delta x + x_1 \quad [49]$$

$$(x) \quad \Delta Z = (\text{Sin}(30) \cdot x_2) + Y_1 - Y_2 \quad [50]$$

where Y_1 is the original depth at entry

$$(xi) \quad F_2 = \frac{V_2}{g \cdot Y_2^{1/2}} \quad [5]$$

$$(xii) \quad Y_{sequ2} = 0,5 \cdot Y_2 [(1 + 8 \cdot F_r^2)^{1/2} - 1] \quad [30]$$

$$(xiii) \quad Y_{sequ2} - Y_2 \quad [51]$$

$$(xiv) \quad \Delta Z = (Y_{sequ2} - Y_2) \quad [52]$$

When step (xiv) becomes negative, hydraulic jump will occur at that point. The depth of the bow profile plate will equal $(Y_{sequ2} - Y_2)$

List of Drawings

Model Tests

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Fig D7	Layout of boom No. 3
Fig D8	Layout of boom No. 4
Fig D9	Layout of boom No. 5
Fig D10	Layout of boom No. 6
Fig D11	Layout of boom No. 7
Figure D12	Layout of skimmer used in boom No. 7
Figure D13	Layout of skimmer used in boom No. 8
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Prototype Layouts

Boom Prototype

Figure D15	Layout of end boom
Figure D16	Layout of centre boom
Figure D17	Layout of deflector floats held by semi-rigid frame
Figure D18	Layout of deflector float
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Skimmer Prototype

Fig D21	Layout of Skimmer Prototype
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Fig D23	Layout of Quarter Size Model
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D.25	Calculations for Depth of Bow Profile Plate for Quarter sized model test on Q-Pro
D.26	Calculations for Depth of Bow Profile Plate for Prototype on Q-Pro
D.27	Letter - Dr. Peter Woods

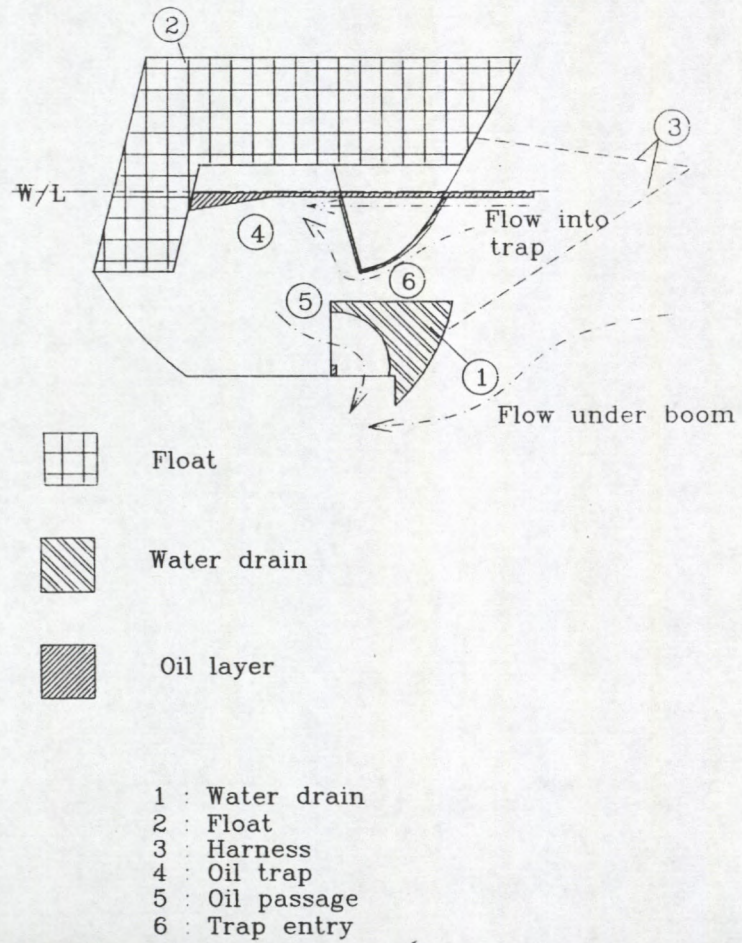


Figure D.4 Principle of boom design No 3

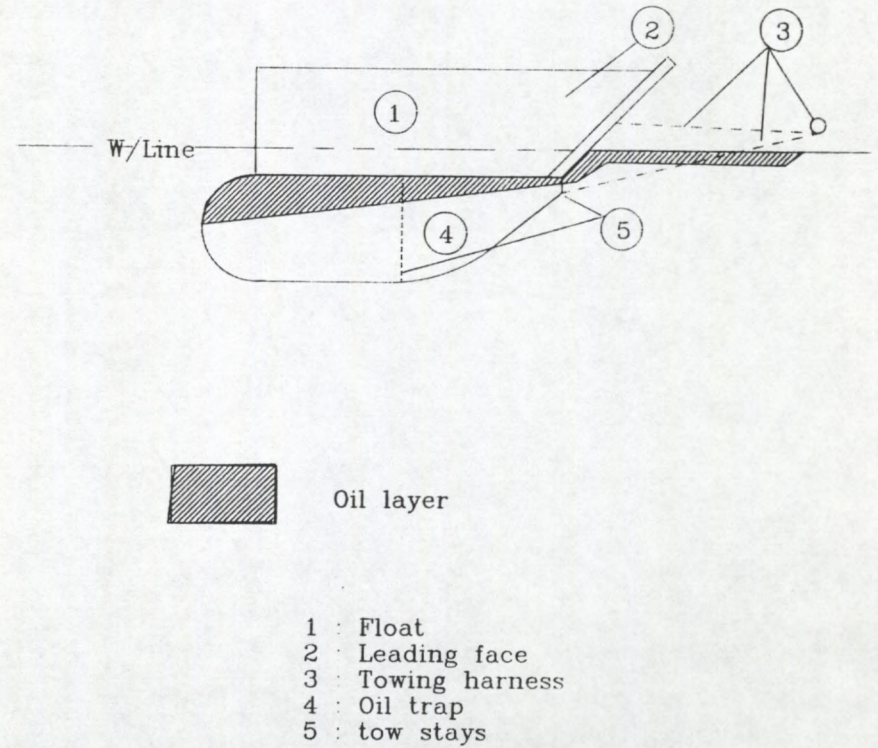


Figure D.3 Principle of boom design No 2

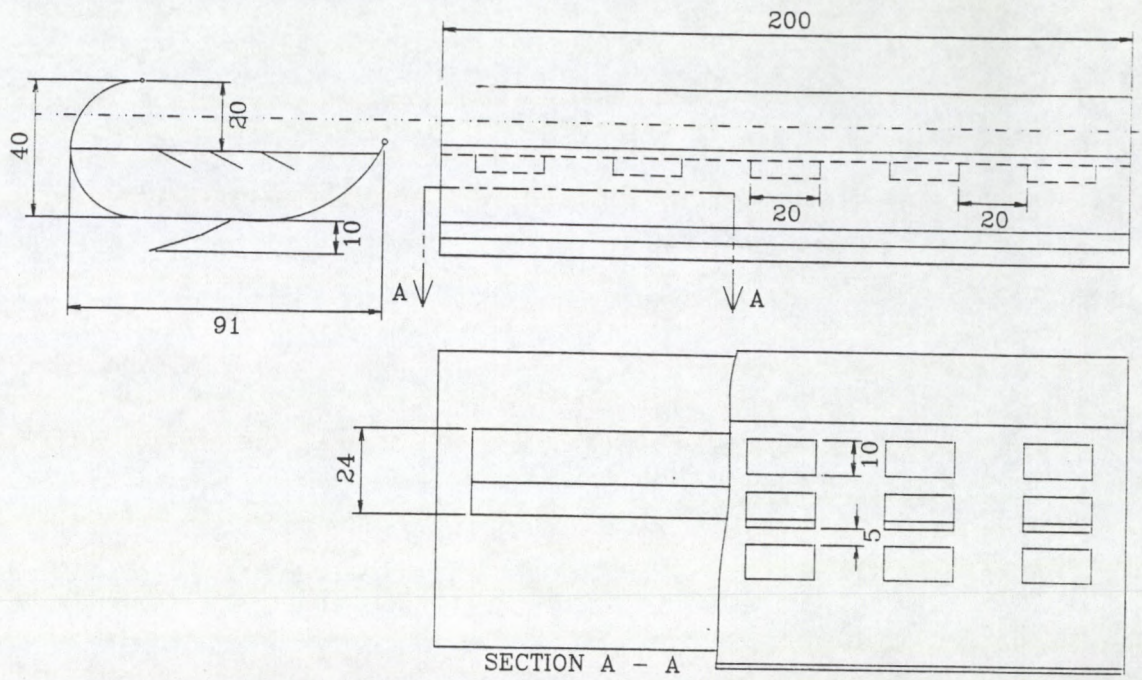


Figure D.5 LAYOUT OF BOOM DESIGN No 1

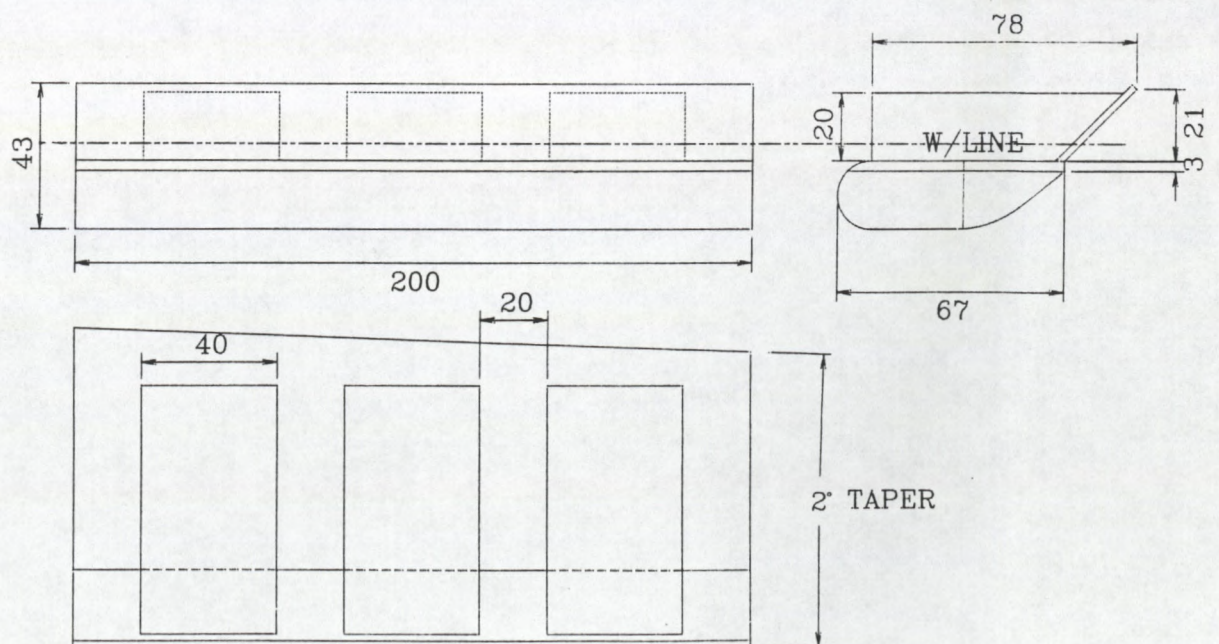


Figure D.6 LAYOUT OF BOOM DESIGN No 2

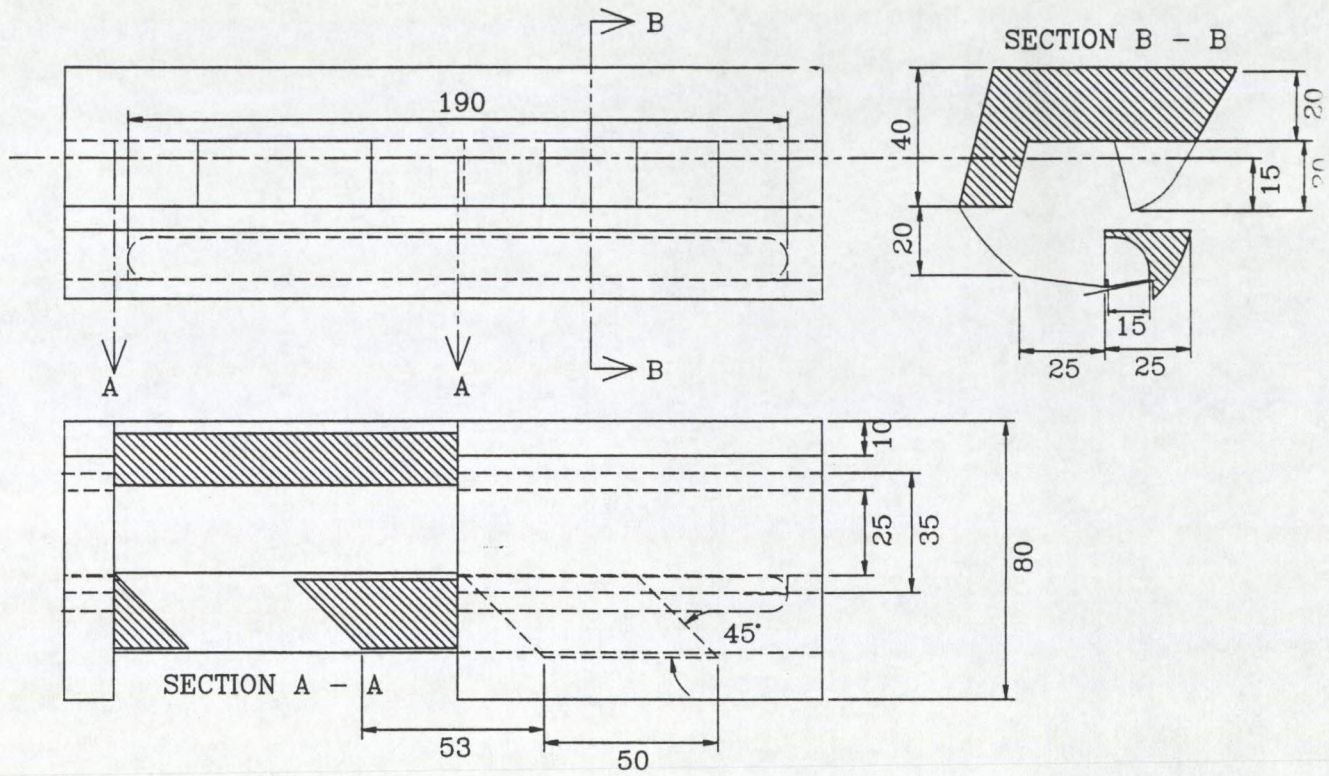


Figure D7 LAYOUT OF BOOM DESIGN No 3

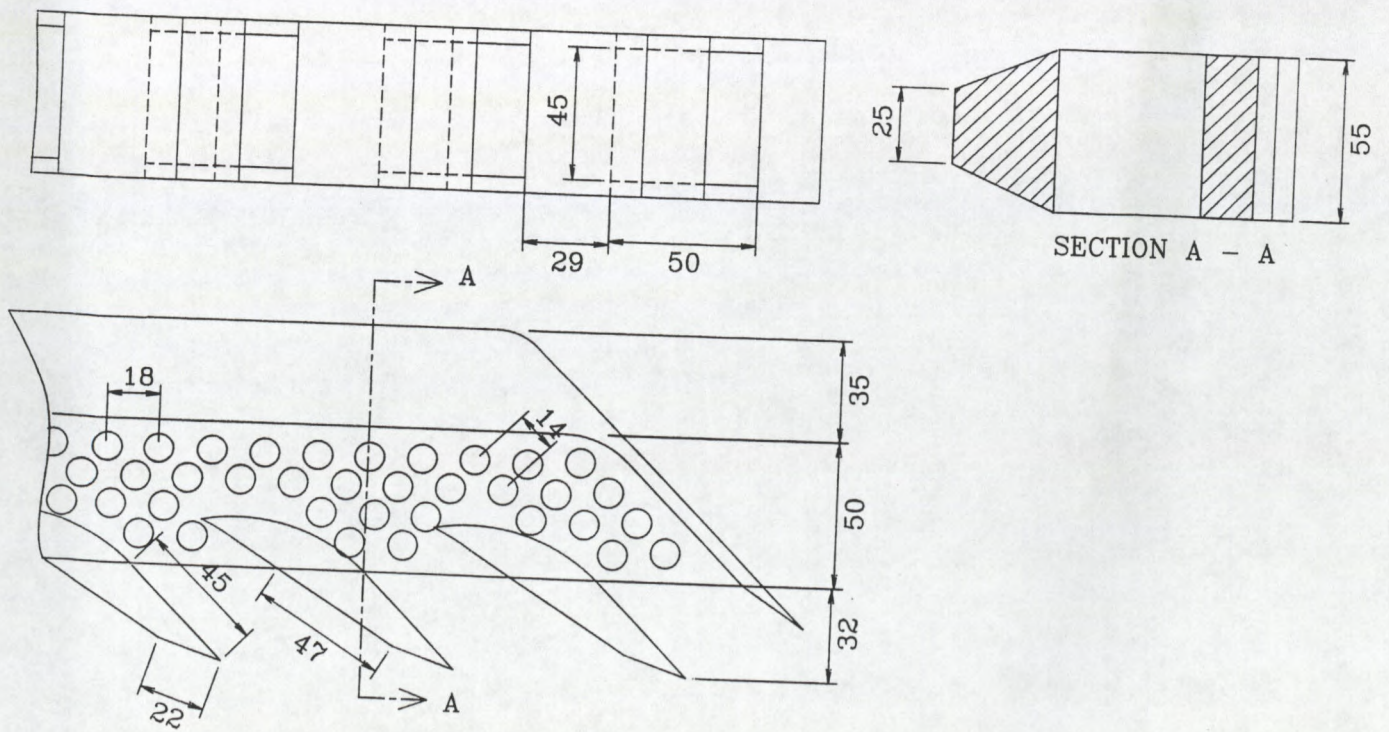


Figure D.8 LAYOUT OF BOOM DESIGN No 4

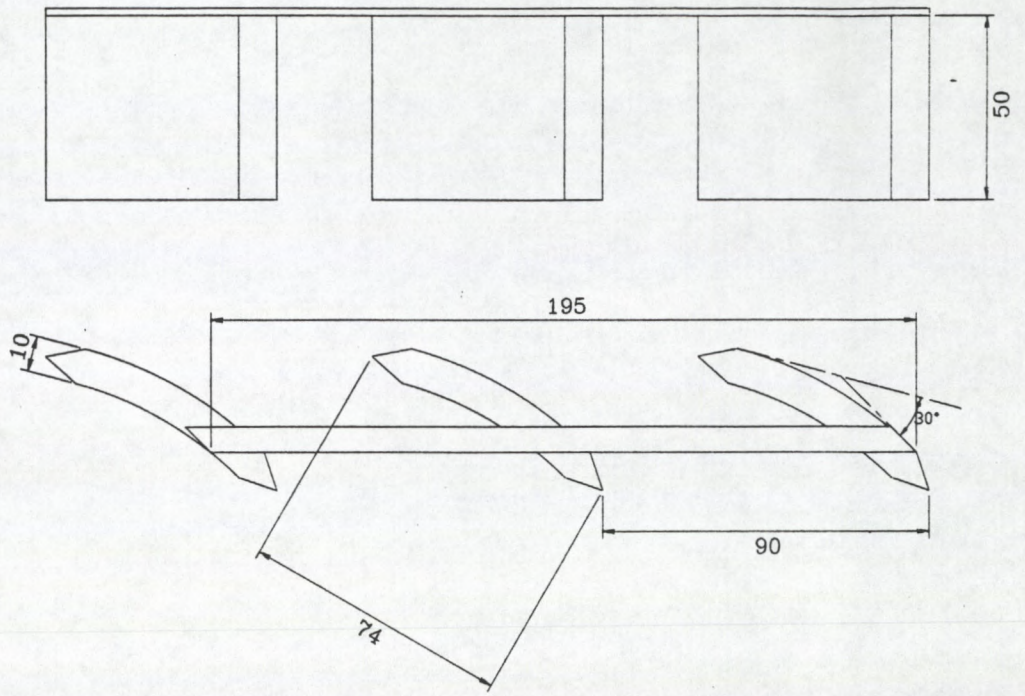


Figure D.9 LAYOUT OF BOOM DESIGN No 5

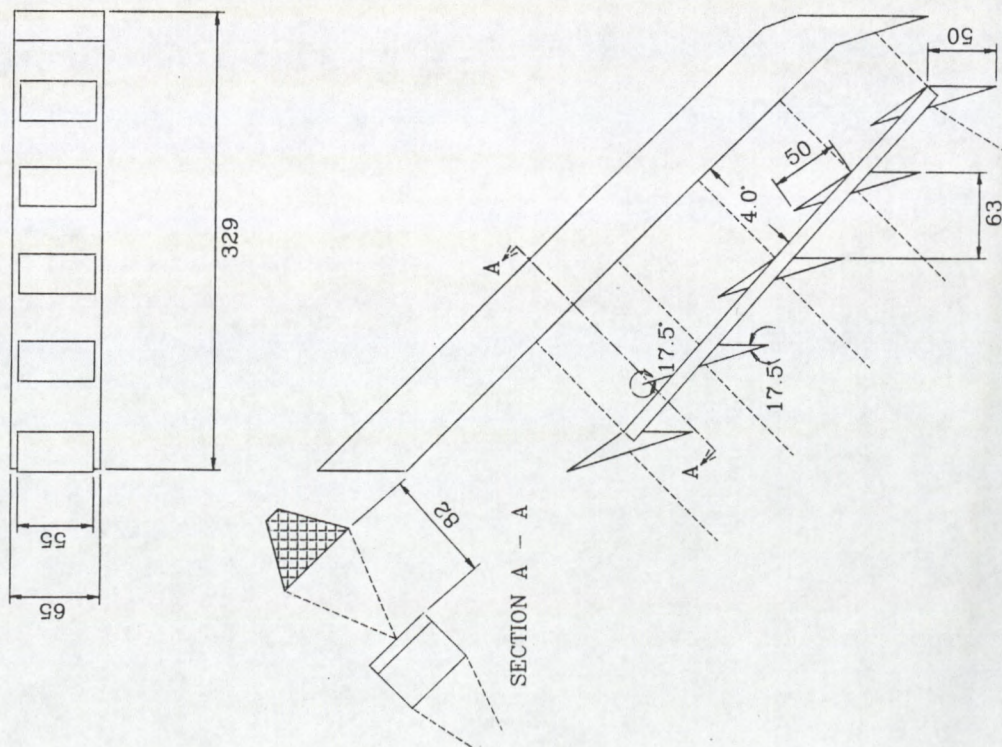


Figure D.10 LAYOUT OF BOOM DESIGN No 6

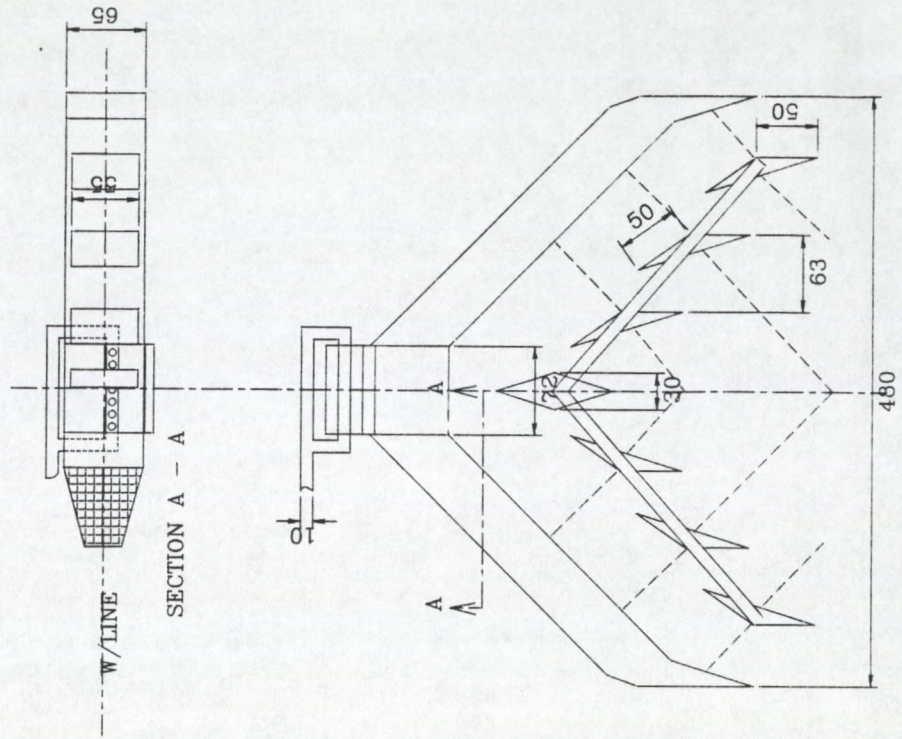


Figure D11 LAYOUT OF BOOM DESIGN No 7

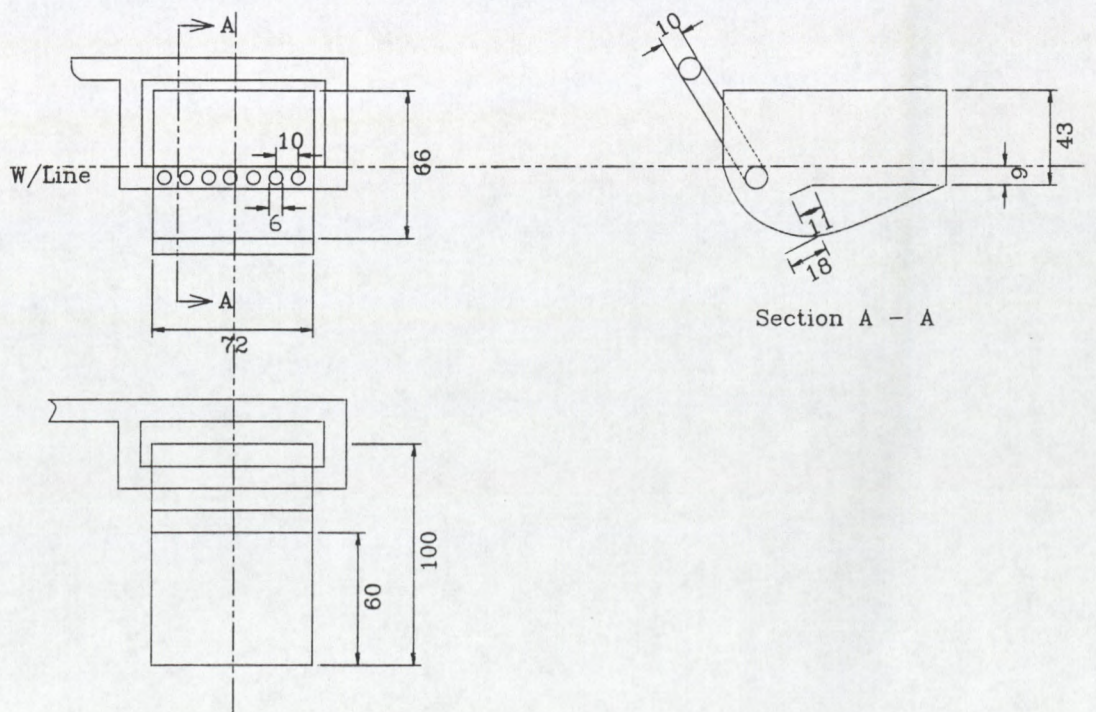


Figure D12 Layout of skimmer used for boom design No 7

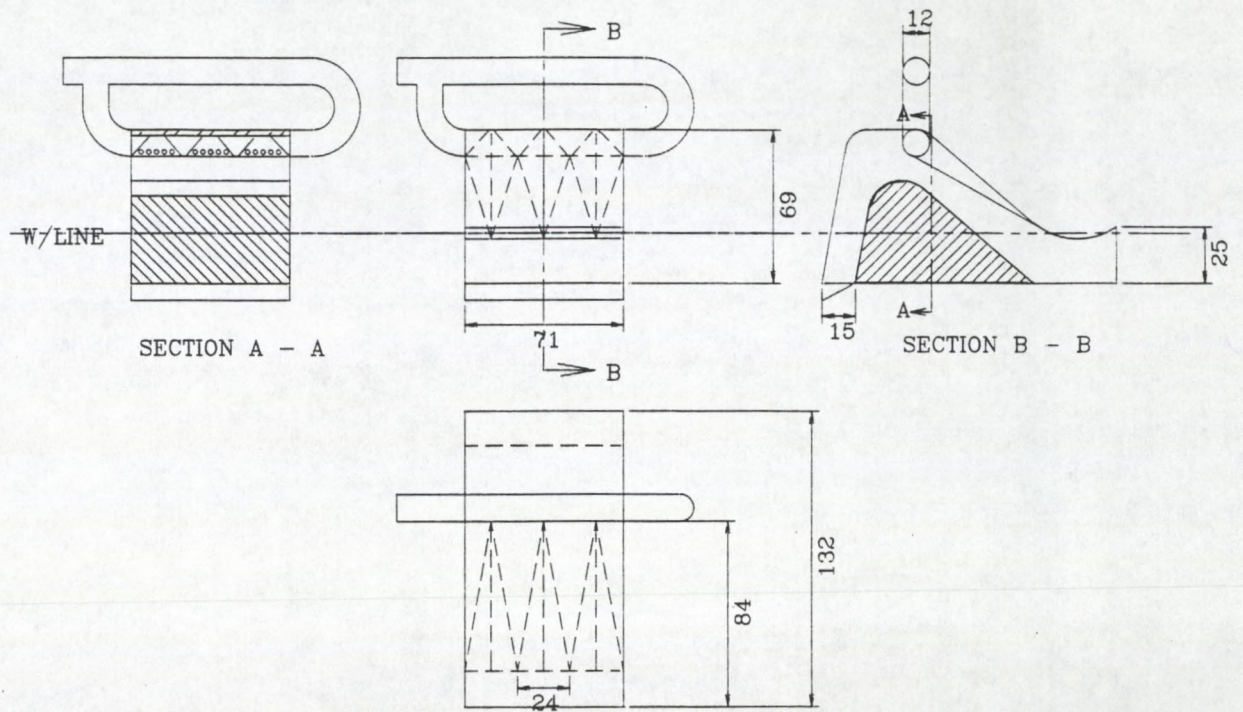


Figure D13 LAYOUT OF SKIMMER FOR BOOM DESIGN TEST No 8

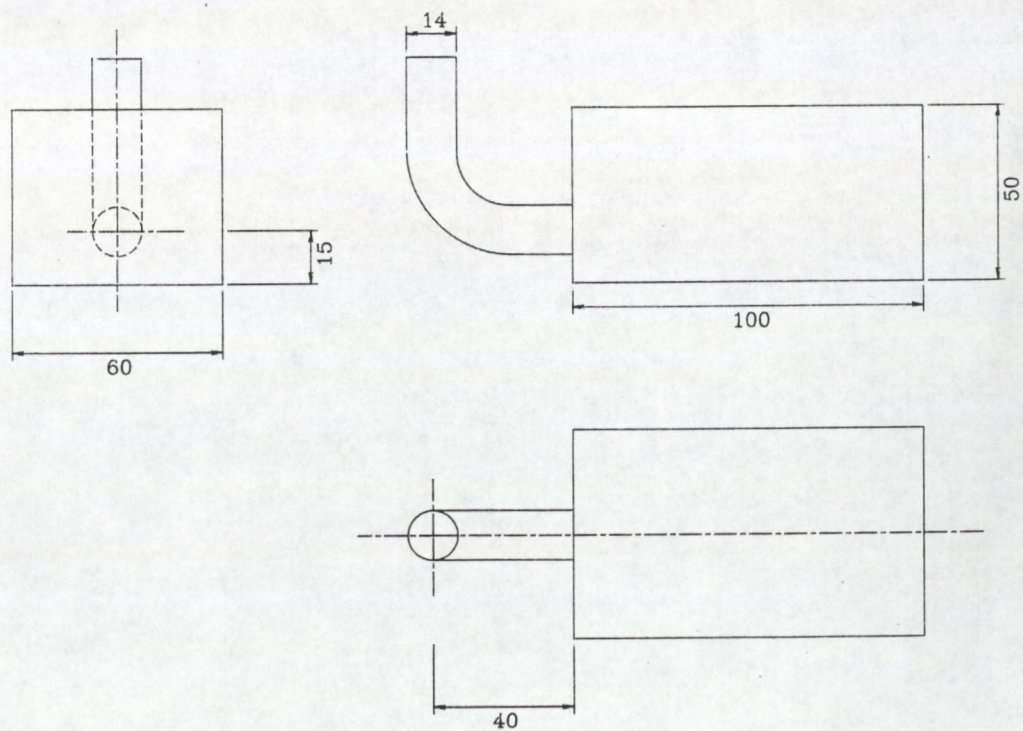


Figure D.14 LAYOUT OF BOOM DESIGN No 9

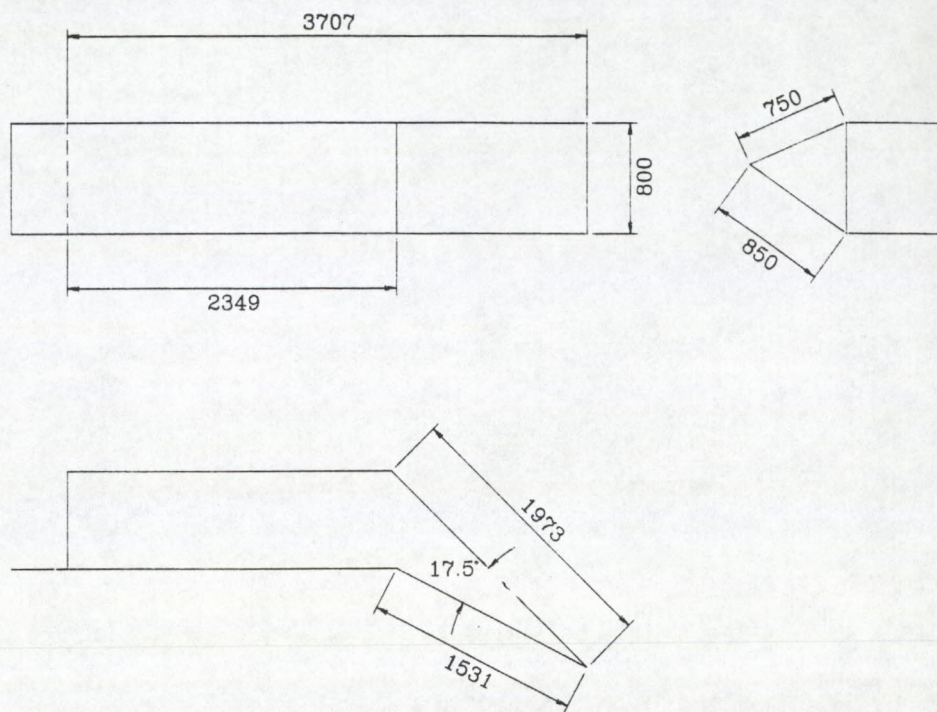


Figure D.15 Layout of end boom

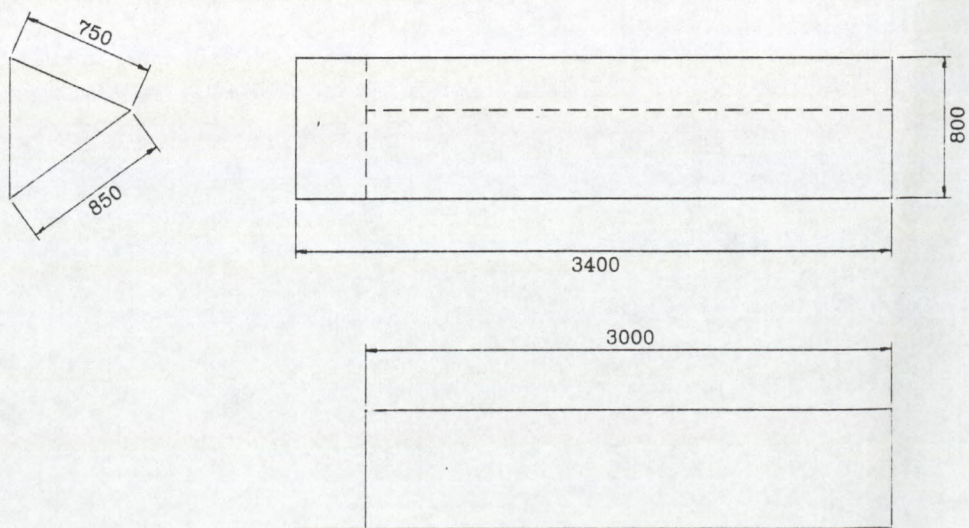


Figure D16 LAYOUT OF CENTRE BOOM

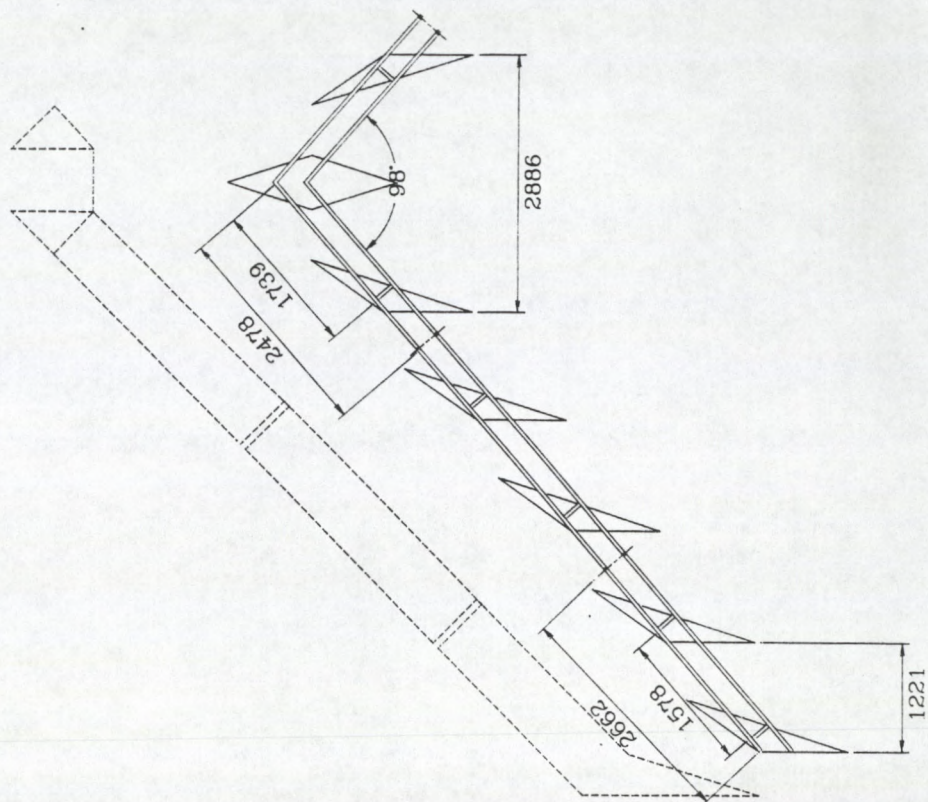


Figure D17 LAYOUT OF DEFLECTOR FLOATS HELD BY SEMI - RIGID FRAME

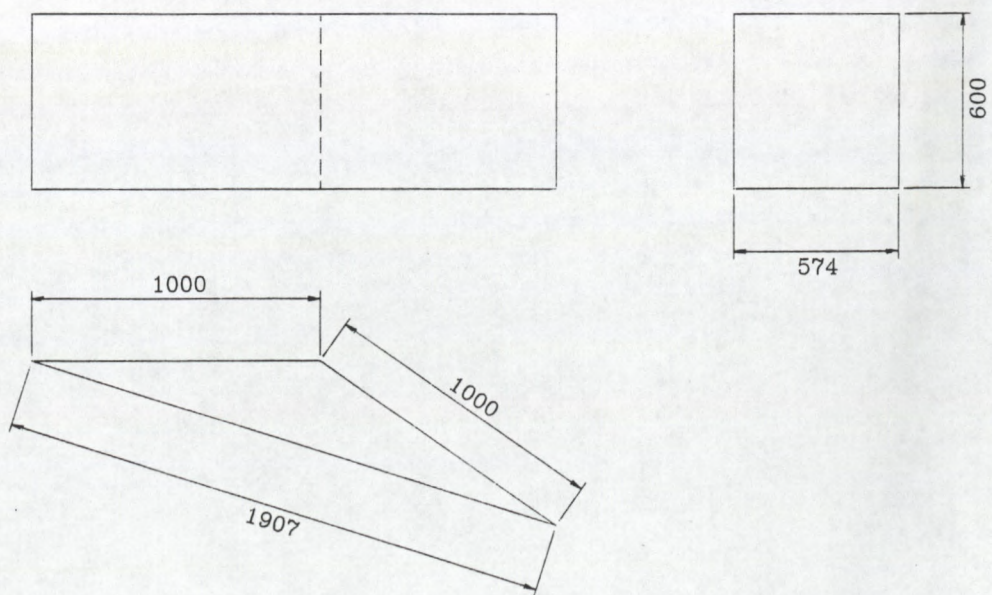


Figure D.18 LAYOUT OF DEFLECTOR FLOAT

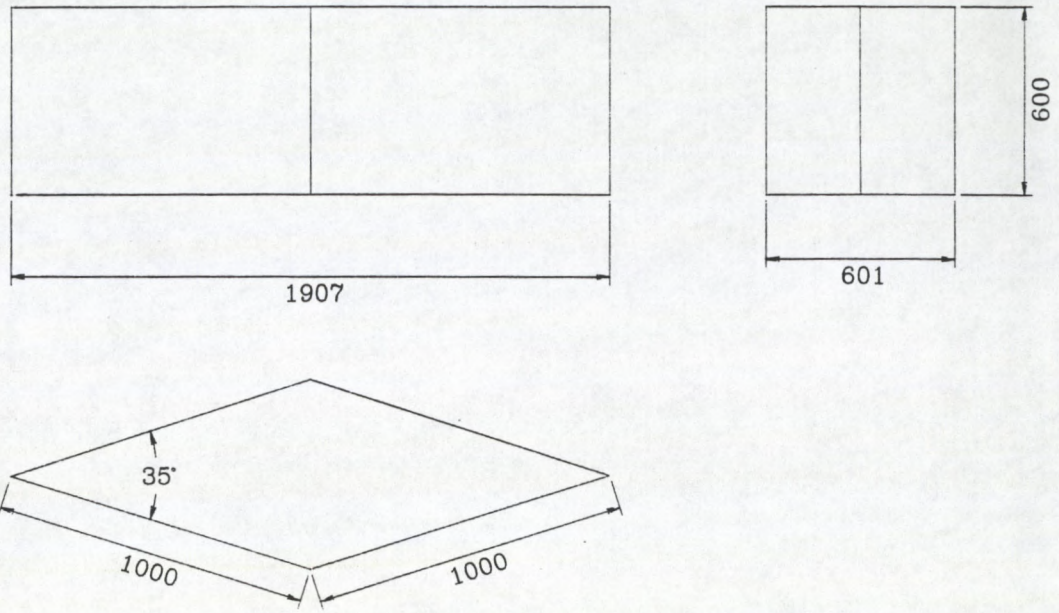


Figure D19 LAYOUT OF TRIANGULAR DEFLECTOR FLOAT

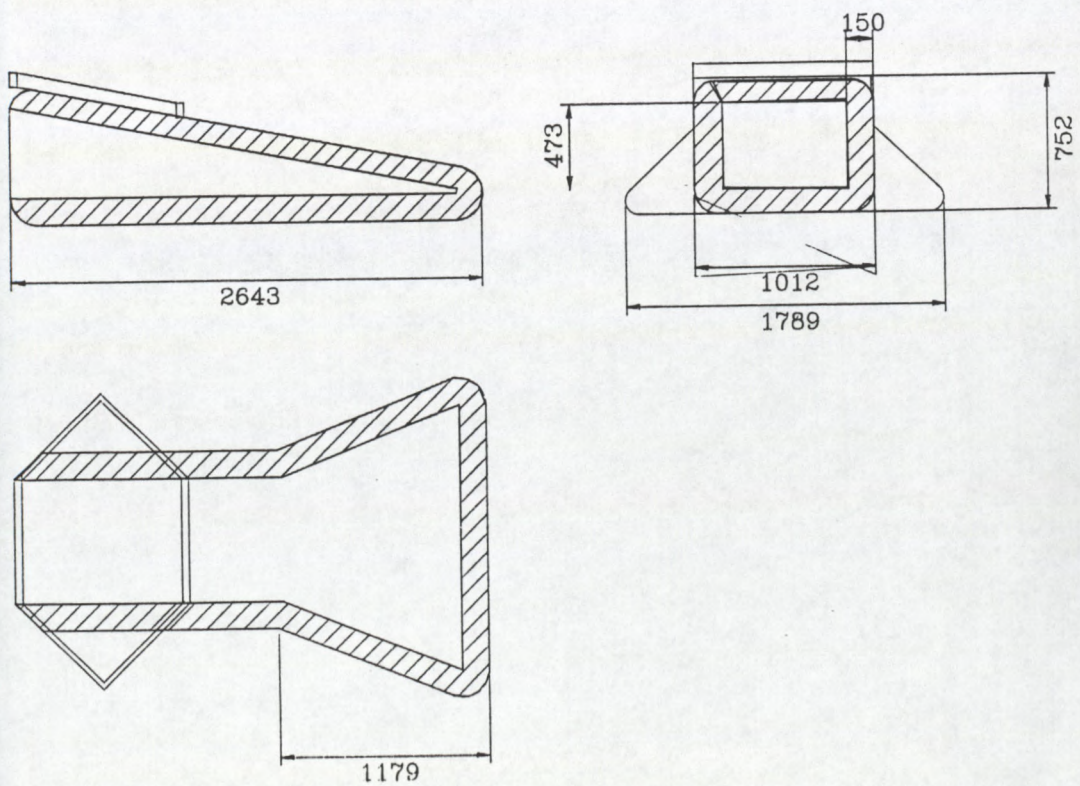


Figure D20 Layout of oil bag

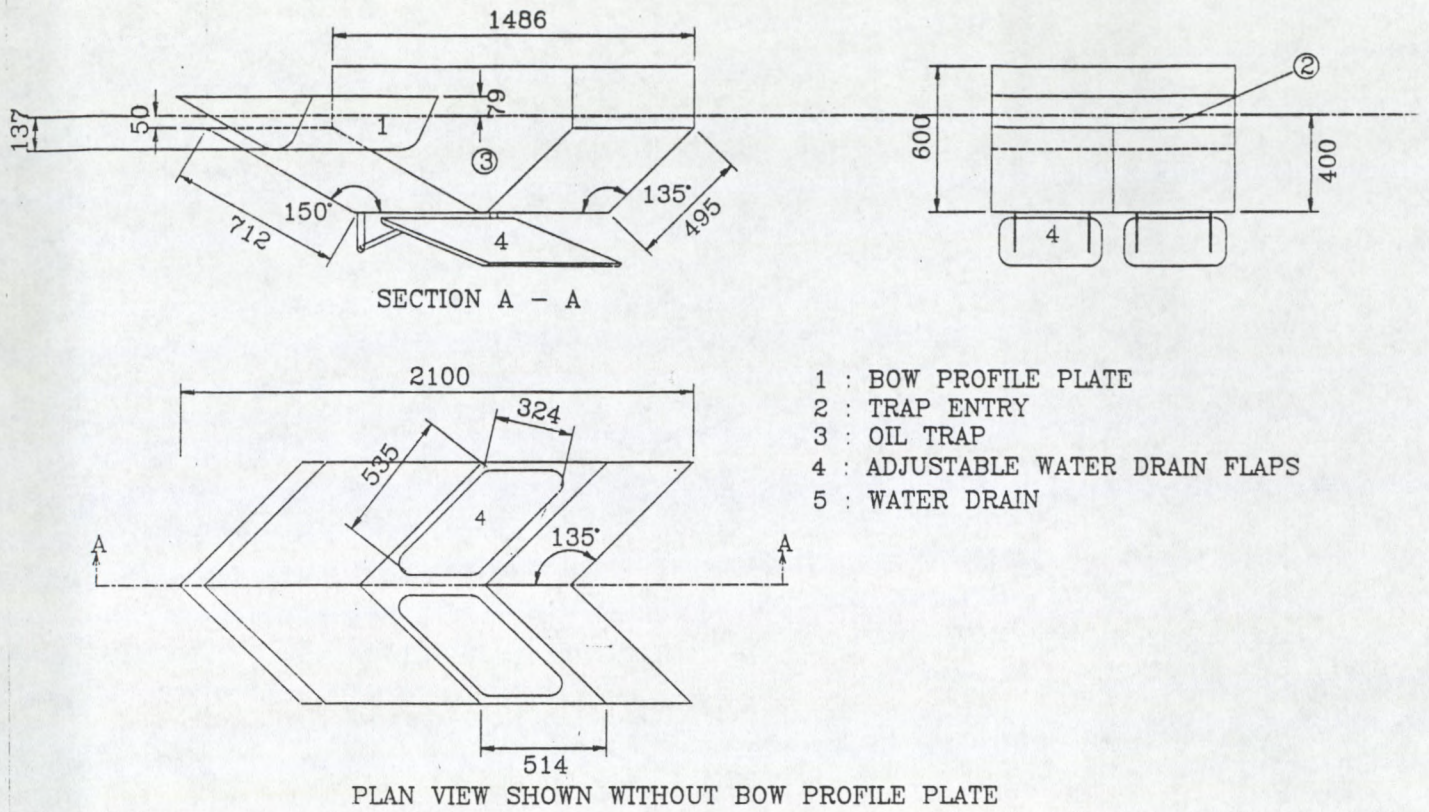


Figure D.21 Layout of oil trap used for catamaran test

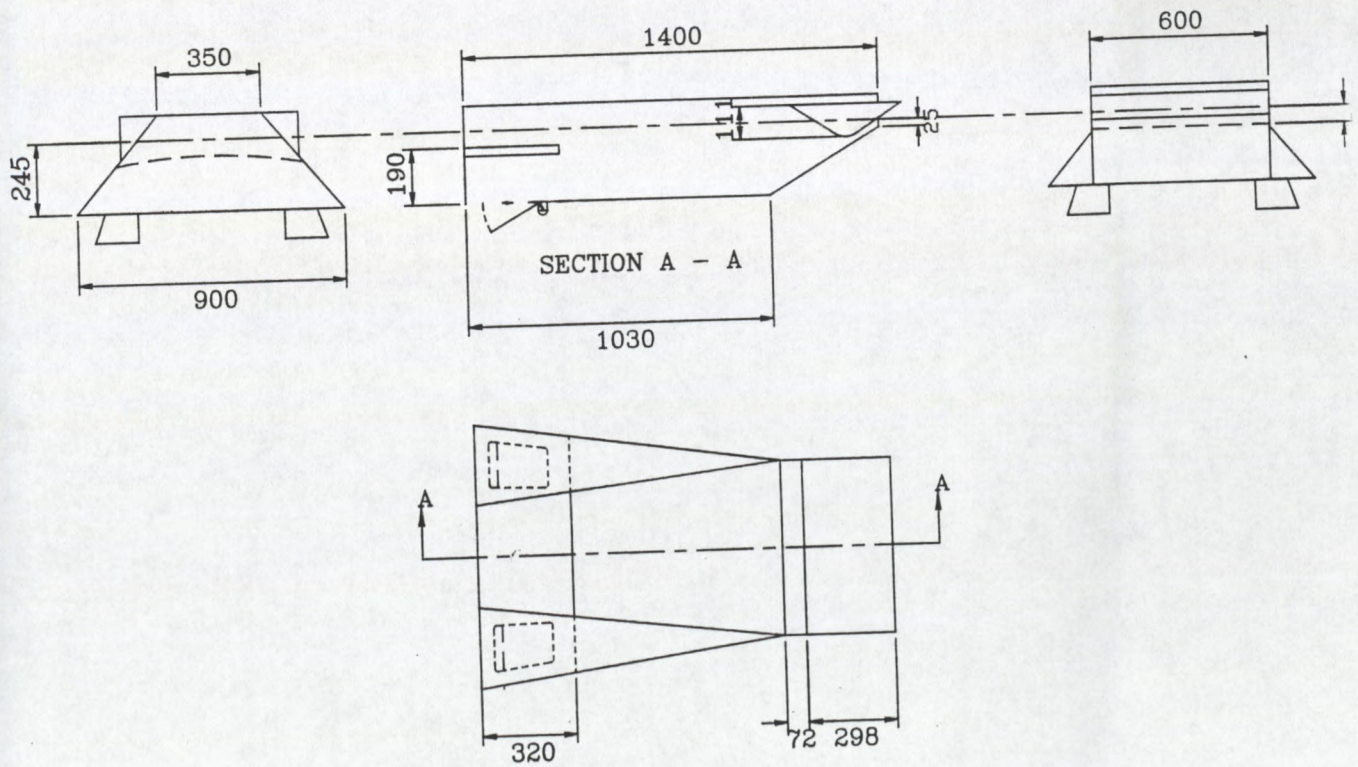
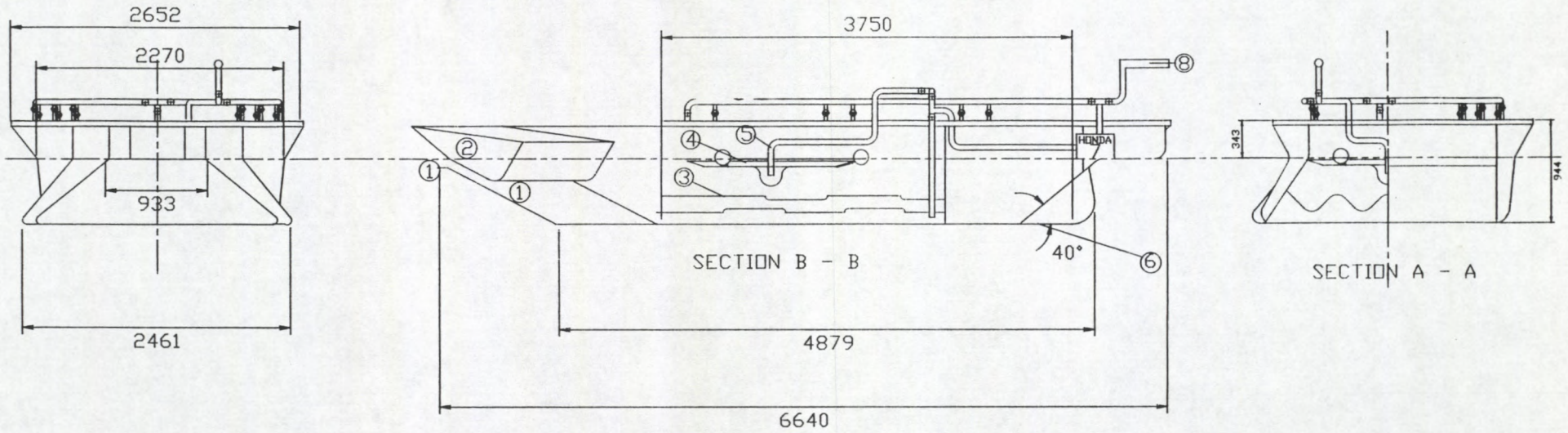


Figure D22 Layout of quarter size model skimmer



1. Trap entry
2. Bow profile plate
3. Oil separation plates
4. Oil suction dish
5. Oil suction pipe
6. Water drains
7. Pump
8. Oil discharge pipe
- Shut off valve

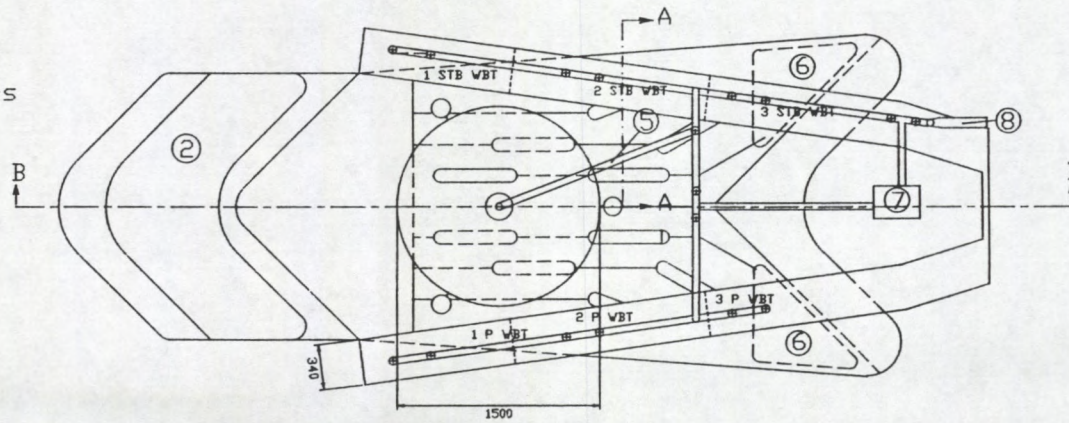


Figure D23: Layout of Skimmer Prototype

D24

HYDRAULIC JUMP PROFILE CATAM RAN

Y1	A	R	$R^{1,333}$	v	$\sim V^2/2g$	E	ΔE	Sf	$\sim Sf$	So	$\sim Sf$	Δx	x	Z1-Z2	Fr	Y3	Y3-Y2	Diff
0.0500	0.0500	0.0455	0.0162	1.6000	0.1435	0.1935		0.0158										
0.0490	0.0490	0.0446	0.0158	1.6327	0.1494	0.1984	0.0049	0.0168	0.0163	0.5617	0.0088	0.0088	0.0054	2.3548	0.1405	0.0915	0.0861	
0.0480	0.0480	0.0438	0.0154	1.6667	0.1557	0.2037	0.0053	0.0180	0.0174	0.5606	0.0094	0.0182	0.0111	2.4288	0.1426	0.0946	0.0835	
0.0470	0.0470	0.0430	0.0150	1.7021	0.1624	0.2094	0.0057	0.0193	0.0186	0.5594	0.0102	0.0284	0.0172	2.5067	0.1448	0.0978	0.0806	
0.0460	0.0460	0.0421	0.0147	1.7391	0.1696	0.2156	0.0061	0.0206	0.0199	0.5581	0.0110	0.0394	0.0237	2.5889	0.1470	0.1010	0.0773	
0.0450	0.0450	0.0413	0.0143	1.7778	0.1772	0.2222	0.0066	0.0221	0.0214	0.5566	0.0119	0.0513	0.0306	2.6757	0.1493	0.1043	0.0736	
0.0440	0.0440	0.0404	0.0139	1.8182	0.1853	0.2293	0.0071	0.0238	0.0230	0.5550	0.0129	0.0642	0.0381	2.7674	0.1516	0.1076	0.0695	
0.0430	0.0430	0.0396	0.0135	1.8605	0.1941	0.2371	0.0077	0.0256	0.0247	0.5533	0.0140	0.0781	0.0461	2.8645	0.1540	0.1110	0.0650	
0.0420	0.0420	0.0387	0.0131	1.9048	0.2034	0.2454	0.0084	0.0277	0.0267	0.5513	0.0151	0.0933	0.0546	2.9674	0.1565	0.1145	0.0599	
0.0410	0.0410	0.0379	0.0127	1.9512	0.2135	0.2545	0.0090	0.0299	0.0288	0.5492	0.0165	0.1097	0.0639	3.0767	0.1591	0.1181	0.0542	
0.0400	0.0400	0.0370	0.0123	2.0000	0.2243	0.2643	0.0098	0.0324	0.0312	0.5468	0.0179	0.1277	0.0738	3.1928	0.1617	0.1217	0.0479	
0.0390	0.0390	0.0362	0.0120	2.0513	0.2359	0.2749	0.0106	0.0352	0.0338	0.5442	0.0196	0.1472	0.0846	3.3163	0.1644	0.1254	0.0408	
0.0380	0.0380	0.0353	0.0116	2.1053	0.2485	0.2865	0.0116	0.0382	0.0367	0.5413	0.0214	0.1686	0.0963	3.4481	0.1673	0.1293	0.0330	
0.0370	0.0370	0.0345	0.0112	2.1622	0.2621	0.2991	0.0126	0.0417	0.0400	0.5380	0.0234	0.1921	0.1090	3.5888	0.1702	0.1332	0.0242	
0.0360	0.0360	0.0336	0.0108	2.2222	0.2769	0.3129	0.0138	0.0456	0.0436	0.5344	0.0258	0.2178	0.1229	3.7394	0.1732	0.1372	0.0143	
0.0350	0.0350	0.0327	0.0105	2.2857	0.2929	0.3279	0.0150	0.0499	0.0478	0.5302	0.0284	0.2462	0.1381	3.9008	0.1764	0.1414	0.0033	

D25


HYDRAULIC JUMP PROFILE QUARTER SIZE MODEL

Y1	A	R	$R^{0.75}$	v	$\sim V^2/2g$	E	ΔE	Sf	$\sim Sf$	So - $\sim Sf$	Δx	x	Z1-Z2	Fr	Y3	Y3-Y2	Diff
0.0250	0.0125	0.0227	0.0064	1.0000	0.0561	0.0811		0.0155									
0.0240	0.0120	0.0219	0.0061	1.0417	0.0608	0.0848	0.0038	0.0177	0.0166	0.5614	0.0067	0.0067	0.0044	2.1468	0.0618	0.0378	0.0335
0.0230	0.0115	0.0211	0.0058	1.0870	0.0662	0.0892	0.0044	0.0203	0.0190	0.5590	0.0079	0.0146	0.0093	2.2883	0.0638	0.0408	0.0315
0.0220	0.0110	0.0202	0.0055	1.1364	0.0724	0.0944	0.0052	0.0234	0.0219	0.5561	0.0093	0.0239	0.0149	2.4461	0.0659	0.0439	0.0290
0.0210	0.0105	0.0194	0.0052	1.1905	0.0795	0.1005	0.0061	0.0272	0.0253	0.5527	0.0110	0.0348	0.0214	2.6229	0.0681	0.0471	0.0257
0.0200	0.0100	0.0185	0.0049	1.2500	0.0876	0.1076	0.0071	0.0319	0.0296	0.5484	0.0130	0.0479	0.0289	2.8220	0.0704	0.0504	0.0215
0.0190	0.0095	0.0177	0.0046	1.3158	0.0971	0.1161	0.0085	0.0376	0.0348	0.5432	0.0156	0.0634	0.0377	3.0477	0.0729	0.0539	0.0162
0.0180	0.0090	0.0168	0.0043	1.3889	0.1082	0.1262	0.0101	0.0449	0.0413	0.5367	0.0188	0.0822	0.0481	3.3052	0.0756	0.0576	0.0095
0.0170	0.0085	0.0159	0.0040	1.4706	0.1212	0.1382	0.0121	0.0540	0.0494	0.5286	0.0229	0.1051	0.0606	3.6011	0.0785	0.0615	0.0009
0.0160	0.0080	0.0150	0.0037	1.5625	0.1369	0.1529	0.0146	0.0658	0.0599	0.5181	0.0282	0.1334	0.0757	3.9439	0.0816	0.0656	-0.0101
0.0150	0.0075	0.0142	0.0034	1.6667	0.1557	0.1707	0.0179	0.0811	0.0735	0.5045	0.0354	0.1688					

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HYDRAU LIC JUMP PROFILE PROTO TYPE

Y1	A	R	R ^{0,75}	v	~V ² /2g	E	ΔE	Sf	~Sf	So - ~Sf	Δx	x	Z1-Z2	Fr	Y3	Y3-Y2	Diff	
	0.08	0.1600	0.0385	0.0130	1.5000	0.1261	0.2061		0.0173									
	0.075	0.1500	0.0361	0.0120	1.6000	0.1435	0.2185	0.0124	0.0214	0.0194	0.5586	0.0222	0.0222	0.0161	1.8653	0.1639	0.0889	0.0728
	0.07	0.1400	0.0338	0.0109	1.7143	0.1648	0.2348	0.0162	0.0269	0.0241	0.5539	0.0293	0.0515	0.0357	2.0687	0.1728	0.1028	0.0670
	0.065	0.1300	0.0315	0.0099	1.8462	0.1911	0.2561	0.0213	0.0343	0.0306	0.5474	0.0390	0.0904	0.0602	2.3119	0.1825	0.1175	0.0573
	0.06	0.1200	0.0291	0.0090	2.0000	0.2243	0.2843	0.0282	0.0446	0.0395	0.5385	0.0523	0.1427	0.0914	2.6069	0.1932	0.1332	0.0419
	0.055	0.1100	0.0268	0.0080	2.1818	0.2669	0.3219	0.0376	0.0595	0.0520	0.5260	0.0715	0.2143	0.1321	2.9703	0.2052	0.1502	0.0180
	0.054	0.1080	0.0263	0.0078	2.2222	0.2769	0.3309	0.0090	0.0632	0.0613	0.5167	0.0174	0.2317	0.1418	3.0532	0.2077	0.1537	0.0119
	0.053	0.1060	0.0258	0.0076	2.2642	0.2874	0.3404	0.0095	0.0672	0.0652	0.5128	0.0186	0.2503	0.1521	3.1400	0.2103	0.1573	0.0052
	0.052	0.1040	0.0253	0.0074	2.3077	0.2986	0.3506	0.0102	0.0715	0.0694	0.5086	0.0200	0.2703	0.1631	3.2310	0.2130	0.1610	-0.0021
	0.051	0.1020	0.0249	0.0073	2.3529	0.3104	0.3614	0.0108	0.0763	0.0739	0.5041	0.0215	0.2917	0.1749	3.3265	0.2158	0.1648	-0.0101
	0.05	0.1000	0.0244	0.0071	2.4000	0.3229	0.3729	0.0115	0.0814	0.0788	0.4992	0.0231	0.3148	0.1874	3.4268	0.2186	0.1686	-0.0188
	0.0497	0.0994	0.0242	0.0070	2.4145	0.3268	0.3765	0.0036	0.0831	0.0822	0.4958	0.0073	0.3221	0.1914	3.4579	0.2195	0.1698	-0.0216
	0.0496	0.0992	0.0242	0.0070	2.4194	0.3282	0.3778	0.0012	0.0836	0.0833	0.4947	0.0025	0.3246	0.1927	3.4684	0.2197	0.1701	-0.0225
	0.047	0.0940	0.0230	0.0065	2.5532	0.3655	0.4125	0.0347	0.0999	0.0917	0.4863	0.0714	0.3960	0.2310	3.7601	0.2275	0.1805	-0.0505
	0.0465	0.0930	0.0227	0.0064	2.5806	0.3734	0.4199	0.0074	0.1035	0.1017	0.4763	0.0155	0.4115	0.2393	3.8209	0.2291	0.1826	-0.0567
	0.0463	0.0926	0.0226	0.0064	2.5918	0.3766	0.4229	0.0030	0.1050	0.1042	0.4738	0.0064	0.4179	0.2427	3.8457	0.2297	0.1834	-0.0592
	0.04625	0.0925	0.0226	0.0064	2.5946	0.3774	0.4237	0.0008	0.1053	0.1051	0.4729	0.0016	0.4195	0.2435	3.8519	0.2299	0.1836	-0.0599


D27

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TESTING OF OIL SPILL RECOVERY EQUIPMENT

I refer to your fax enquiring about simulants for oil for the testing of skimming equipment. It is our consideration that sawdust is not necessarily a very good test material because the density differences between sawdust and water are more than the density difference between oil and water. This would mean that sawdust is less likely to be entrained in the seawater by turbulence and is also more easily separated from the seawater.

Unfortunately we are unable to suggest any other material that is suitable to simulate crude. It is a problem we have ourselves and is the reason why we use crude oil in our sea trials. You may wish to know that we have some sea trials planned for later this year. It may be possible for us to incorporate the testing of your equipment in these trials should you wish. As an indication of possible costs you may wish to know that sea trials are very expensive; I would suggest that you might need to be thinking of something in the region of £5000 to £10000.

Peter Wood