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Research and Development of Oil Containment Boom Designs

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Executive Summary

The primary purpose of this project was to develop, assess, and validate alternative boom designs that would allow containment and collection of oil at speeds above the current standard maximum. A secondary objective was to investigate and demonstrate the usefulness of modern computational fluid dynamics (CFD) methods and large-scale physical modelling in advancing oil recovery technologies. The research and development involved a collaborative effort between S.L. Ross Environmental Research Ltd. (SL Ross) and the National Research Council of Canada (NRC), and was funded by the U.S. Bureau of Safety and Environmental Enforcement (BSEE).

NRC and SL Ross conducted an extensive literature review on the existing knowledge in oil spill boom science and technology, particularly concerning high-speed conditions. This review was followed by a comprehensive series of two- and three-dimensional CFD simulations and physical modelling experiments, conducted by NRC, to investigate the oil containment performance characteristics of several oil spill containment boom concepts (and variations thereof) at high speeds subjected to varying quantities of light, medium, and heavy oil.

For the CFD simulations, the problem was modelled as a two-phase incompressible flow moving past a fixed boom system using the OpenFOAM® CFD toolbox. The results of the CFD simulations were then used to inform a series of novel scaled laboratory tests. In the 2D experiments, the water and oil flowed past scale models of the oil containment booms that were fixed in place. In the 3D experiments, the model booms were towed through a tank of water. Some of the 3D experiments were conducted in calm water, while wavy conditions were modelled in others. Through this study, CFD techniques and scaled laboratory experiments were both shown to be a useful and cost-effective means for studying the interaction of oil and water with various styles of oil containment booms, assessing their relative performance, and developing modifications to improve their performance.

Among others, some of the boom concepts investigated by the CFD simulations and physical modelling experiments included conventional booms and booms with ramped or screen components to manage the oil slick at high speeds. The extensive laboratory and computational modelling revealed the promise of several new and modified concepts suggesting the possibility for collection of oil at speeds of 3 knots. Although the Ramped-boom is not a commercially available product, the design appears highly promising and should be further pursued and developed in future research.

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1. Introduction

Mechanical containment and recovery is the most commonly used and most environmentally acceptable response technique to clean up oil spills. Mechanical spill response uses physical barriers (containment booms) to contain and concentrate floating oil, mechanical devices (skimmers) as well as natural and synthetic sorbent materials to remove oil from the water's surface, and temporary storage devices to store the recovered oil and water until it can be disposed of properly. Where possible, mechanical techniques are preferable to other methods such as the use of dispersants or in-situ burning, since mechanical methods remove oil from the natural environment to be recycled or properly disposed.

Spilled oil floating on the water's surface is affected by wind, currents, and gravity, all of which cause it to spread, fragment, and disperse. The first stage of an effective response is to deploy containment booms to limit further spreading and concentrate the oil for recovery. Oil containment booms come in many different shapes, sizes, and styles ranging from small, lightweight models intended for manual deployment in harbours, to large, robust units deployed using sizeable vessels designed for the open seas. Booms vary considerably in their design, but all normally incorporate the following features:

- freeboard to prevent or reduce splashover,
- a sub-surface skirt to prevent or reduce escape of oil under the boom,
- floatation by air or some buoyant materials, and
- a longitudinal tension member (chain or wire) which functions to provide resistance against the effect of winds, waves, and currents. This is often used to provide ballast to keep the boom upright in the water.

A key performance metric for a boom is its capability to contain or deflect oil, which is determined by its interaction with and response to the movement of water. The boom should be flexible enough to conform to wave motion but rigid enough to retain as much oil as possible. Most booms are not capable of containing oil in current speeds greater than 0.7 knots (0.36 m/s) flowing at right angles to the boom, irrespective of boom size or skirt depth. These performance characteristics place practical constraints on the maximum speed at which booms can be towed, typically less than 0.5 knots (0.26 m/s). The performance of containment booms is dependent on currents, wind, and waves. Even weak currents can draw oil under the boom, waves may cause splashover, and wind and/or currents may cause the boom to sink or plane (adapted from Mullin, 2010).

The purpose of this project was to develop, assess, and validate alternative boom designs that would allow containment and collection of oil at speeds above the current standard maximum. A second objective was to investigate the feasibility of using computational fluid dynamics simulations and scaled hydraulic model experiments to assess the relative performance of boom systems. The research and development involved a collaborative effort between S.L. Ross Environmental Research Ltd. (SL Ross) and the National Research Council of Canada (NRC). SL Ross is an environmental consulting firm specializing in research and development related to oil spills and countermeasures, and also provides consulting services in the areas of oil spill contingency planning, countermeasures strategies and equipment, and training. The NRC is Canada's leading research and technology organization and, through its Research Centre for Ocean, Coastal and River Engineering (OCRE), operates one of the world's largest and most advanced hydraulics laboratories and has extensive expertise researching the effects of ice and waves on ships, structures, and shorelines. The NRC is a leader in developing and evaluating solutions for harsh marine environments using numerical modelling tools, field investigations, and world-class model testing facilities.

1.1. Oil Boom Designs

While a large variety of oil booms exist for different applications, this research focused on four particular designs intended for open-ocean towing in a U-shape at high speeds. In addition to these designs, several variations and modifications developed to improve performance at higher tow speeds were also investigated. It is important to note that this research did not involve the use of skimmers, and focused purely on the oil collection effectiveness for the various boom designs.

As a point of comparison, the first boom design selected was based on the Ro-Boom 2200, manufactured by DESMI Inc., chosen to represent a "conventional" single-skirt oil boom. The Ro-Boom is a pressure-inflatable skirt-type boom made with synthetic rubber with a CSM (Hypalon) external layer (see Figure 1). The 2200 model features a freeboard of 830 mm, a draft of 950 mm, and a 13 mm chain at the base of the skirt to act as ballast and to provide tension along the length of the boom. The nominal cross-section design of the Ro-Boom 2200 was adopted as the conventional boom for this study (see Figure 2).

Figure 1. Ro-Boom manufactured by DESMI Inc.

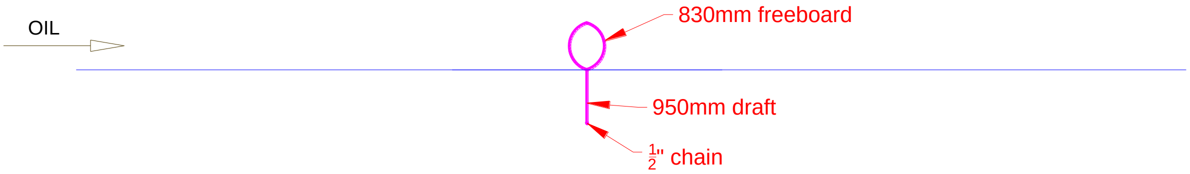


Figure 2. Nominal prototype design for a conventional boom.

The second boom design selected was based on the Speed-Sweep 2200, also manufactured by DESMI Inc. The Speed-Sweep 2200 model has the same overall make-up as the Ro-Boom 2200, with the addition of one horizontal and three vertical screens (see Figure 3). The horizontal screen is stretched across the bottom of the skirt in the apex region, while the vertical screens are stretched across the centre of the U-shaped boom (perpendicular to the tow direction) and use spherical floats to hold the screens in an upright position. The horizontal and vertical screens serve to slow the relative velocity between the water and the boom near the surface and thereby contain oil at faster tow speeds as compared with a conventional boom design without screens. The nominal cross-section design of the Speed-Sweep 2200 was adopted as the Screen-boom system for this study (see Figure 4).

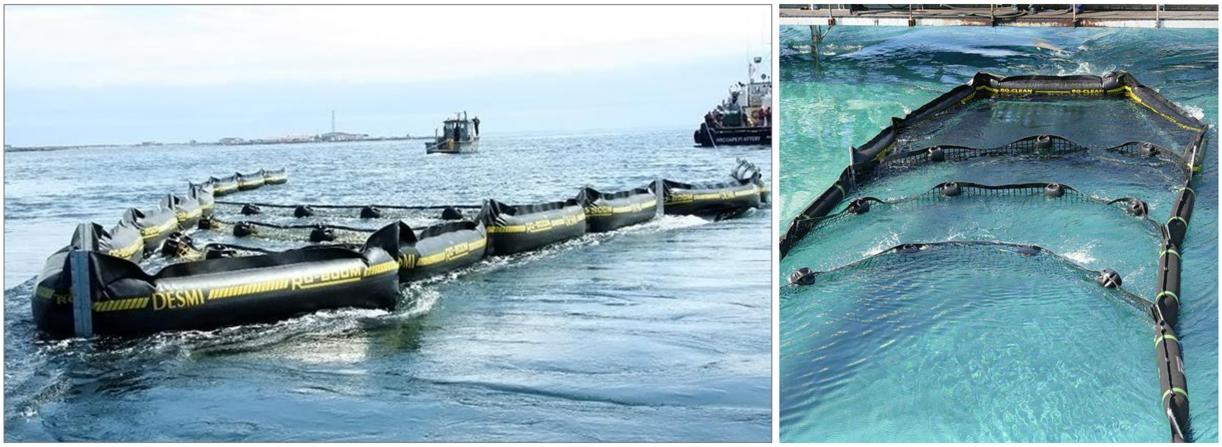


Figure 3. Speed-Sweep manufactured by DESMI Inc.

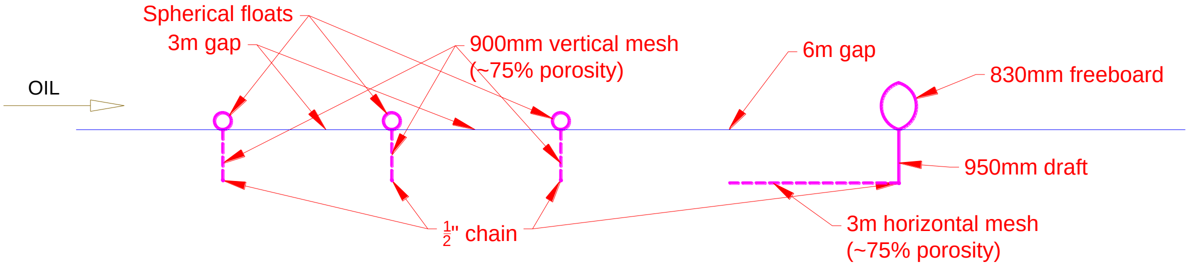


Figure 4. Nominal prototype design for the Screen-boom system.

The third boom design selected was based on the Current Buster 6 (CB6), manufactured by NOFI (see Figure 5). The CB6 features a V-shaped boom with a floating oil storage reservoir at the apex. Detailed schematics of the CB6 were not available, and therefore several assumptions for the geometry of the boom and storage tank inlet had to be made.

Figure 5. Current Buster 6 manufactured by NOFI.

The fourth boom design investigated was a Ramped-boom system, which has been investigated previously at model and prototype scales (see Wong *et al.*, 2002 & 2003), but is not a commercially-available product at this time. The Ramped-boom system features a conventional U-shaped boom with an impermeable ramp located near the mouth of the boom, which acts to force the approaching oil and water below the surface to be trapped in a low-velocity zone that forms above the ramp. Two intermediate skirts (similar to the Screen-boom system, but solid) stretch across the middle of the boom behind the ramp (perpendicular to the tow direction). The nominal cross-section design of the Ramped-boom system adopted for this study is shown in Figure 6.

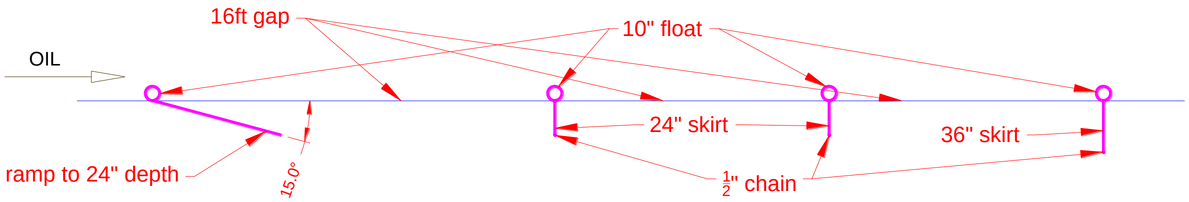


Figure 6. Nominal prototype design for the Ramped-boom system.

1.2. Oil Boom Failure Mechanisms

Containment booms can be highly effective for collecting and recovering oil slicks on water. However, they do not perform well in all environmental conditions. To understand how booms operate and what features affect their performance, it is useful to understand how booms fail. There are five basic modes of operating failure:

- entrainment,
- drainage,
- splashover,
- submergence, and
- planing.

These operating failures occur when the boom is intact and do not necessarily coincide with structural failure. The following sub-sections described these operating failures in further details and are adapted from SL Ross (2017). In addition, the ASTM Standard F2084 (2018) defines the following terminology:

- First-loss tow/current velocity – the minimum tow/current velocity normal to the membrane at which oil *continually* escapes past a boom. This applies to the boom in the catenary position. First-loss does not include scenarios where oil droplets occasionally pass the boom.
- Gross-loss tow/current velocity – the minimum speed at which *massive continual* oil loss is observed escaping past the boom.

1.2.1. Entrainment Failure

When oil is contained in strong currents or at high speeds, a headwave often builds upstream of the boom, where the oil is being collected. With high current speeds, turbulence occurs at the downstream side of the headwave. This turbulence causes oil droplets to break away from the headwave, become trapped in the flowing water, and pass under the boom (see Figure 7). Unless the headwave is a considerable distance upstream, oil droplets will not have time to resurface to be contained by the boom. The amount of oil lost in headwave failure depends on the thickness of the oil in the headwave, which is a result of the combination of water/tow velocity, specific gravity, and viscosity of the oil. If oil droplets that have broken away lack buoyancy to rejoin the slick, they will be carried under the boom. The velocity at which the headwave becomes unstable and droplets of oil begin to strip off is called the critical velocity. At this velocity, droplets are entrained in the water streamlines and flow under the boom. The critical velocity for many crude oils and refined products ranges from 0.7 to 1.2 knots (0.7 knots is generally accepted as a conservative estimate). Entrainment loss determines how fast a boom can be towed, or the maximum current in which it will be effective.

Both currents and waves contribute to determining the critical velocity for entrainment failure. Waves induce orbital velocities that are superimposed on the current/tow velocity. For example, a steady current perpendicular to a boom at 0.6 knots plus an orbital water particle velocity caused by waves will almost certainly result in some entrainment failure.

The critical velocity is usually defined in terms of the component of water velocity perpendicular to the boom. Entrainment failure can be delayed by reducing the velocity perpendicular to the boom, which can be achieved (for example) by deploying the boom at oblique angles to the flow.

Spill containment performance depends on the angle between the boom and the current. However, a flexible boom cannot be maintained at a fixed angle with the current, and will instead be expected to take some catenary shape. When the angle with the direction of flow becomes small, the catenary may be more like a J-shape. The curvature of the J represents a greater angle to the flow and therefore has a lower speed at which failure occurs. As a result, expect failure to occur first in that part of the boom curving to cross the direction of flow.

When booms fail in fast currents (or fast tow speeds), oil escaping under the boom tends to collect in the water flowing along the backside of the boom. This provides a spill response crew with another opportunity for containment. A secondary boom can be deployed just downstream from the primary boom to enhance oil recovery.

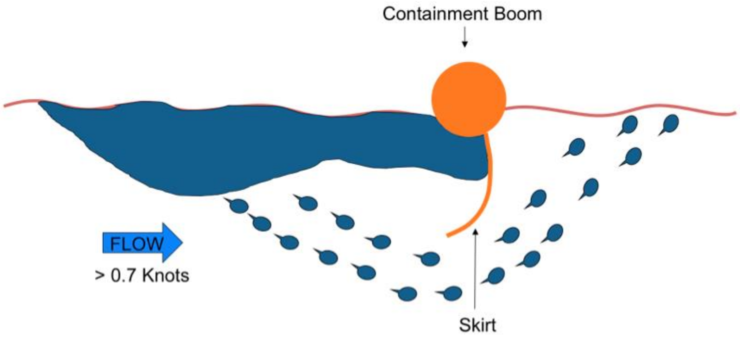


Figure 7. Entrainment failure.
Source: ACME Environmental

1.2.2. Drainage Failure

As oil collecting at the boom face becomes thicker, it may reach a point where it flows down the face of the boom and escapes under the skirt. This loss is known as drainage failure (see Figure 8). Water (and oil) at the boom face is diverted downward, accelerating to keep up with water flowing directly under the skirt. The problem can actually be exacerbated by having a deeper skirt. Increasing skirt depth also increases the distance that water on the face of the boom must travel to stay with the flow, which causes drainage failure to occur at a lower critical velocity. A boom that can exhibit high critical velocities at high tow speeds is resistant to draining failure.

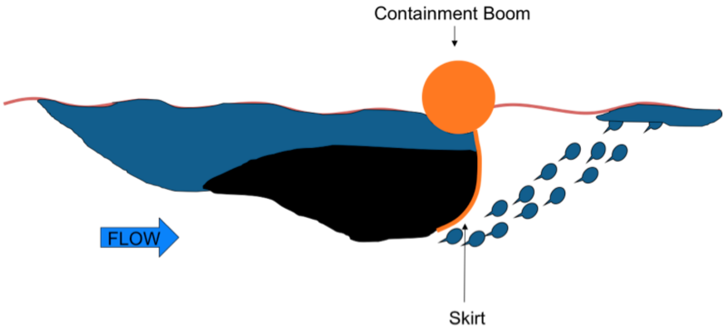


Figure 8. Drainage failure.
Source: ACME Environmental

The critical velocity at which drainage failure occurs depends on the skirt depth, oil viscosity, specific gravity, and the depth of the oil being retained by the boom. The critical velocity for drainage failure is greater than the critical velocity for entrainment failure, so entrainment failure is most likely to occur first in fast currents.

Both entrainment failure and drainage failure involve leakage from large pools of oil that may collect ahead of the boom. These types of failure can often be avoided by preventing the formation of large pools by deploying skimmers. Weirs installed along the face of boom skimmers are generally effective in preventing drainage losses. It is also possible to reduce the turbulence at the headwave, and therefore the loss of oil, by placing sorbent mats on the upstream edge of the slick where the headwave forms.

The way the skirt hangs below the boom also affects oil recovery and loss. Figure 9 shows diagrams illustrating the results of laboratory tests of containment booms operating in moving currents. Figure 9a shows the bottom of the skirt being drawn upstream, developing a pocket with a rather large area for oil to collect. In this case, only a small amount of oil escapes under the boom. If the bottom of the skirt is not controlled with a tension member or if it is poorly ballasted, the boom will not be as effective in a strong current, and oil will escape beneath it (see Figure 9c). As previously noted, most booms typically begin to fail in current speeds of about 0.7 knots, assuming deep water under the skirt. In shallower water depths, the water velocity under the boom will be significantly higher, and failure occurs at lower speeds, in the range of 0.3 to 0.4 knots. This example illustrates the need for short skirts in shallow water. For optimal oil recovery performance, the depth of water under the boom should be at least five times the draft.

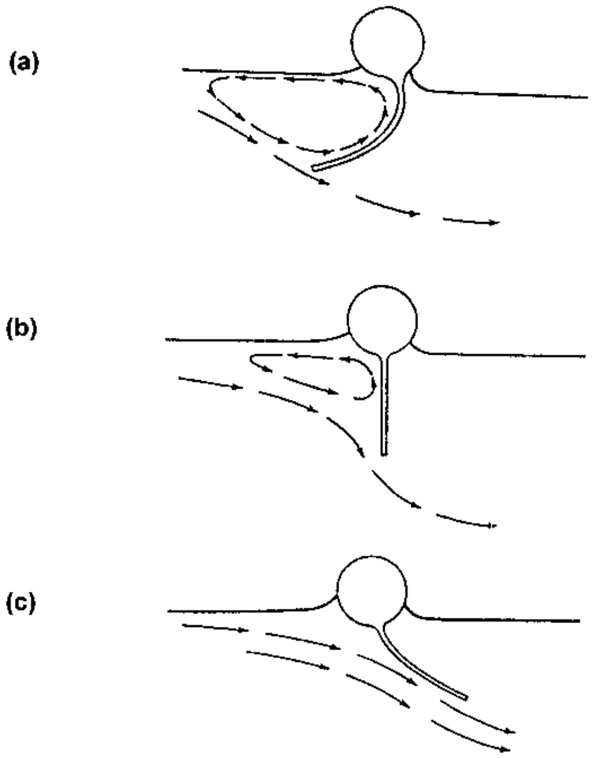


Figure 9. Flow under boom skirt.
Source: SL Ross (2017)

1.2.3. Splashover Failure

Failure occurs in choppy seas when oil splashes over the boom freeboard (see Figure 10). Splashover failure may occur if the wave height is greater than the boom freeboard and the wave length-to-height ratio is less than 10:1. When the length-to-height ratio falls below 5:1, as in choppy or rapidly shoaling water, most booms will have some splashover failure. Most booms perform well in gentle swell conditions, even when the wave height is much larger than the freeboard. In a medium swell, "bridging" may occur (unless the boom is very flexible) and oil could pass under it.

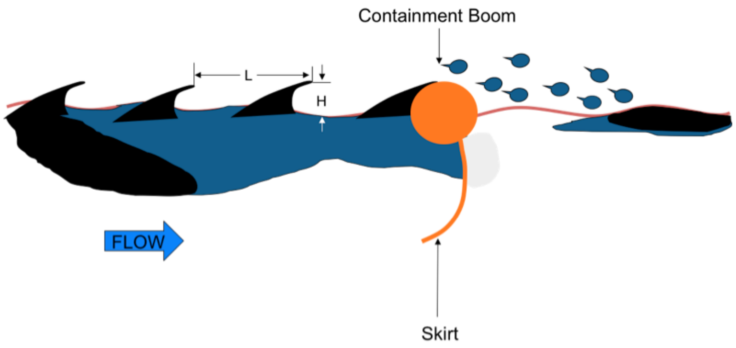


Figure 10. Splashover failure.
Source: ACME Environmental

1.2.4. Submergence Failure

Submergence failure may occur when a boom is deployed or anchored in a fast current, or is being towed at a high velocity in still water (see Figure 11). The tendency to submerge at a given velocity is determined by the boom's reserve buoyancy. Reserve buoyancy is the buoyancy in excess of that required to keep a boom afloat in still water. Higher reserve buoyancy reduces the tendency to submerge. Booms with air-chamber floatation generally have greater reserve buoyancy than those with solid floatation and are less likely to suffer submergence failure. Submergence failure is not common in typical oil spill response situations because entrainment failure usually occurs first (i.e., at a lower speed); however, submergence must be carefully considered in the case of high-speed booms.

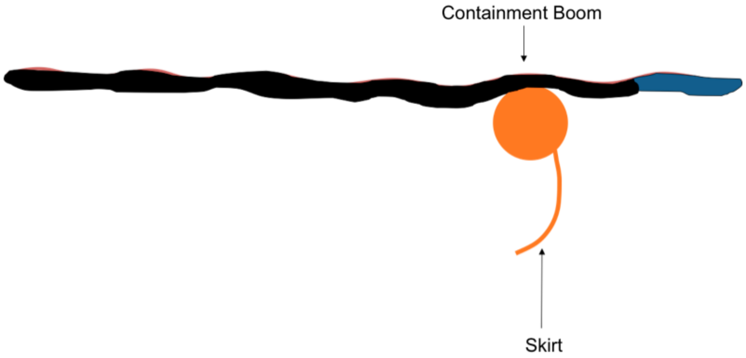


Figure 11. Submergence failure.
Source: ACME Environmental

1.2.5. Planing Failure

A strong wind and strong current moving in opposite directions may cause a boom to heel flat on the water surface. The resulting loss of oil is called planing failure (see Figure 12). This failure is most likely to occur when a boom has inadequate ballasting or when an internal tension member is near or above the waterline.

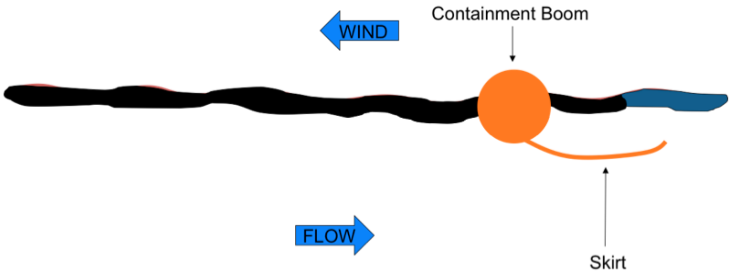


Figure 12. Planing failure.
Source: ACME Environmental

2. Research Program

The research project involved the following four phases, which were executed from Fall 2018 to Summer 2019:

- Phase 1 – Review and Assimilation of Past Research and Development.
- Phase 2 – Computational Fluid Dynamics Simulations.
- Phase 3 – Scaled Laboratory Testing.
- Phase 4 – Reporting.

Further detail on each of these project phases is provided in the following sections.

3. Phase 1 – Review and Assimilation of Past R&D

The first phase of the project involved a literature review on the subject matter. Two areas of particular interest were the identification of a suitable test oil and guidance for the computational and scale modelling.

The first part of the search involved contacting the developers of three recent fast-current containment systems. Emails were sent to DESMI (Speed-Sweep), NOFI (Current Buster), and Egersund (MOS Sweeper), but only DESMI responded. No technical papers were found for these three products, except for some early testing at Ohmsett of a prototype of the DESMI product.

NRC then conducted an extensive literature review from the libraries of SL Ross and the National Research Council. NRC tasked the National Science Library (NSL) to produce a search in accessible databases. The literature search was conducted in Scopus, Aquatic Sciences and Fisheries Abstracts and Advanced Technologies & Aerospace Database (Proquest). In order to identify as many relevant papers as possible, the search was conducted on the topic of “oil spill containment boom / barrier” in combination with the terms of “CFD or Scale model”. Table 1 summarizes the search terms.

Table 1. Search topics and terms for the literature review.

Topics	Examples of terms used
Oil	Oil
Spill	Spill OR slick
Containment	Containment
Boom / Barrier	Boom OR barrier OR fence OR barrage
Collection	Recover* OR collection OR clean up OR cleanup OR clean-up
CFD	CFD OR computational fluid dynamics OR fluid dynamics
Numerical model	Numerical modelling OR numerical models OR theoretical modelling OR mathematical modelling
Scale model	Scale model
Physical modelling	Physical modelling OR experimentation OR experimental OR laboratory testing

The search encompassed the years 1960 to present, and produced a list of some 271 citations. A two-stage process was used to screen this list down to approximately 30 through a 5-point ranking system: 1 indicating “must read”, 2 indicating “should read”, 3 indicating “can read if time available”, 4 indicating “lesser priority”, and 5 indicating “not relevant”. This list was used as a starting point for the in-depth review process.

As to the physical properties of potential test oils, Table 2 provides further information.

Table 2. Physical properties of candidate test oils.

Oil Type	**Density, g/mL; 15℃**	**Dynamic Viscosity, mPa.s @ 15℃**	**Surface tension, mN/m @ 15℃**
Canola	0.9205	86	35
Soybean	0.9232	73	32
Olive	0.9087	96	33
Electrical Insulating Oil*	0.8818	19	30

* Naphthenic-based oil for use in electrical transformers, circuit breakers and other kinds of electrical equipment.

For comparison, Table 3 provides information from ASTM F631, Standard protocol for testing skimmers. The project team decided to focus on Categories “I” and “II”, although even Category “I” is more viscous than any of the candidate vegetable oils.

Table 3. Candidate test oils for ASTM F631.

	Viscosity, mm^2/s	**Density, g/mL**	**Oil-Air Interfacial Tension, mN/m**	**Oil-Water Interfacial Tension, mN/m**	**Pour Point, °C**
I	150 to 250	0.90 to 0.93	28 to 34	20 to 30	< -3
II	1,500 to 2,500	0.92 to 0.95	30 to 40	20 to 30	< -3
III	17,000 to 23,000	0.95 to 0.98	20 to 40	20 to 40	< 10
IV	50,000 to 70,000	0.96 to 0.99	20 to 40	20 to 40	--
V	130,000 to 170,000	0.96 to 0.99	20 to 40	20 to 40	--

3.1. Key Findings of the Literature Review

It was noted that many of the papers were from a limited number of research groups with similar boom concepts and tests. Many of the key findings are expressed formally and informally throughout the relevant sections of this report. The following is a bullet-point summary for ten of the most relevant papers from the review process. The full literature search summary is listed in Appendix A.

Wicks, M. (1969). Fluid dynamics of floating oil containment by mechanical barriers in the presence of water currents.

- Mathematical model to produce results of a scale-model test related to different failure models of booms in water current.
- Design charts were given to find out whether boom of given length and skirt depth are able contain oil in different current conditions.
- Information of what speeds of towing relative to current should be to prevent containment failure were provided.
- Scale test involved a 6’ x 6’ x 60’ (width, depth, length) water channel. Vortex baffles were installed to reduce channel end effects. Oil was released to a flat plate just below the water surface, to avoid droplet formation, at current speed of 0.6 feet/s. A stable headwave forms at the upstream end of the slick after the slick comes in contact with the boom. Above 0.85 feet/s current values, oil is detached from the headwave and moves with the current downstream of the headwave. Droplet size could be up to ¾ inch in diameter. Tested oil viscosity, specific gravity, volume of oil and skirt

depth were, respectively, in the following ranges: 3.7 to 62 centistokes, 0.864 to 0.914, 10 to 60 gallons, and 6 to 12 inches.

- The thickness and the contact angle of the headwave with the water surface were correctly estimated by Von Karman equations. The headwave is at least ten times thicker than the after-headwave region whose thickness is also correctly estimated theoretically to be related to current speed, water, and oil density and gravity given by an equation in the paper. Observation of the droplet size is also consistent with another theoretical prediction cited in the paper.
- Weber number of 22 governs the critical velocity of the current associated with the onset of oil entrainment in the water current.
- The mathematical model solves three simplified equations simultaneously to impose circulation on oil, drag on oil, and the interfacial slope to calculate oil thickness among other quantities.
- Threshold slick length larger than which the entrained oil will coalesce back to the slick and do not move past the boom were also computed and presented.
- Regardless of the volume of spilled oil per unit breadth, if the current velocity is small, no entrainment failure occurs.
- The minimum skirt depth to prevent drainage failure was also computed as a function of current speed, speed of the flow in the skirt region, density of oil, water gravity, and the thickness of the oil in the skirt region. Velocities required for drainage failure were found to be independent of the spilled oil volume for skirt depths of 6’’, 12’’ and 24 ‘’.
- Model was also extended to calculate the total oil slick size upstream of booms with computed thickness of oil and knowing the total volume of spilled oil.

Amini, A., Schleiss, A.J. (2009). Numerical modelling of oil-water multiphase flow contained by an oil spill barrier.

- 2D CFD modelling of flows involved in oil containment boom problems.
- Volume of Fluid model of commercial FLUENT CFD toolbox was employed.
- Single- and double-barrier boom systems with both rigid and flexible booms were studied.
- The CFD results were compared with results of a lab test study to validate the model.
- The authors relate type of the failure mechanism of booms to oil viscosity: For low viscosity oils, when the current is fast, entrainment failure could occur which is the detachment of oil droplets from the headwave and the passage of the droplets from beneath the boom skirt. The drainage failure is also probable for low viscosity oil combined with short skirt drafts. This failure is the plunge of oil towards the boom skirt bottom edge and its escape from under the boom downstream of the boom. The last failure mechanism is named critical accumulation and is more probable for oils with high viscosities and when water-oil emulsions exist. This failure is the accumulation of oil behind the skirt and eventual passage of it from under the skirt after this accumulation reaches a maximum critical value.
- The experimental part of the work was done in a flume of 0.12 m x 6.5 m x 1.2 m (width, length, depth) size and oil used was rapeseed oil. Current speed ranged between 0.1 to 0.45 m/s. Skirt drafts were either 0.1 m or 0.2 m and spilled volume of oil was 20 m^3/m of the boom. The oil layer thickness was 30, 50, and 70 mm.

- The turbulent model for the CFD modelling part of the work was standard k-epsilon model. The upstream boundary of the numerical flume was more than 15x skirt draft. This is recommended by another paper cited by the paper.
- It was observed both experimentally and numerically that the flow field upstream of the boom is impacted over a distance equal to approximately 4x skirt draft. For rigid skirts a circulation region immediately upstream of the skirt is formed. This circulation region is much smaller when the skirt is deformable.
- Since the velocity of the fluid between two skirts for the double-skirt boom system is usually very small, this type of booms can be used to trap oil between the skirts and reduce the spreading of the oil slick.
- For double-barrier boom systems to be effective against failure, the spacing between the booms must be at least 12x barrier draft. This spacing provides enough time for droplets to rejoin the surface and be contained by the second skirt.
- Modelling the problem as a three-phase (air, oil, water) flow didn’t improve the results enough to warrant the assignment of stronger computational power and time. Most of the results of the paper were hence based on a two-phase (oil and water) flow representation of the problem.

Goodman, R.H., Brown, H.M., An, C.F., Rowe, R.D. (1996). Dynamic modelling of oil boom failure using computational fluid dynamics

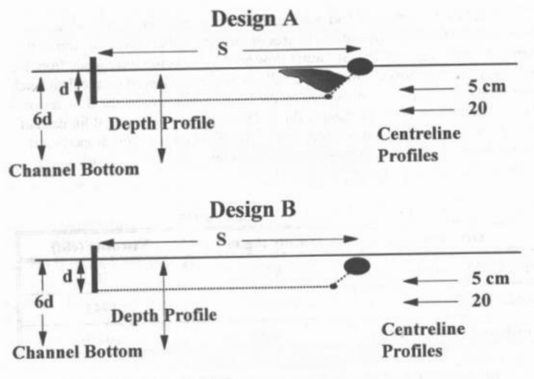
- 2D CFD modelling of the failure modes of booms was the topic of this study.
- The existence of the oil drastically changes the flow condition and hence tests to improve design of booms must be done when oil is present.
- The commercial FLUENT model was the toolbox for the modelling exercise and the two-phase flow modelling approach was Volume of Fluid (VOF).
- The model could successfully reproduce results of a test experiment for drainage, entrainment, and critical accumulation failure.
- Three different oils were modelled: Weathered Federated, Bunker B, and Shell Valvata 1000. The range of current speeds was between 0.09 to 0.24 m/s and the 2D numerical flume was 8 x 1 m with grid cell resolution of approximately 281 x 41. Barrier drafts were either 10 or 70 mm.
- The drainage failure consists of the encounter of oil with the barrier and passage of oil from under the boom shortly after. This failure leads to the drain of the entire slick towards the downstream of the boom. When skirts are deeper, a “surging” phenomenon occurs: The oil is initially reflected towards the upstream and back towards the skirt until a stable length and shape is reached.
- Whether the boom fails under any of the three main failure modes depends on oil properties, skirt depth, and current speed. The critical accumulation is usually associated with thick and heavier oils.

Gong, K., Tkalich, P., Xu, H. (2014). The numerical investigation on oil slick behavior behind the oil boom.

- 2D CFD study of oil slick behind a boom using VOF method.
- It was concluded that the thickness of oil relative to its original initial slick length is linearly related to the Froude number.
- Cites a study in which critical accumulation is found to happen for oils more viscous than 3,000 cSt for velocities more than 0.15 m/s regardless of the boom draft.
- OpenFOAM (v2.2.2) was used for the CFD modelling with k-epsilon turbulent model.
- Modeled boom drafts were 0.5 and 1 m and the computational domain was 30 x 5 m and the current speeds ranges from 0.1 to 0.5 m/s. Four oil types were considered and volume of oil was 1.2 m^3 or 3.6 m^3 per unit width of the boom.
- Modeled oil viscosities ranged between 70 to 3500 micro m^2/s. Minimum cell size was 25 mm.

Brown, H.M., Goodman, R.H., An, C.F. (1999). Development of containment booms for oil spills in fast flowing water.

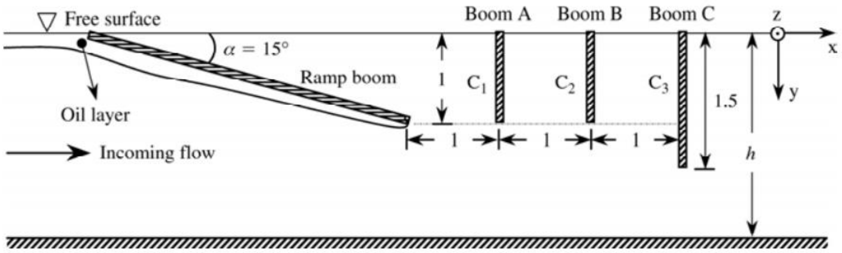
- A double-boom system to trap oil in fast currents was designed, tested, and CFD modeled.
- The system can successfully trap oil in currents speeds two times more than the failure speed of single-barrier booms.
- Traditional booms fail at approximately 1 knot current speeds. This speed in scale tests is approximately 0.5 knot.
- Boom designs for fast currents can be categorized into three systems: (1) Designs with energy dissipation mechanism to slow the slick and the current upstream of the boom, (2) Designs with shields to separate the slick from fast flows under, and (3) Designs with the rapid removal of oil without first containing oil.
- Oil containment was successful for speeds up to 3 knots.
- Scale tests were done in a flume with dimensions of 30 x 1.25 x 0.8 m (length, width, depth).
- The channel width to depth ratio must be at least 1.5 to prevent the generation of unwanted vortex and its interference with failure processes.
- Volume of spilled oil in the scale test was 5 litre, and three different oils with viscosities ranges between 10 cSt to 10,420 cSt with densities between 834 and 964 kg/m^3 were tested.
- The tested double-boom system had two different configurations: One with a vertical plate boom and a floating cylindrical boom (axis along the water surface) with angled porous and solid skirts, and the other one with generally similar configuration but with a slightly submerged cylindrical boom allowing oil and water to pass towards the vertical skirt, the second boom downstream. See figure below:



- Both boom systems have horizontal shields to separate collected oil from flows at higher depths. The boom system with slightly submerged cylindrical boom was less successful in trapping heavy oils than the boom system with the floating cylinder.

Fang, J., Wong, K-F.V. (2006). An advanced VOF algorithm for oil boom design.

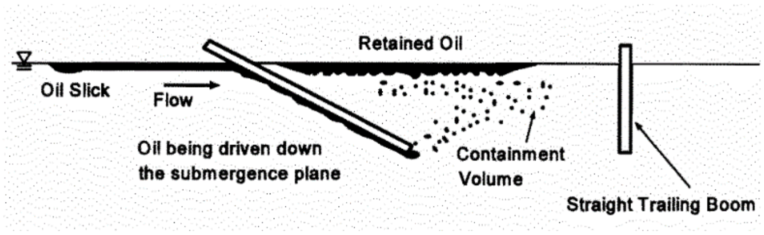
- A Volume of Fluid model for the interface tracking of oil slicks subject to boom was developed and tested for the design of an innovative boom system.
- The innovative boom consisted of three vertical booms and a ramped boom angled at 15 deg. from the water free surface at the far upstream region of the boom system. The horizontal distance between the vertical booms and between the first boom downstream of the ramp boom and the lower edge of the ramp boom were equal and similar to the skirt depth of the first boom. This skirt depth was 4.5 cm (see figure below):



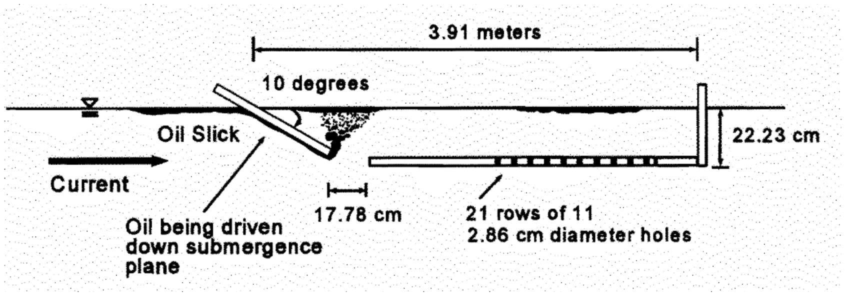
- The smallest computational cell size was 0.005 x 0.005 m.
- When current speed is lower than 0.2 m/s, the slick stays in front of the ramped boom. When the speed is between 0.2 m/s to 0.25 m/s, the slick moves downstream of the ramp and is collected in the space between the ramp and the first skirt and between the first and second skirt. When the current speed is 0.4 m/s, some of the oil passes under the boom system and some others are trapped in the region between the vertical skirts. The efficiency of the containment for this case was approximately 70%.
- The initial oil thickness in the experiment, whose results were compared with the CFD results, was approximately 0.2 mm. This thickness could not be resolved in the CFD. The resolution of the grid at the upstream of the numerical domain was approximately 2.25 mm.
- Typical released oil thickness in the CFD model was 0.5 cm with an average volume of 5 cm^3/cm of the boom width.

Swift, M.R., Coyne, P.M., Celikkol, B., Doane, C.W. (1996). Oil containment performance of submergence plane barriers.

- Large-scale experimental tests related to the performance of a boom system with an inclined submerged plane were carried out.
- Such a system was tested as an alternative to conventional booms which fail when high current speeds are involved. Such failures are usually governed by the value of the current speed perpendicular to the boom. When this value exceeds a threshold, droplets from the headwave of the slick start to form and move under the boom and escape the containment system. This value is usually in the range of 0.5 knot to 1 knot, which is usually easy exceeded in actual operating conditions.
- The basic concept of the tested boom for fast current is an inclined submerged plane that guide the oil downstream and a conventional vertical trailing boom. The oil moves downstream while partially in contact with the submergence plate and then oil is released between the plane and the trailing boom for collection (see figure below):



- The objective of the work was to find optimum shape, position and configuration of the boom system and its components for oils of different densities and viscosities.
- The size of the flume in which experimentation were carried out was 12.2 x 1.22 x 0.61 m (length, depth, width).
- Results show that the oil containment is more successful for smaller submergence plane angles (with the downstream water surface) for tested angle range of 20 deg-90 deg. Additionally as the specific gravity of the oil increases, the containment is less successful. Moreover, increase in the distance between the location of the interface of the plane with the water surface and the trailing boom increases the containment success. This investigated range for this distance was between 0.76 and 2.29 m.
- After testing several different conditions and configurations, the best system was found (figure shown below):



- It was observed that the containment success is reduced by increase in Reynolds number and also by increase in internal Froude number.

Amini, A., Bollaert, E., Boillat, J-L., Schleiss, A.J. (2008a). Dynamics of low-viscosity oils retained by rigid and flexible barriers.

- The paper involves scale and numerical modelling of boom with flexible and rigid skirts with special attention to their performance when the boom forms a closed circular reservoir (overhead view). The numerical modelling was done by FLUENT toolbox for 2D cases without oil and streamlines and vortexes were studied.
- Low viscosity oils were tested.
- The paper provides an empirical relationship relating the maximum permissible oil-water relative velocity as a function of barrier draft and oil type. The paper also proposes some equations to calculate the headwave thickness and slick length for given contained oil volume.
- The author mentions that the application of deformable skirts is increasing for their potentially better performance to contain oil.
- For oils less viscous than 1,000 cSt, the first failure mechanism is entrainment failure.
- The paper refers to a prior paper which states that when the Weber number is less than 14, no droplets are detached from the headwave, when this number is between 15.5 to 28, the droplets are detached from the headwave and when the Weber number is more than 28, the droplets can be detached from all part of the slick. There is controversy about the actual speeds associated with entrainment failure. However, all speed values fall in the 25 to 35 cm/s range.
- Experiments were done in a flume sized 6.5 x 1.1 x 0.12 m (length, depth, width). The channel width was selected to be 0.12 m to reduce the effect of vortex generation.
- Tested oil volume was 10 and 20 litre/m (of the skirt width), speed: 0.10 m/s to 0.35 m/s, skirt depth: 0.10, 0.15, and 0.2 m.
- Rapeseed oil was used for the physical modelling: Viscosity: 88.8 cSt, Density 0.91 g/cm^3, Interfacial tension: 30 mN/m
- According to a paper cited therein, geometric downscaling is not needed when studying the droplet formation and instability of headwave.
- The critical accumulation failure mode is independent of the skirt geometry and its depth and to study this failure mode, no scaling needs to be considered, similar to studying the entrainment failure. However, for modelling the drainage failure, results must be scaled using Froude and densimetric Froude scaling.
- To be considered as deep condition, the depth of the flume must be at least four times more than the depth of the skirt.
- The horizontal extent of oil slick is a strong function of the initial spilled oil volume.
- The slick thickness does not depend on the draft size except for a region close to the skirt with a length less than the draft.
- Barrier draft shape and its depth have no influence on the headwave thickness of the investigated oil. The headwave thickness is usually 1.5 to 2.5 times larger than the equivalent thickness of the slick which is its volume/area.
- A double-barrier boom system was studied and it was found that if the spacing between the barriers is not more than six times the skirt depth, the failure speed could be as high as 45 cm/s.

Fang. J., Wong, K-F.V. (2000). Instability study of oil slicks contained by a single boom.

- The study involved 2D numerical modelling (based on the Volume of Fluid method) of passage of oil-water under a single-skirt boom.
- The effect of different quantities of oil on the failure of booms and the hydrodynamics of the slick upstream of the boom was tested. Variables included gravity, viscosity, density, surface tension, boom draft, and current speed.
- Results suggest that the interfacial tension force does not contribute to the drainage and critical accumulation failure of the boom, but it substantially impacts the vertical shape of the slick.
- The depth of the numerical flume is “seen” by the slick if the depth is less than 10 times larger than that depth of the skirt.
- As the Froude number increases, containment is less successful.
- Oils with relative viscosities (with respect to water) of 3,000 or higher, has high chance of failing the boom under the critical accumulation failure mode.
- More viscous oil is associated with generally thicker slicks compared with lower viscosity oils.

Lee, C.M., Kang, K.H., Cho, N.S. (1998). Trapping of leaked oil with tandem oil fences with lagrangian analysis of oil droplet motion.

- The work involved numerical and experimental investigation of the effectiveness of a boom system consisting of two tandem oil fences consisting of only two vertical skirts.
- It was shown that the two-fence system can trap oil when the distance between the fences is 10 times larger than the skirt depth.
- The paper provides information about how results of a scale-model test could be representative of reality. This is through the introduction of some non-dimensional numbers.
- The numerical model is 2D. The author believes this is a reasonable representation of reality since booms are usually long.
- The distance between the fore fence and the upstream boundary of the numerical domain is 20 times the depth of the skirt. This value for the distance between the trailing skirt and the downstream boundary is 30 times the depth of the skirt.
- The numerical model only investigated the motion of oil-free current in the presence of the boom system, i.e., oil was not modeled. Draft of the fences was 4 cm.
- The velocity of the scale model was 0.14 m/s which is equivalent to full scale velocity of 0.5 m/s (Fr = 0.22 and Re = 5,600). The two-tandem fence system can effectively trap oil for such current speeds. Numerical results suggest that this successful trapping could be achievable for speeds up to 2 m/s at full scale.

Summary

The literature review identified key properties for test oils and essential information required to initiate the CFD and scale modelling process in Phases 2 and 3 of this project. Noteworthy is the requirement that the water depth needs to be more than four time the skirt draft to be considered “deep water” such that the influence of the bottom boundary on containment can be ignored (Amini *et al.*, 2008a). Additional literature was consulted as required.

4. Phase 2 – CFD Modelling

This chapter summarizes a computational fluid dynamics (CFD) study of the performance of innovative oil spill containment boom concept designs intended to deliver improved performance in fast currents or at higher tow speeds. Conventional oil spill containment booms usually consist of a floatation element and a vertical solid barrier or skirt to contain oil floating at the water surface. The performance of conventional booms deteriorates quickly when the relative speed of the boom with respect to water is greater than approximately 1 knot (Giron-Sierra *et al.*, 2015).

The purpose of this portion of the study was to assess the performance of several leading existing boom designs using CFD simulations, propose changes to improve performance (if possible), and introduce new concepts for effective containment of floating oil in faster currents. The focus of this work has been to attempt to improve boom performance for relative speeds of 3 knots or more, and in a few cases, boom performance has even been investigated in relative speeds up to 5 knots. The work has focused mainly on the containment of light and medium oils but heavy oil was also simulated in a few cases.

This chapter begins with a short introduction of the CFD tool used in this study and general modelling assumptions and conditions. The chapter continues with a section on validation of the OpenFOAM two-phase flow solver used in this study, with reference to publically available results of a lab test on the performance of a conventional boom. The remainder of this chapter focuses on summarizing results from two- and three-dimensional CFD simulations of several different containment boom design concepts, and in particular their performance or ability to retain oil at relative speeds greater than 1 knot. Finally, a summary and conclusions section is presented that includes suggestions for design changes to improve boom performance and for future work.

4.1. OpenFOAM® CFD Model and Assumptions

The CFD software used for this study is OpenFOAM, a general-purpose finite-volume solver, mainly developed for modelling problems involving fluid flow. NRC has extensive experience using OpenFOAM for applied fluid mechanics problems. The software is open source, and is extensively validated and documented. OpenFOAM has previously been used to simulate oil spill boom behaviour (e.g. Gong *et al.*, 2014; Bjørvik, 2015).

Two laws of physics relevant to this problem are the conservation of mass and momentum, expressed mathematically through the Navier-Stokes equations. OpenFOAM’s interFOAM solver (Deshpande *et al.*, 2012) simulates the behaviour of 2 incompressible, isothermal immiscible fluids (water and oil in this study) using a VOF (volume of fluid), phase-fraction based, interface-capturing approach. With this approach, one set of Navier-Stokes equations with an additional interface advection equation is solved to compute the flow of both oil and water. Density (viscosity) at any location in the domain is a function of density (viscosity) of oil and water and the volume fraction of the water in the computational cell associated with the location.

As an example, for a computational cell filled equally with oil and water (50% oil and 50% water), the density (viscosity) is computed to be mathematical average of those of oil and water. The turbulence was parameterized using the k-ε model incorporated in OpenFOAM. Several utilities within the OpenFOAM platform were used to generate the computational mesh (e.g. blockMesh and SnappyHexMesh). Additional information about these utilities can be found in OpenFOAM's user's manual available at https://www.openfoam.com.

The interaction of flowing water and oil with a floating oil spill boom is complex, and several simplifying assumptions needed to be made to obtain useful results within the time frame and scope of this project.

1. The geometry of the boom and its orientation and vertical position within the water column were assumed to be static or constant.
2. The simulations modelled the case where the water (and oil) flow past a stationary boom, and not the case where the boom is towed through still water, i.e., the relative speed is constant.
3. Although the existence of air above the floating oil is known to have some influence on the oil dynamics, this influence is not strong enough to justify three-phase flow modelling (Amini & Schleiss, 2009); hence the CFD simulations considered only two fluid phases, namely water and oil, plus the boom structure itself.
4. Both the oil and the water were assumed to be incompressible fluids (i.e., the fluid density remains constant).
5. Both the oil and the water were assumed to be Newtonian fluids (i.e., the viscous stresses arising from the fluid flow are linearly proportional to the local strain rate).
6. The oil and the water were assumed to have the same temperature.
7. The effect of wind and waves on boom performance was not considered in the CFD simulations.

4.2. Validation of OpenFOAM's Two-Phase Flow Solver

Prior to the testing of improved design concepts, which is the main focus of the present research, OpenFOAM simulation results were compared with 2D laboratory experimental observations on the performance of conventional booms (Amini *et al.*, 2008a). This was done to test OpenFOAM's ability to reproduce laboratory observations in order to gain confidence in the model capabilities. The laboratory experiments consisted of testing several combinations of boom depth and current speed, and also included tests with flexible booms. Three cases were simulated using OpenFOAM, with different volumes of spilled oil, for a conventional boom with a 0.1 m skirt depth in a steady 0.2 m/s current speed. The laboratory tests used rapeseed oil with a kinematic viscosity of 88.8 cSt and a density of 910 kg/m^3, and these properties were prescribed for the oil phase in OpenFOAM. The freshwater had a kinematic viscosity of 1.035 cSt and density of 1000 kg/m^3. The interfacial tension between the oil and water is 0.03 N/m. Table 4 shows the main parameters for each of the three simulations.

Table 4. Test conditions for validation of the two-phase flow solver (Amini *et al.*, 2008a).

Simulation #	Depth of the boom (underwater), m	Current Speed, m/s	Volume of spilled oil, L/m (of the boom width)
1	0.1	0.2	10
2			20
3			30

A constant and vertically uniform water current is produced at the upstream vertical boundary of the numerical domain. After the flow of water reached a steady-state condition, the oil is “injected” into the numerical flume. The oil and the water can freely exit the numerical flume at the downstream vertical boundary of the computational domain. The flow cannot leave the domain from the top and bottom horizontal boundaries, but can freely move tangentially to those boundaries. Figure 13 depicts computed (OpenFOAM) and observed (Amini, 2008b) slick shapes for the three simulations listed in Table 4. The observed data has been digitized from results presented in Amini (2008b). The figure shows that the thickness of the computed and observed headwaves are consistent at the thickest part of the slick. Additionally, the computed slick length is well predicted, although it is underestimated in the CFD simulations by 10%. Figure 13 shows that the computed and observed thickness of the slick immediately upstream of the boom (in the region very close to the boom) are not as consistent. The CFD results in Figure 13 are associated with a time beyond when the headwave shape and slick length seem to have reached stability. One of the simulations was allowed to run for a longer duration which seemed to lead to closer agreement between the modelled and observed thickness of the slick very close to the boom without significant change to the headwave shape and slick length. The impact of longer simulation times on slick shape could be further investigated in future work.

Other potential sources of inconsistency between the present CFD and the laboratory test results given in (Amini, 2008b) could stem from errors introduced through the digitization of the observed data given in (Amini, 2008b) by the present authors and deviation from true two-dimensional conditions during the laboratory experiments. Such deviation from two-dimensional conditions could easily be caused by viscous effects along the flume walls and bottom that distort the flow field and generate plug-hole vortices along the flume walls and in regions close to the corners between the boom and the walls.

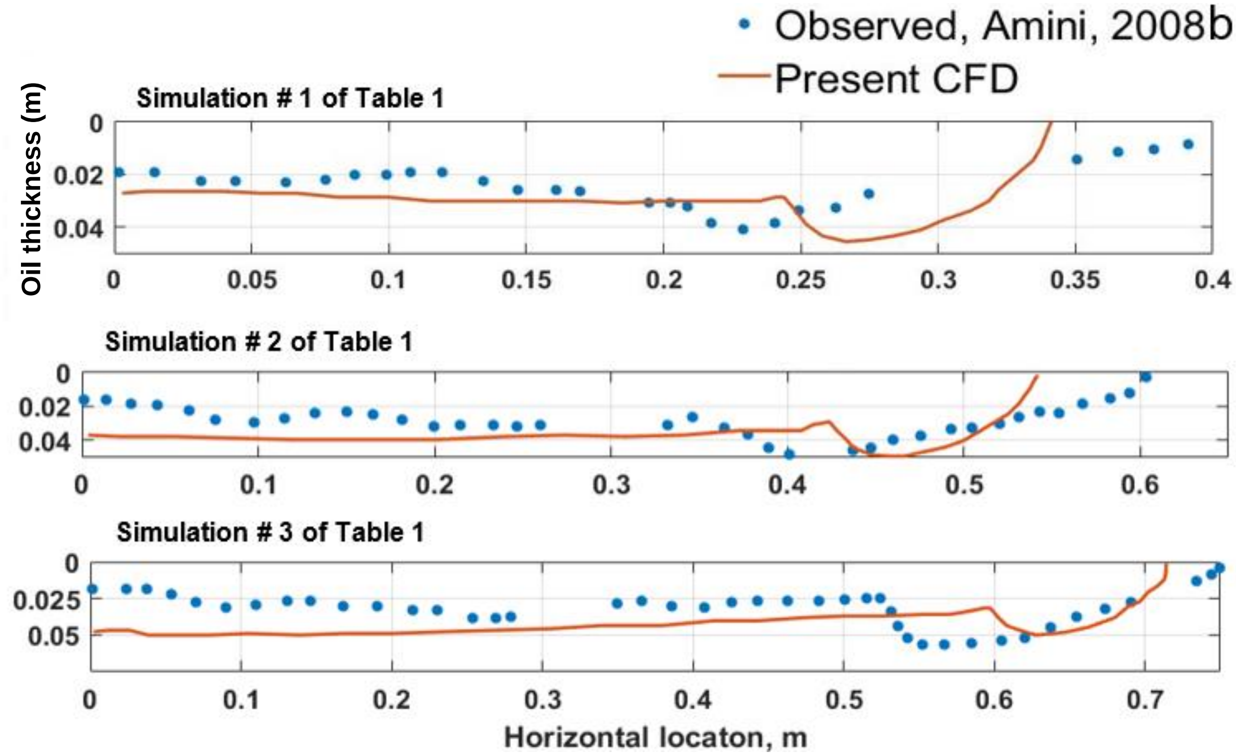


Figure 13. Comparison of laboratory testing (Amini, 2008b) and CFD simulation results.

This figure shows the side view of the slick (interface between oil and water). The current is moving right-to-left and the vertical boom is on the vertical axis at the left. Zero on the vertical axis indicates the water surface.

Amini (2008b) and Amini *et al.* (2008a) observed that the initiation of entrainment of oil, in droplet form, and escape under the boom was associated with current speeds of approximately 0.27 m/s. This critical speed remained constant for all experiments, regardless of the volumes of spilled oil and boom depths. The CFD model is incapable of capturing the droplet formation which could be attributed to small spatial and temporal scales associated with the formation and detachment of droplets. The CFD model is, however, capable of capturing the loss of oil from the headwave at speeds close to those observed for oil droplet entrainment in the laboratory. Figure 14 shows a snapshot of the slick shape associated with loss of oil from the headwave for a 0.2 m deep conventional boom in a 0.385 m/s current speed and 20 L/m oil.

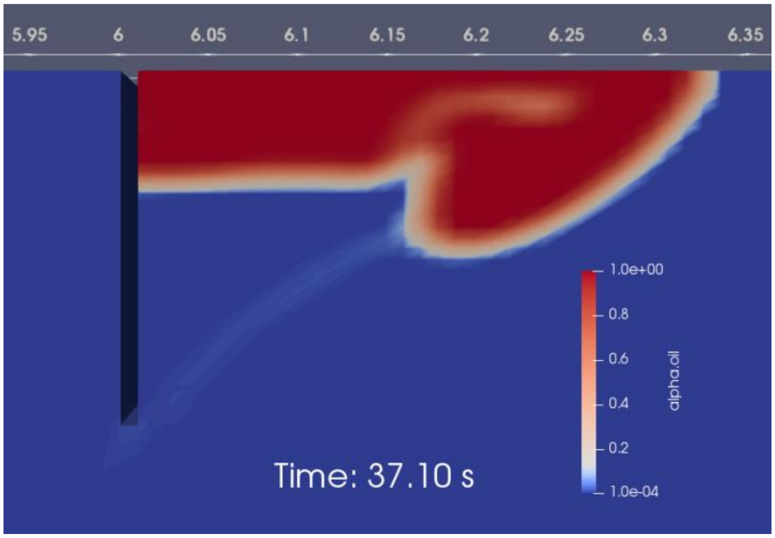


Figure 14. Loss of oil from the headwave.
The simulation involves a 0.2 m deep boom subjected to 0.385 m/s current and 20 L/m oil. Oil properties are similar to rapeseed oil. Dark blue denotes pure water, while other colours denote the existence of oil at different concentrations. Loss of oil from the headwave is shown by the light blue trace.

The CFD model also captures the failure of the boom due to drainage. Figure 15 shows drainage failure of the boom in a current speed of 0.77 m/s.

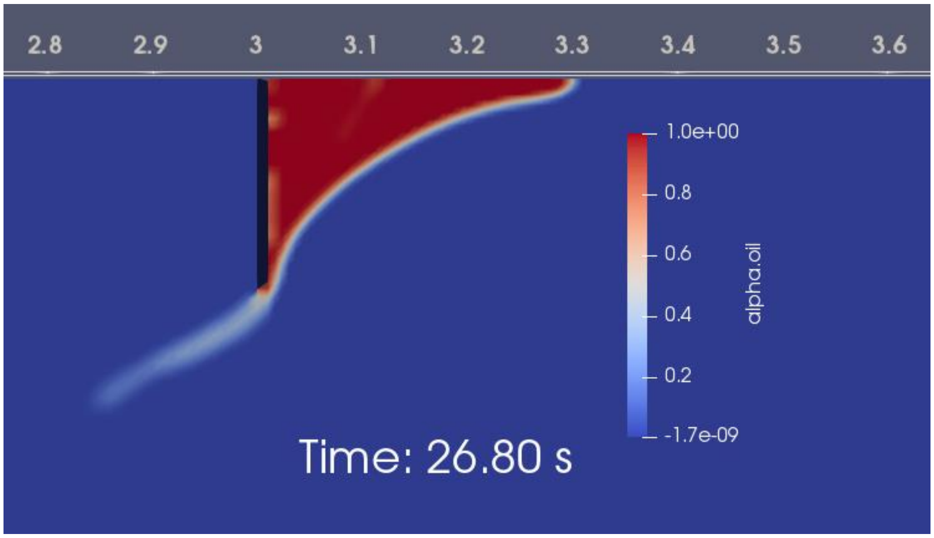


Figure 15. CFD simulation of drainage failure for a conventional boom.

4.3. Systematic Simulation of Conventional and Conceptual Booms in Fast Currents

This section summarizes results of several two- and three-dimensional CFD simulations of different oil spill containment boom systems subjected to fast currents and different spilled oil volumes and oil types. The focus is mainly on 3-knot speeds with light oils, however other speeds and oil types are also examined. Based upon discussions with SL Ross and BSEE, Table 5 provides characteristics for representative crude oils that were suggested for the purposes of this study. In consideration for the allowable scope of work and for ease of research, it was decided to focus on the light and medium oils for both the computational and physical modelling simulations.

Table 5. Crude oil characteristics.

Oil type	Kinematic viscosity (cSt)	Density (kg/m^3)	Oil–water interfacial tension (N/m)
Light (L)	100	900	0.03
Medium (M)	1,000	940	0.03
Heavy (H)	100,000	980	0.03

The present CFD simulations were done in a reduced scale. The reason for this is twofold: (1) Significant reduction of computational time compared with the full-scale case, and (2) Prevention of potential sources of discrepancy (since the subsequent physical modelling would also be conducted at reduced scale). Scaling in the CFD simulations followed Froude similarity, which requires the Froude number (a measure of inertial to gravity forces) in model (reduced) scale to be equal to that of the prototype (full) scale, i.e., $Fr_M = \frac{U_M}{\sqrt{D_M g}} = Fr_P = \frac{U_P}{\sqrt{D_P g}}$ where U is the flow speed, d is a characteristic length (the deepest boom component), and g is the gravitational acceleration. Subscripts $_M$ and $_P$ respectively denote model (reduced) scale, and prototype (full) scale values. Froude similarity is required to correctly scale drainage failure. The other two failure modes, entrainment and critical accumulation failures, are arguably believed to be scale independent (Amini *et al.*, 2008a). All of the CFD simulations were also setup such that the bottom boundary was at least four times deeper than the skirt depth to respect deep water conditions (Amini *et al.*, 2008a).

It is important to note that the boom geometries used in the CFD simulations do not match exactly with the physical modelling experiments for several reasons. Firstly, the setup of the CFD models was partially based on assumed water depths and speeds that would be modelled in the physical experiments, which were later adjusted for practical considerations or not possible due to limitations with the existing facilities and test equipment. Secondly, more detailed information about the various prototype booms was gathered throughout the time the CFD simulations were on-going, and in leading up to the commencement of Phase 3 (physical modelling experiments). BSEE, SL Ross, and NRC collectively agreed that it would be more worthwhile for the physical models to match the prototype versions than to match exactly with what had already been modelled by the CFD simulations.

Further, the CFD simulations provide an exact mathematical result, while the physical modelling experiments provide a more subjective test score (see §5.3.4 for further explanation). It is possible to directly compare CFD results from one test with another, and it is similarly possible to directly compare physical modelling results from one test with another. However, it is not really possible to directly compare CFD and physical modelling results with each other, aside from making general comparisons on the observed boom performance.

4.3.1. Two-Dimensional Simulations

More than thirty 2D simulations were conducted to understand the performance of different booms subjected to different current speed conditions. Although three-dimensional effects can be important under certain circumstances, a two-dimensional assumption (i.e., integrated along the boom length) is reasonably valid for long booms and towards the apex/centre of the boom (Grilli *et al.*, 2000) (see Figure 16). The reduced computational time associated with 2D simulations compared with 3D simulations allowed for simulation of multiple booms and flow speed conditions.

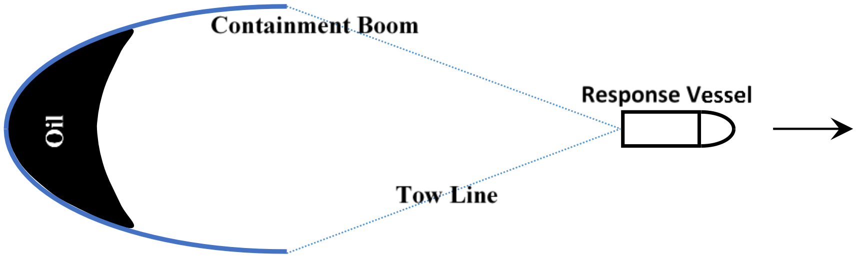


Figure 16. Aerial view of a containment boom being towed by a response vessel.

The two-dimensional simulations involved injecting a 0.01 m thick oil slick at a surface inlet located at least fifteen times the boom depth upstream of the boom. The outlet boundary was located at a distance at least ten times the boom depth downstream. The depth of the computational domain was five times the boom depth to comply with general recommendations for minimizing bottom effects on the containment dynamics (Fang & Johnston, 2001). The injected oil was discretized by at least four grid cells in the vertical direction, i.e., the vertical side of the grid cells are 0.0025 m. The horizontal scale of grid cells were generally twice the vertical cell length scale. The grid resolution increased close to boom components, to better capture the flow details including the boundary layer effects, and decreased close to the bottom of the computational domain where no oil is expected to reach.

Simulations were conducted for several boom systems including conventional single-skirt booms, Ramped-boom systems, Screen-boom systems, and L-shaped booms.

Conventional Single-Skirt Booms

The first 2D boom model investigated was a conventional single-skirt boom, similar to the Ro-Boom 2200. Figure 17 shows this simple boom in 2D.

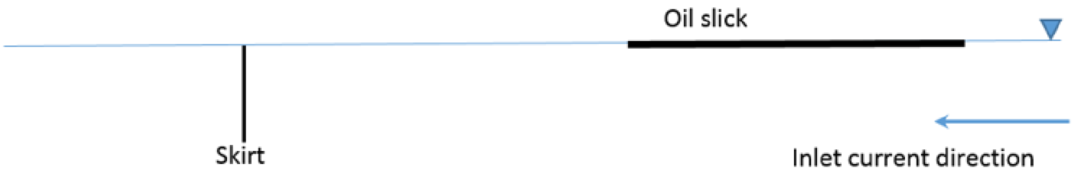


Figure 17. Schematic of the conventional single-skirt boom.

Table 6 shows the test matrix of simulation parameters and simulation results for containment success, defined as the ratio of oil collected upstream of the boom to the total volume of spilled oil. Note that the simulations were carried out in model (small) scale. As an example, in full scale, simulation CB1 is associated with a 0.72 m deep boom subjected to a 3 knot current speed, and CB4 is a 1.44 m deep boom subjected to a 5 knot current speed.

The performance of the boom is significantly improved when the depth of the skirt is doubled. This is particularly the case for light oil, however medium and heavy oils proved more difficult to contain. This improved performance has already been reported in literature. For example, Wicks (1969) observed that the drainage failure of the booms are delayed when skirt depth is increased. Continuous detachment of oil in droplet form from the headwave is not captured in the present CFD simulations due to the small temporal and spatial scales associated with the entrainment of oil into the water current. For this reason, whether an increase in the skirt depth will alleviate the entrainment failure was not studied. Considering that the onset of entrainment failure is likely associated with the thickness of the headwave, an indirect approach in studying entrainment failure with the present CFD modelling approach would be to investigate the headwave thickness as a function of skirt depth, however this was not within the scope of the present study.

Table 6. Test matrix for 2D conventional single-skirt boom simulations.

Simulation ID	Skirt depth, m (full scale depth, m)	Oil type	Current speed, m/s (full scale speed, knots)	Volume of spilled oil, L/m (of the boom width)	Containment success (%)
CB1	0.14 **(0.72)**	L	0.68 **(3)**	10	11
CB2		M			~ 0
CB3		H			~ 0
CB4		L	1.13 **(5)**		~ 0
CB5		M			~ 0
CB6		H			~ 0
CB7	0.28 **(1.44)**	L	0.68 **(3)**	10	95
CB8		M			86
CB9		H			43
CB10		L	1.13 **(5)**		40
CB11		M			~ 0
CB12		H			~ 0

Figure 18 illustrates flow patterns around a 0.28 m deep boom subjected to a 0.68 m/s steady current speed. Figure 18a depicts steady streamlines just before light oil is introduced into the computational domain. The horizontal length of the boom wake (the distance downstream of the boom where the flow field is impacted by the existence of the boom) is approximately nine times the depth of the boom. It is noted that some oil that moves past the boom usually ends up in the wake. Figure 18b shows the steady streamlines associated with the steady shape of the slick. As seen, the existence of oil modifies the streamlines by the formation of three evident circulation regions: one inside the headwave, one immediately downstream of the headwave, and one immediately upstream of the boom. Additionally, the streamlines extending to the far upstream of the domain conform to the upstream boundary of the headwave.

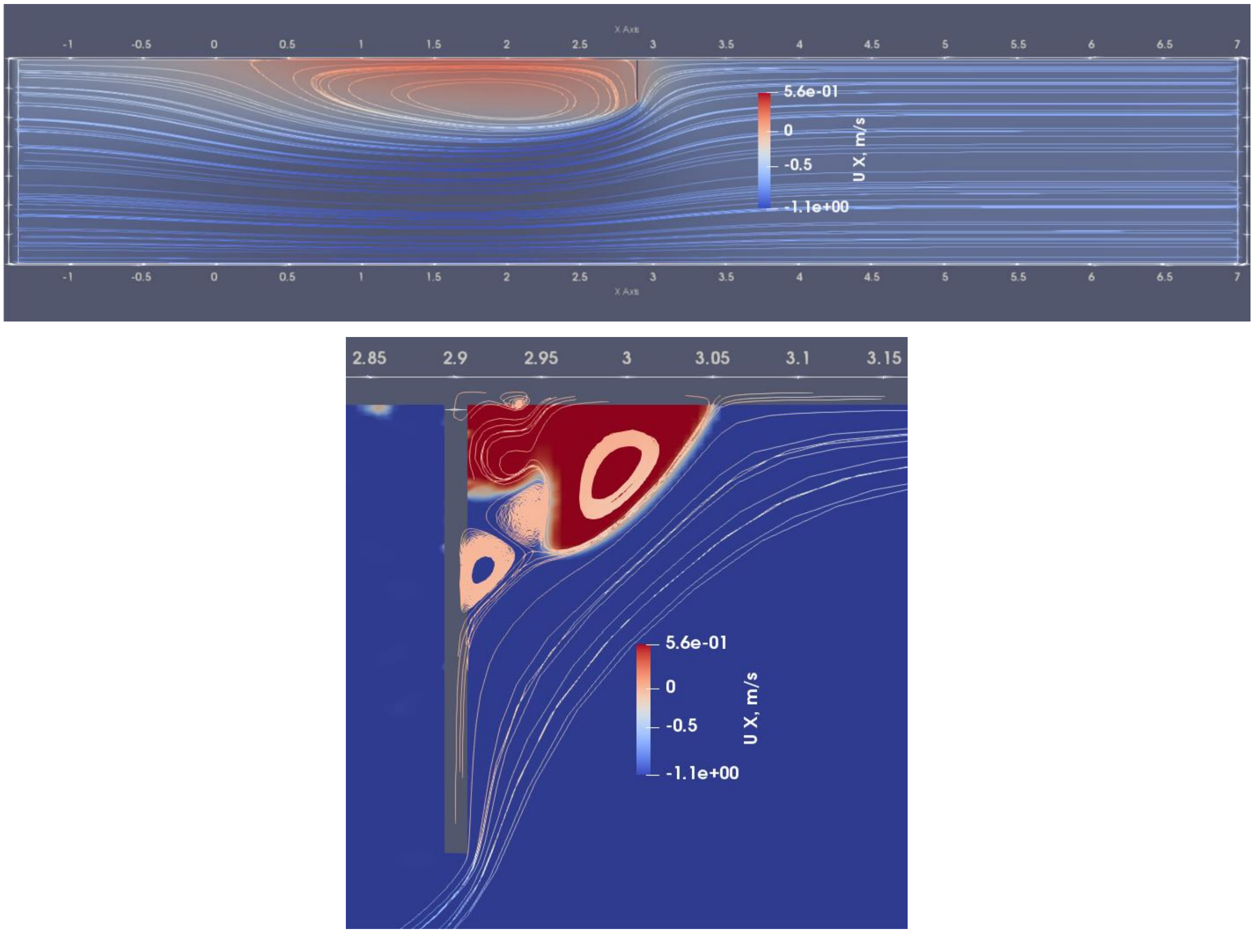


Figure 18. Steady streamlines for 0.28 m deep conventional boom subjected to 0.681 m/s current.
(Top) before the “injection” of oil into the domain, (Bottom) after the light oil slick has reached its final shape, CB7 case of Table 6.
Note the wake downstream of the boom where some oil is usually trapped (top), and circulations in and around the slick (bottom).
Note that the color map for U_X in (bottom) is associated with streamlines coloring.

Ramped-Boom Systems

The second 2D model investigated was a Ramped-boom system. This concept consists of a submerged ramp followed by three conventional skirts, and has previously shown some promise in containing a large proportion of spilled oils in currents of up to 1.5 knots (Fang & Wong, 2001; Wong *et al.*, 2002; Fang & Wong, 2006).

The concept was modified in terms of the spacing between the boom components to collect oil in higher current speeds (3- and 5-knot full-scale). The schematic of the system is shown in Figure 19. Note that the lower edge of the ramp is at the same depth as the lower edge of the next skirt (with the exception of case RB_Config3_8). Five different configurations were tested with different oil types and volumes. Table 7 shows the corresponding test matrix and containment success values.

NRC started modifying the boom from the proposed configuration given in Wong *et al.* (2002) by adjusting the spacing to improve performance. When a configuration showed promise for containment of light oil, its performance was also tested for medium and heavy oils. The 21 simulations and associated configurations, test conditions and results (in terms of containment success) are shown in Table 7.

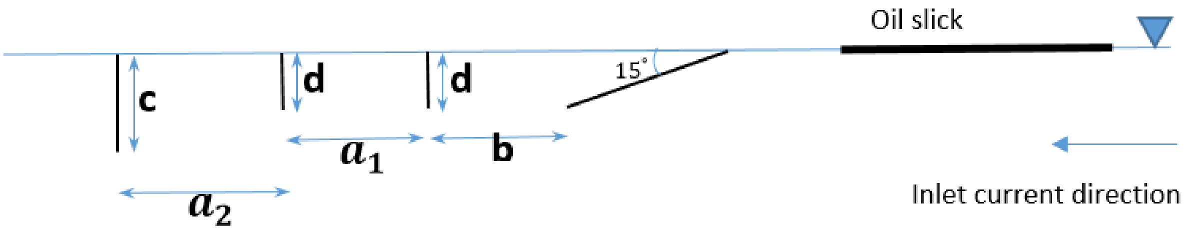


Figure 19. Schematic of the Ramped-boom system.

Table 7. Test matrix for 2D Ramped-boom simulations.

Simulation ID	**Dimensions, m** a_1, a_2, b, c, d **(full scale, m)**	**Oil type**	**Current speed, m/s (full scale speed, knots)**	**Volume of spilled oil, L/m (of the boom width)**	**Containment success (%)**
RB_Config1_1	0.373, 0.373, 0.373, 0.14, 0.093 **(2.435, 2.435, 2.435, 0.914, 0.607)**	L	0.6 **(3)**	10	76
RB_Config1_2				30	79
RB_Config1_3			1 **(5)**	10	63
RB_Config1_4				30	48
RB_Config2_1	0.373, 0.3730, 1.492, 0.14, 0.0930 **(2.435, 2.435, 9.739, 0.914, 0.607)**	L	0.6 **(3)**	10	71
RB_Config2_2				30	77
RB_Config2_3			1 **(5)**	10	35
RB_Config2_4				30	41
RB_Config3_1	0.746, 0.746, 0.746, 0.14, 0.093 **(4.869, 4.869, 4.869, 0.914, 0.607)**	L	0.6 **(3)**	10	78
RB_Config3_2				30	78
RB_Config3_3			1 **(5)**	10	64
RB_Config3_4				30	57
RB_Config3_5		M	0.6 **(3)**	10	49
RB_Config3_6		H			~ 0
RB_Config3_7		L	0.3 **(1.5)**		94
RB_Config3_8	Same as other Config3 cases except the ramped boom depth was halved		0.6 **(3)**		64
RB_Config4_1	0.373, 0.56, 0.85, 0.14, 0.093 **(2.435, 3.655, 5.548, 0.914, 0.607)**	L	0.6 **(3)**	10	75
RB_Config4_2				30	76
RB_Config4_3			1 **(5)**	10	55
RB_Config4_4				30	39
RB_Config5_1	0.373, 0.373, 0.746, 0.14, 0.093 **(2.435, 2.435, 4.869, 0.914, 0.607)**	L		10	44

The results of simulations listed in Table 7 indicated the following:

1. Light oil was more effectively contained by comparison to medium and heavy oils for the boom configuration and flow speed where all three oil types were tested;
2. Containment success is not correlated with the volume of spilled oil, particularly for lower current speeds;
3. Higher current or towing speeds are associated with reduced containment effectiveness;
4. Among all tested configurations, Config3 showed the best performance in terms of containing oil at both 3 and 5 knots (full scale) speeds. This configuration resulted in 94% containment success at 1.5 knots (full scale) speed (Simulation ID RB_Config3_7); and,
5. For configuration RB_Config3_8, where the depth of the ramp was reduced by half in an attempt to reduce the turning moment exerted by the flow on the ramp (for easier construction), containment effectiveness was significantly reduced by comparison to the deeper boom.

Figure 20 shows the results of simulation RB_Config3_1, as listed in Table 7. Figure 20a depicts streamlines and the velocity field under steady flow conditions in the absence of oil. Only streamlines inside or passing through the volume indicated by the sphere shown in the figure are shown. A relatively stagnant recirculation zone forms in the lee region of the ramped boom to the next boom. This zone of recirculation helps to trap and contain oil. Oil capture is also sensitive to the velocity field in a narrow horizontal band between the lower front of the ramp and the next skirt. The triangular region immediately downstream of the ramp shelters the collected oil and helps to reduce the risk of entrainment failure. Figure 20b shows the final shape of the contained oil, with the oil phase indicated by red shading and the water phase indicated by blue shading.

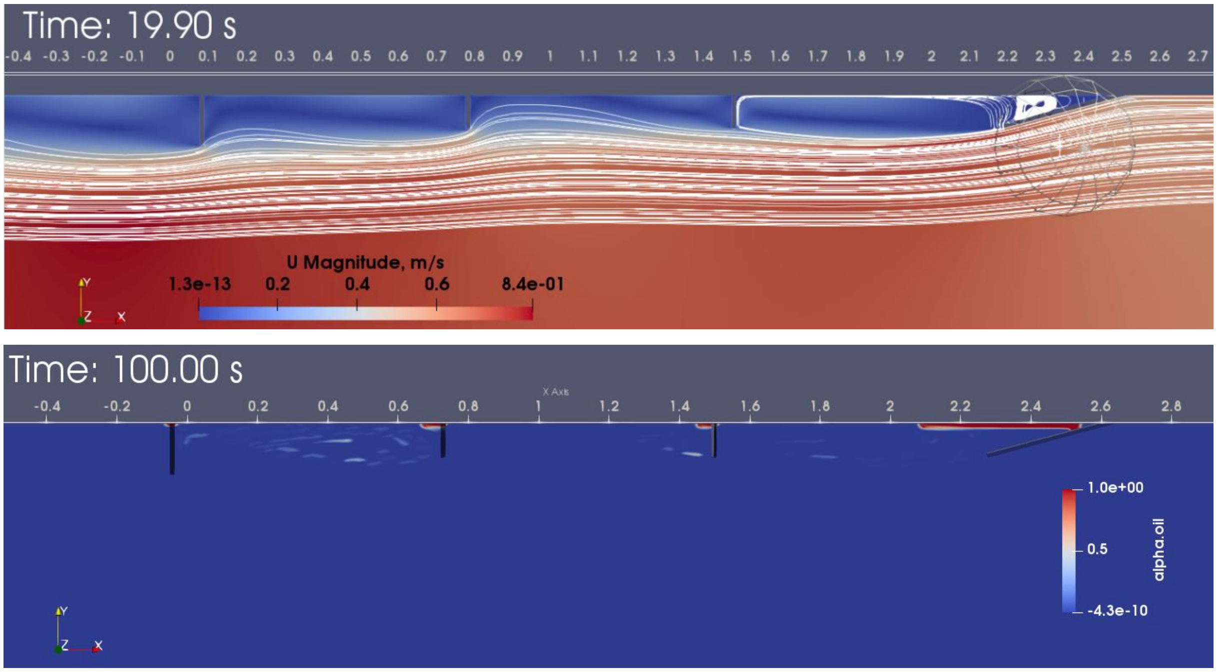


Figure 20. Depiction of Case RB_Config3_1.
(Top) Selected streamlines before the release of oil into the numerical domain. (Bottom) Final configuration of the collected oil. Most of the collected oil is immediately downstream of the ramp.

To assess the sensitivity of the simulation results to downscaling, the RB_Config1_1 scenario was simulated at full scale (not listed in Table 7) and compared with the results for the scaled down simulation listed in Table 7. Approximately 10% more oil was contained in the full-scale case compared with the downscaled simulation. The ratio of contained oil in each collection zone (zones between adjacent booms) to the total collected oil for the small-scale case was similar to that of the full scale.

Several additional cases with a ramp subject to 10 L/m light oil were also simulated: (1) a Ramped-boom system, similar to the above, with a vertical screen located 2c (see Figure 19) upstream of the ramp with a depth of c and porosities (void ratios) of 50% and 75%. The containment success of the case with the smaller void ratio subject to 5-knots (full scale) speed was 39%. The containment success for the case with the higher void ratio subject to 3-knots speed was 73%; (2) a Ramped-boom system without the two intermediate downstream skirts (see Figure 19), with and without an upstream screen. The containment success of these two concepts were smaller than those of RB_Config3. Particularly, the Ramped-boom system without the two intermediate skirts contained 68% of the oil at 3-knots (full scale) speed.

Screen-Boom Systems

The third 2D boom model investigated was a Screen-boom system, similar to the DESMI Speed-Sweep. A concept consisting of one conventional boom and a series of upstream vertical and horizontal screens to manage the flow field has shown promise for high-speed oil containment applications. Figure 21 shows a 2D view of the system according to information extracted/inferred from the online brochure and videos of the system in action.

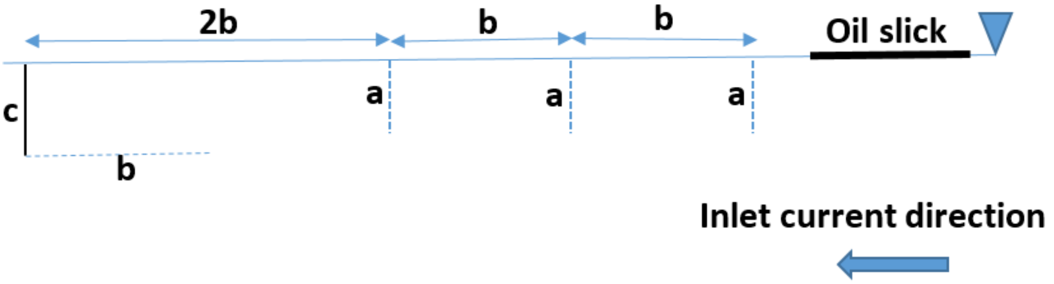


Figure 21. Schematic of the Screen-boom system.
Lengths in model (small) scale are c = 0.14 m, b = 0.5833 m, a = 0.1167 m which is equivalent to a geometric scale factor of 0.194 when considering the DESMI Speed-Sweep. The porosity of the screens is 75%.

The simulated performance of the boom without additional screens is presented in a previous sub-section of this report, entitled “Conventional single-skirt booms”. The simulation results showed that for a 0.14 m deep conventional boom in full scale current speeds of 3 and 5 knots, little (simulation CB1) or no oil (simulations CB2 through CB6) was contained, regardless of oil type.

To understand the impact of the number of screens on containment success, several simulations with a different number of upstream screens were conducted, with different current speeds and oil types. The screens were represented in the model by refining the computational mesh in the regions between screen “threads” as shown in Figure 22. Starting with a single screen, additional screens were incrementally added for each simulation until the final screen-boom system shown in Figure 21 was reached. Table 8 shows the test matrix and predicted containment success for each simulation.

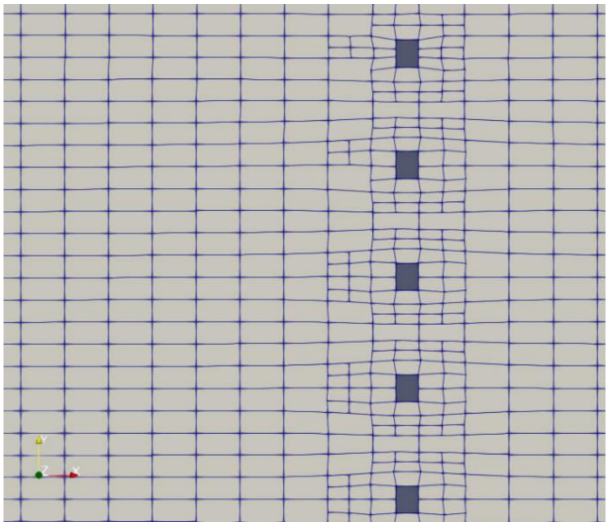
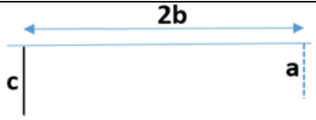
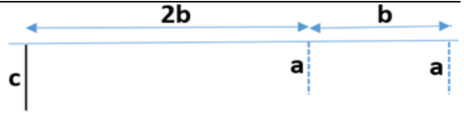
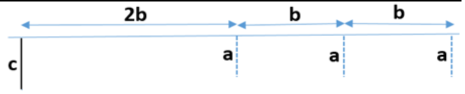
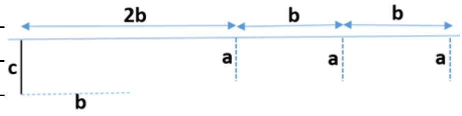


Figure 22. Computational mesh close to a screen. The width of the screen is 0.0025 m.

Table 8. Test matrix for 2D Screen-boom simulations.

Simulation ID	**Oil type**	**Current speed, m/s (full scale speed, knots)**	**Volume of spilled oil, L/m (of the boom width)**	**Containment success (%)**	**Boom arrangement**
SB1	L	0.68 **(3)**	10	41	
SB2	L	0.68 **(3)**	10	68	
SB3	L	0.68 **(3)**	10	~100	
SB4	L	0.68 **(3)**	10	~100	
SB5	L	0.68 **(3)**	30	52	
SB6	M	0.68 **(3)**	10	55	
SB7	L	1.13 **(5)**	10	51	

The results of simulations listed in Table 8 indicate the following:

1. The addition of upstream vertical screens increases the containment success. The containment success is 100% with three vertical screens and when the current is 3 knots (full scale value) and with light oil at a volume of 0.01 m^3/m;
2. The addition of the horizontal screen has a negligible impact on the performance of the boom; and,
3. Containment effectiveness decreases in response to increases in the volume of spilled oil and current speeds.

The increase in containment success with increasing number of screens is attributed to the reduced current speeds in the lee regions of the screens. For the boom shown in Figure 21, each additional screen reduces the horizontal component of the velocity field by approximately 20%. Figure 23 illustrates horizontal velocity components for this boom system subjected to a 3 knot (full scale) flow speed just before the oil is released in the numerical domain.

When the oil is medium or heavy, which have much higher viscosities than the light oil, the screen openings (aperture) in small scale simulations are not large enough to prevent the blockage of the oils. This blockage is highly unlikely (at least for the medium oil) at full scale where the oil thickness to aperture ratio is very low and it is hence expected that the oil will not directly interact with the screens and rather with the velocity field impacted by the screens. To prevent this likely unrealistic blockage in the numerical simulations, the initial oil thickness was reduced to 0.0025 m to ease the passage of the oil (simulation SB6). This initial thickness reduction was helpful in the medium oil simulation. However, the problem persisted for the heavy oil hence not providing any results herein.

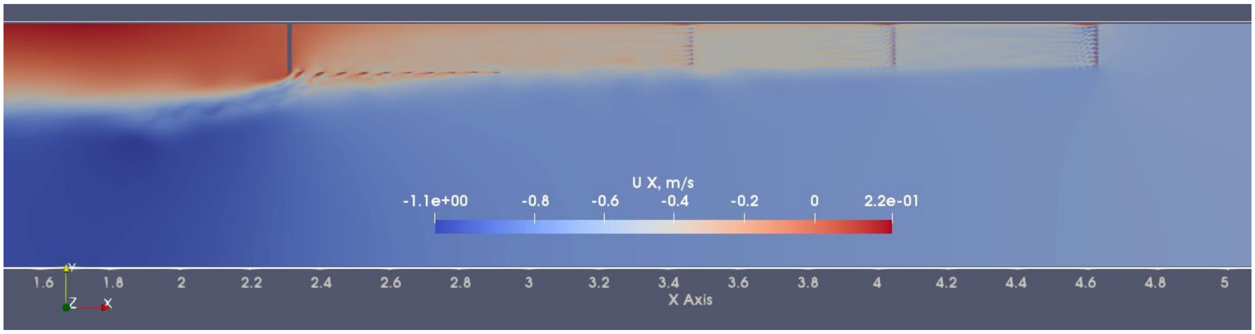


Figure 23. Horizontal velocity field of a Screen-boom system subjected to a 3 knot current.

L-Shaped Booms

The last series of two-dimensional simulations investigated the oil containment performance of an L-shaped boom concept. This was an exploratory test to understand how effective this concept might be. The geometry of the L-shaped boom is shown in Figure 24.

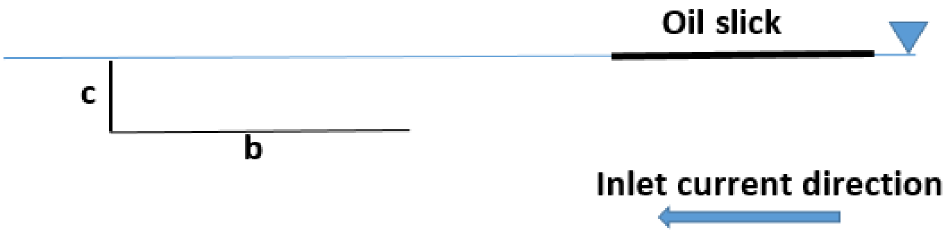


Figure 24. Schematic of the L-shaped boom.
Lengths in model (small) scale are c = 0.14 m and b = 0.5833 m.
This is equivalent to a geometric scale factor of 0.194 when full-scale c and b are 0.72 m and 3 m, respectively.

The test matrix and containment success for the three L-shaped boom simulations are listed in Table 9. For the single current speed and oil spill volume investigated, the boom was 100% effective at containing the heavy oil. For light and medium oil types, the volume of the contained oil was time-dependent, decreasing with time (refer to Figure 25).

Table 9. Test matrix for 2D L-shaped boom simulations.

Simulation ID	Oil type	Current speed, m/s (full scale speed, knots)	Volume of spilled oil, L/m (of the boom width)	Containment success (%)
LS1	L	0.681 **(3)**	10	55*
LS2	M			63*
LS3	H			100

* This value is time-dependent for the simulated duration. The value given is at 100 s (in small scale) after release of oil into the numerical domain.

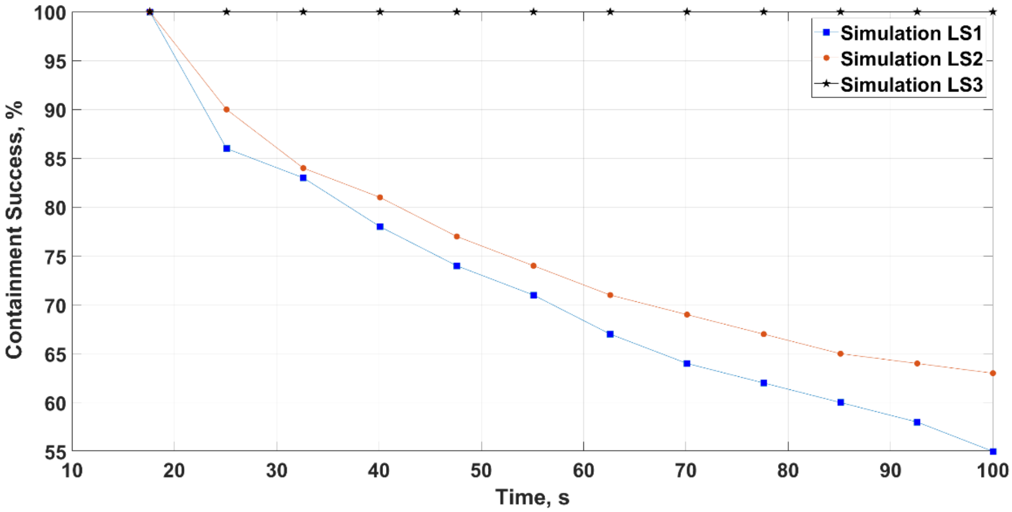


Figure 25. Time-dependent containment success of an L-shaped boom subject to different oil types. Note that the leading edge of the slick reaches the containment region at approximately 18.3 s. The time is in small (model) scale. The full scale equivalent of time is $\sqrt{1/0.194} \approx 2.3$ times larger than the time in small scale. 0.194 is the geometric scale factor.

Figure 26a through Figure 26e show streamlines and slick shape at different times for the simulations of light and heavy oils. Both the light and heavy oils form two separate slicks; one thinner slick, located closer to the vertical boom, and the other, thicker slick above the upstream tip of the boom (Figure 26b and Figure 26c). The latter slick intermittently escapes escaping under the boom. Occasionally, the upstream edge of the thinner slick migrates upstream, joins the thicker slick, and supplies it with more oil, which is then lost under the boom. For heavy oil, separate slicks do not develop and all oil is contained for the duration of the simulation.

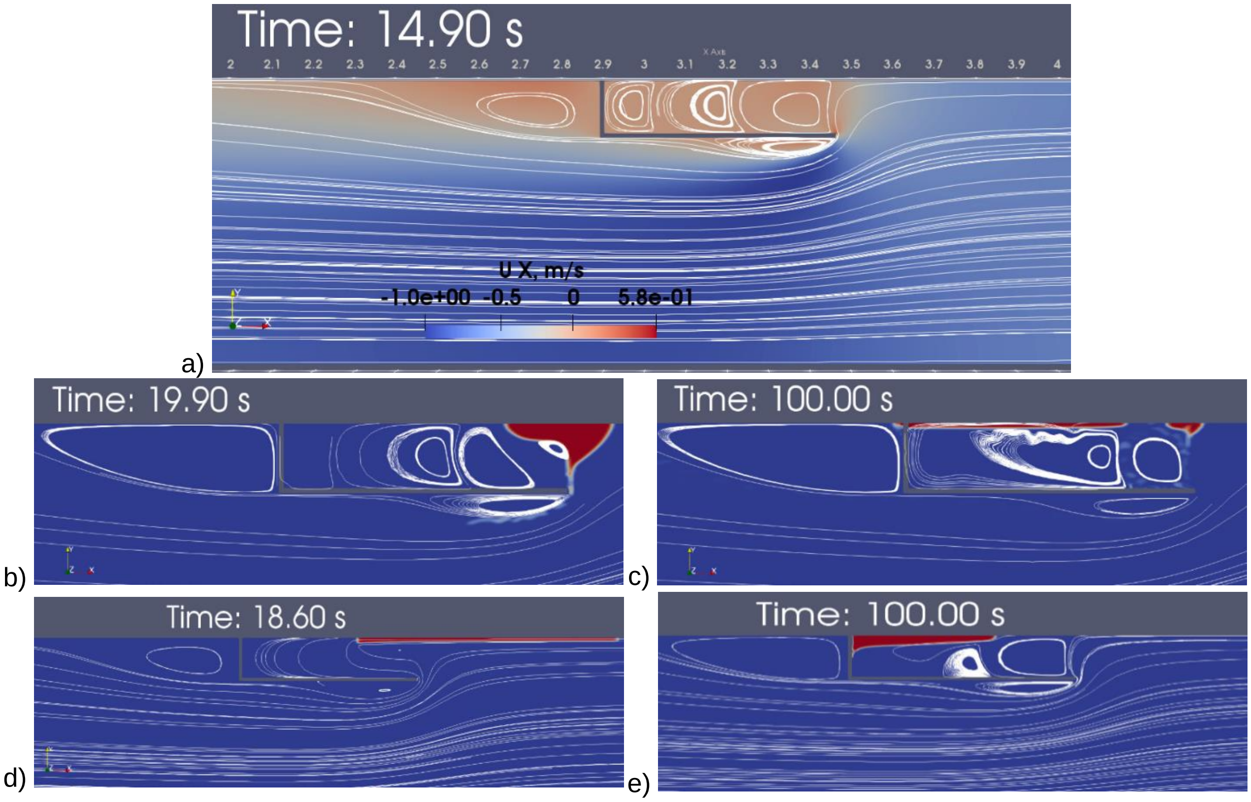


Figure 26. Streamlines and slick shapes.

(a) Before the release of oil. (b) when light oil is entering the containment region, (c) at 100 s, (d) when heavy oil is entering the containment region, and (e) at 100 s. Note that the existence of oil changes the streamlines. Heavy oil is fully contained.

4.3.2. Three-Dimensional Simulations

Three-dimensional CFD simulations were implemented to assess the oil containment performance of three types of oil boom concepts, two of which are based on commercially available products (see Figure 3 and Figure 5), and the third concept being the Ramped-boom system illustrated in Figure 19. For each boom-type, a series of tests were conducted for current speeds of 3 to 5 knots with light and medium oils. The oil containment effectiveness was evaluated for each boom technology. The potential to improve containment effectiveness was investigated by conducting additional simulations with modifications to the boom concept design (e.g. the skirt depth).

The computational mesh for the OpenFOAM CFD models consisted of hexahedral prisms/cells. The mesh was generated using SnappyHexMesh, OpenFOAM’s built-in mesh generator, which facilitates generating geometry-conforming hexahedral meshes. Because the problem is symmetric with respect to the central plane, only half of the boom was incorporated in the mesh (see Figure 27), to reduce the computational burden. A symmetry boundary condition was applied along the center of the boom (AB in Figure 27). To reduce the number of grid cells and computational expense, the depth of the domain was reduced compared with the 2D simulations, and an open-boundary condition was applied at the bottom of the model. To minimize the influence of the open boundary condition on hydrodynamics in areas of interest while balancing computational demands, the open boundary was maintained as far as reasonably possible from the underside of the boom.

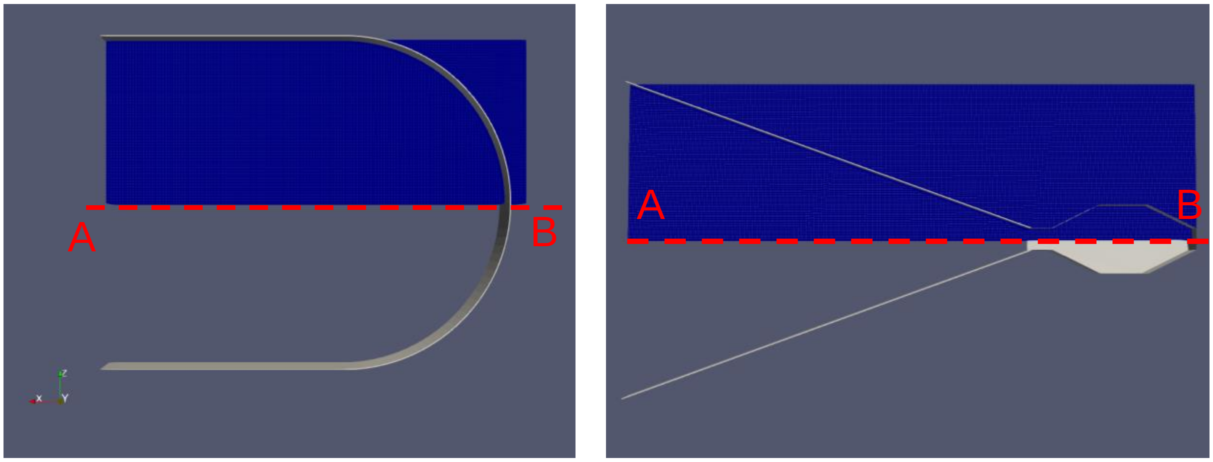


Figure 27. Plan view of model domain in 3D simulations.
Conventional U-shaped boom (left) and V-shaped boom (right).

Similar to the 2D simulations, the oil slick was injected with a vertical thickness of 1 cm at the inlet. To reduce computation times to manageable durations, the inlet boundary in the 3D model was discretized by two cells, instead of the four cells used in the 2D model. The element length scale in the vertical direction (y) was half the length scale in the horizontal direction (x and z). The minimum cell size in the y direction in the model was 0.5 cm. Where necessary, cell sizes were refined to better resolve the geometry of the booms. The mesh was refined near the boom for the V-shaped model and in the vicinity of screens for the screen-boom model.

The 3D model computational mesh was composed of 6 to 8.5 million cells, depending on the testing scenario, with a minimum cell size of 1 cm in the vicinity of the boom. The mesh resolution was selected to provide a reasonable balance between the computational cost and accuracy of the results.

The mesh configuration selected for the model typically resulted in simulations lasting 7 days (using 120 cores) to provide 50 sec (model scale) of simulation time. The following sub-sections describe simulations conducted for each boom technology including the simulation scenarios and specification, and a summary of the calculated results.

It should be noted that the dimension values used to describe the boom geometries in the next section are reported in the prototype (full) scale (P). The models were built at the reduced geometric scale of 0.224.

V-Shaped Boom Systems

The first 3D boom model investigated was a V-shaped boom system, similar to the NOFI Current Buster 6. The V-shaped Boom system consists of two components: side booms and a floating storage reservoir as depicted in Figure 28. It should be noted that no concrete information regarding the geometry of the CB6 boom was available, therefore some assumptions had to be made in the CFD model. In particular, it was assumed that the depth of the storage reservoir was equal to the depth of the skirt i.e., there was no “shelf” at the entrance to the reservoir. The first round of simulations was conducted based on the boom geometry shown in Figure 28. Table 10 summarizes these simulations and their configuration parameters, and containment success.

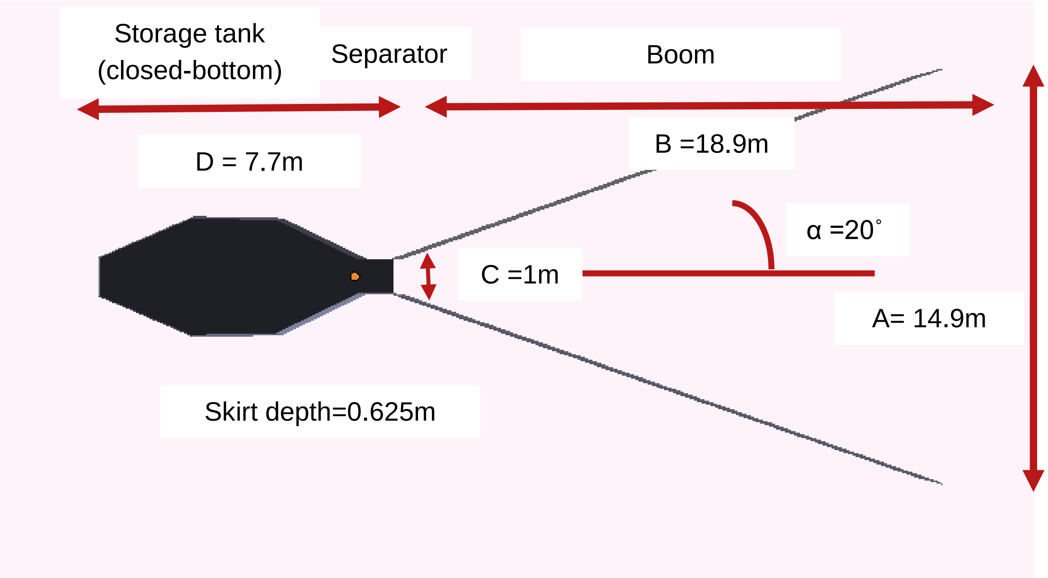


Figure 28. Plan view of the V-shaped boom system.

Table 10. Test matrix 1 for 3D V-shaped boom simulations.

Simulation ID	**Skirt depth, m (full scale depth, m)**	**Oil type**	**Current speed, m/s (full scale speed, knots)**	**Volume of spilled oil, L/m (of the boom width)**	**Containment success (%)**
NF1	0.14 **(0.625)**	L	0.73 **(3)**	10	24
NF2		M			13
NF3		L	1.21 **(5)**		16
NF4		M			6

Figure 29 illustrates the oil slick shape after 22.6 sec and 50.1 sec of simulation for simulation NF1 in Table 10. The oil phase is indicated by red shading and the water phase is indicated by blue shading. The narrowing of the boom geometry towards the storage tank contracted and thickened the oil slick at the apex. The water trapped in the closed-bottom storage reservoir additionally obstructed the oil flow through the separator area (see Figure 29a). A combination of these factors resulted in a significant portion of the oil initially passing through the boom mouth escaping from beneath the storage reservoir upon reaching the reservoir entrance. In an attempt to improve the containment rate, further simulations were conducted by changing the apex width and the skirt/storage reservoir depth.

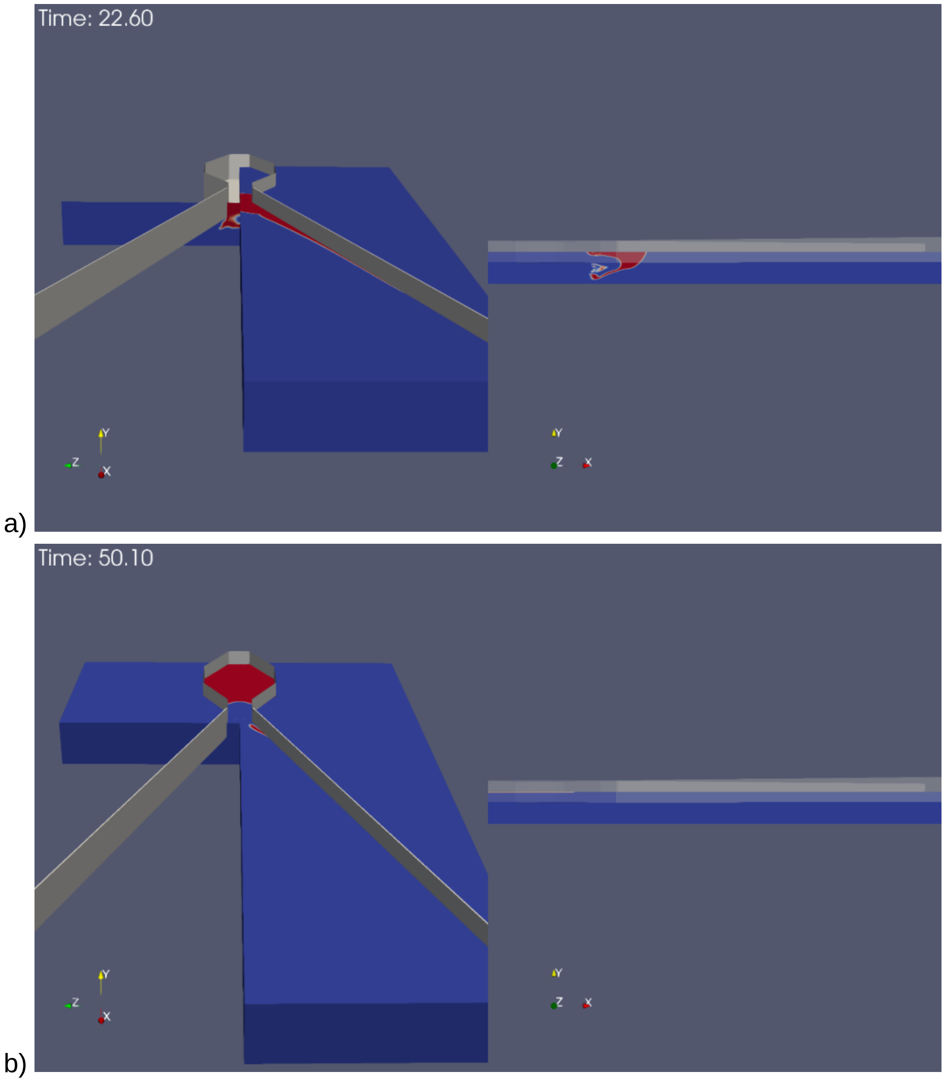


Figure 29. Oil slick shape in NF1 after (a) 22.6 sec, and (b) 50.1 sec of simulation.

In the second round of simulations, the width of the V-shaped boom apex (C in Figure 28) was increased to 2 m. All of the other parameters were the same as in the first round. A summary of the simulation scenarios and the containment success associated with each case is provided in Table 11.

Table 11. Test matrix 2 for 3D V-shaped boom simulations (with increased apex width).

Simulation ID	**Skirt depth, m (full scale depth, m)**	**Oil type**	**Current speed, m/s (full scale speed, knots)**	**Volume of spilled oil L/m (of the boom width)**	**Containment success (%)**
NF5	0.14 **(0.625)**	L	0.73 **(3)**	10	48
NF6		M			33
NF7		L	1.21 **(5)**		38
NF8		M			24

Figure 30 illustrates the oil slick shape after 22.6 sec and 50 sec of simulation for NF5 (see Table 11). Increasing the apex width from 1 m to 2 m improved the containment success of the boom for the light oil by 100% in current speeds of 3 knots. The improvement was even better for the medium oil, and for higher current speed (5 knots, full scale). The improvement observed for the wider apex is because it results in a thinner oil slick at the storage reservoir entrance, allowing larger volumes of the oil to flow into the storage reservoir.

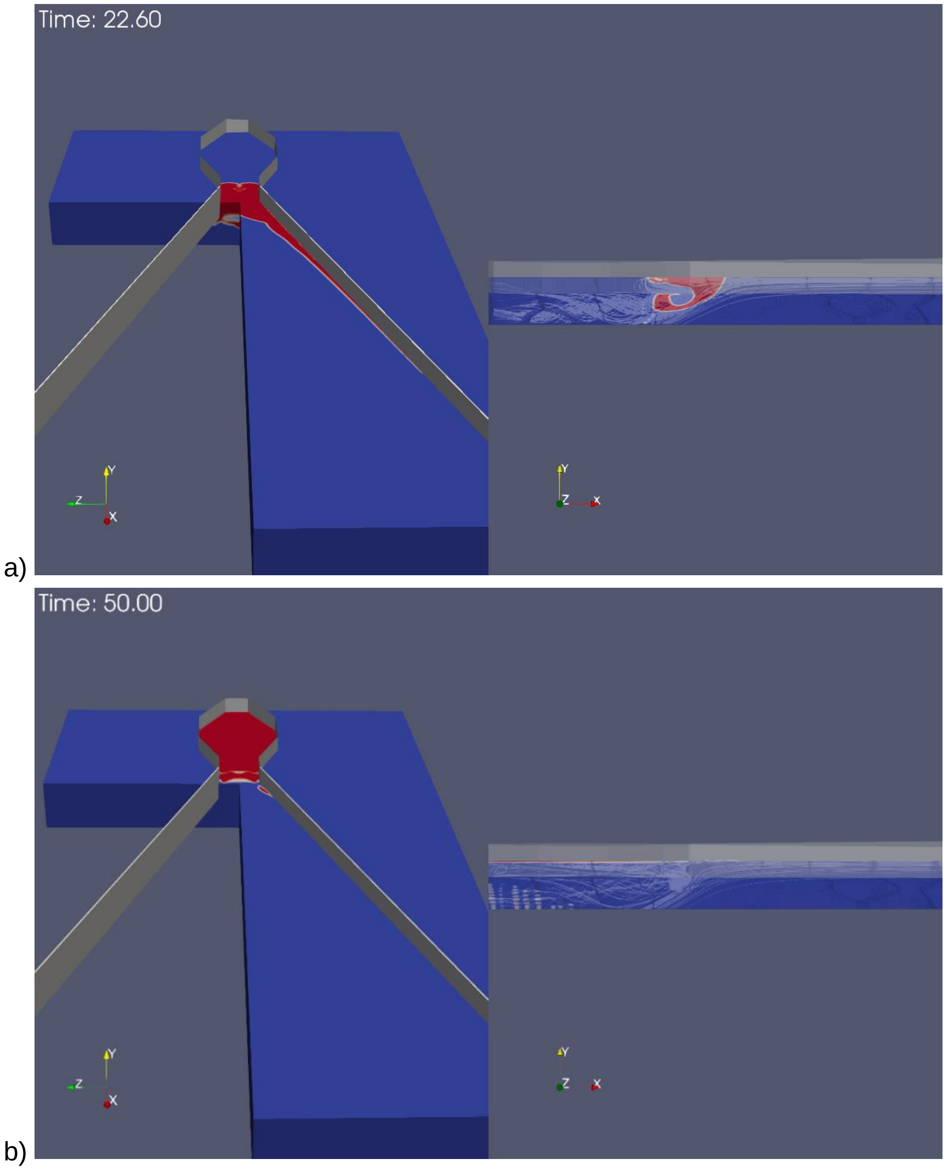


Figure 30. Oil slick shape in NF5 after (a) 22.6 sec, and (b) 50 sec of simulation.

In the third round of simulations based on the V-shaped boom concept, the apex size and all other parameters were kept the same as in the second round but the skirt depth was increased by 50% compared with the previous simulations. A summary of the simulation scenarios and the containment success is provided in Table 12.

Table 12. Test matrix 3 for 3D V-shaped boom simulations (with increased apex width and skirt depth).

Simulation ID	Skirt depth, m (full scale depth, m)	Oil type	Current speed, m/s (full scale speed, knots)	Volume of spilled oil, L/m (of the boom width)	Containment success (%)
NF9	0.21 **(0.94)**	L	0.73 **(3)**	10	61
NF10		M			32
NF11		L	1.21 **(5)**		34
NF12		M			10

Figure 31 illustrates the oil slick shape after 22.6 sec and 50 sec of simulation for NF9 (see Table 12). Increasing the skirt/storage depth by 50% improved the containment performance of the boom for light oil in current speeds of 3 knots (full scale) by 27%. The boom performance was not improved for the medium oil at the same current speed (NF10), and light oil at the current speed of 5 knots (full scale). Increasing the skirt depth was observed to reduce the containment success rate of the boom for the medium oil in a 5 knot (full scale) current.

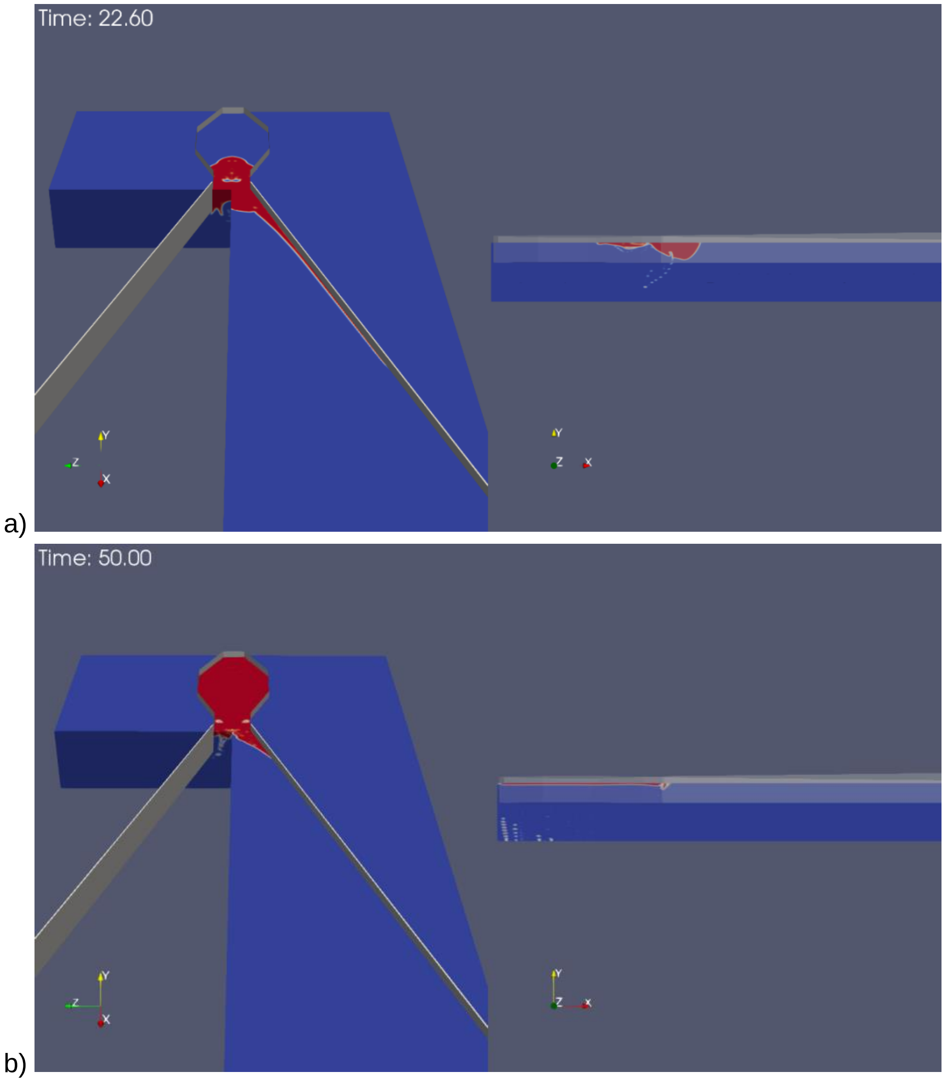


Figure 31. Oil slick shape in NF9 after (a) 22.6 sec, and (b) 50 sec of simulation.

Screen-Boom Systems

The main components of the Screen-boom are a 45 m long U-shaped boom, three vertical screens (VN1, VN2, and VN3), and a horizontal (HN) screen placed at the bottom of the apex zone as shown in Figure 32. The skirt depth is 950 mm which is constant for all regions of the boom.

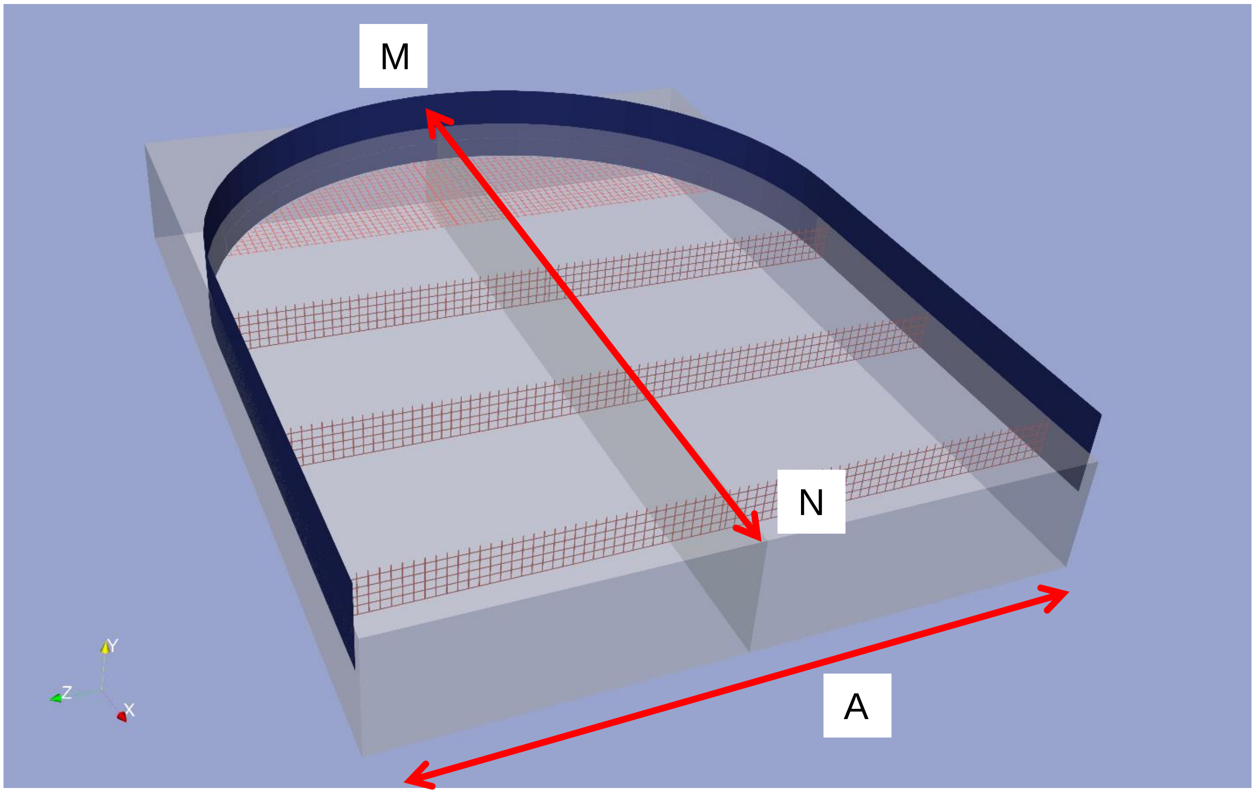


Figure 32. Schematic view of DESMI Speed-Sweep boom.

The opening width of the boom (A in Figure 32) was selected based on consultations with SL Ross in such a way that a gap ratio ($G_r = \frac{A}{L}$) of 0.3, wherein L is the total length of the boom, is provided. A CFD model was built at a geometric scale of 0.224 based on this geometrical information. The width of the horizontal screen in the model was 1 m. The depth of the vertical screens was identical to the boom depth. The screens were placed at 1 m distance from each other.

One of the main challenges in simulating the Screen-boom system was the implementation of screens in the model. The screens had to be implemented in the numerical model in a way that realistically represented the physics of the flow through the porous mediums/apertures, while balancing computational effort. The screens were replicated by blocking flow through individual cells occupied by the screen strips (see Figure 33). A porosity value of 80% was chosen for all screens, based on consultation with SL Ross.

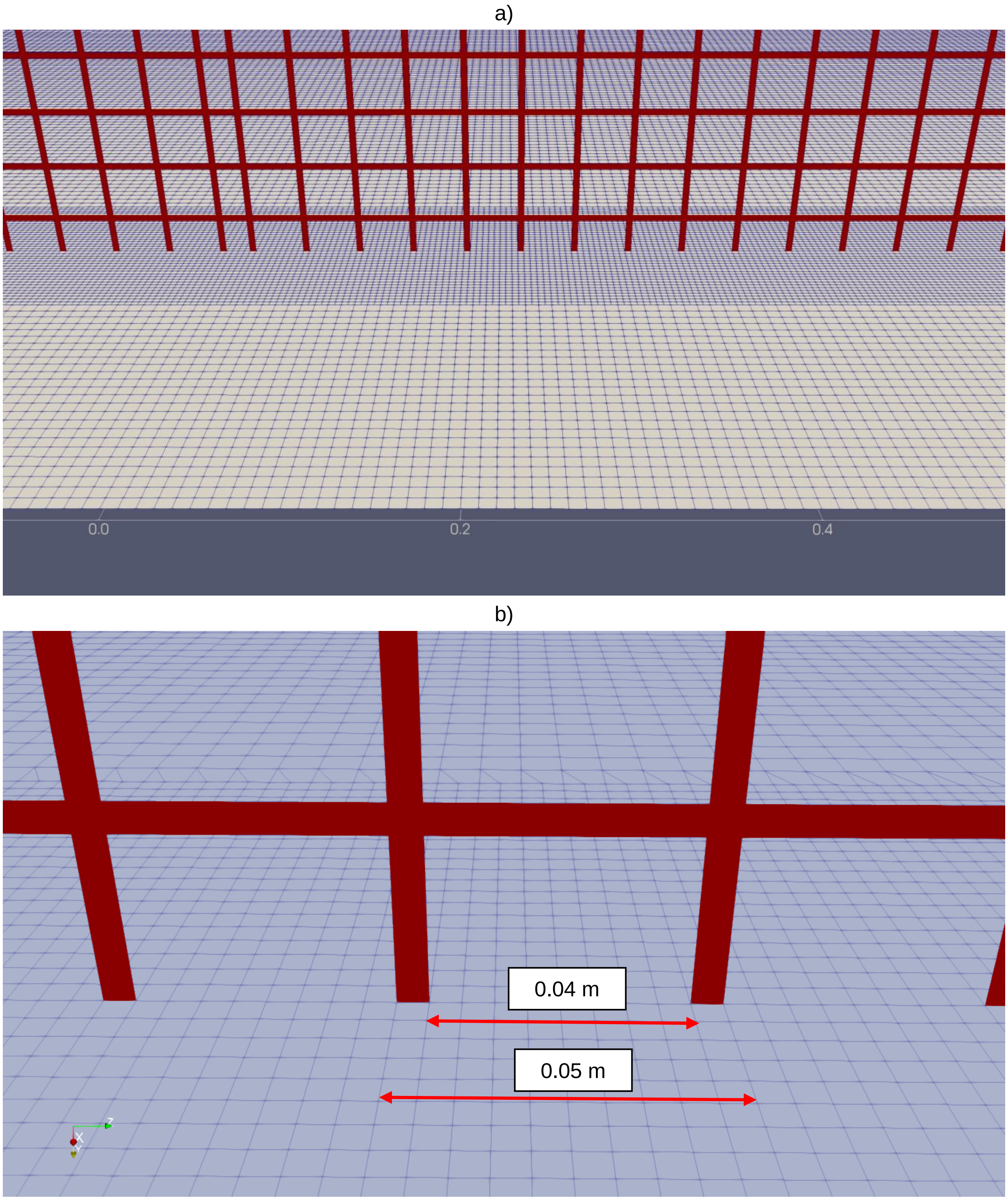


Figure 33. Replication of the screens in the numerical model.
Red cells represent where flow is blocked.

Figure 34 illustrates the impact of the vertical screens on horizontal component of the flow velocity along the boom. The velocity values are based on the model results at cells located 10 cm below the water surface and 5 cm from the boom main axis (MN in Figure 32). The positive values indicate velocity in direction of the main flow and the negative values indicate velocity in opposite direction to the main flow (see Figure 34).

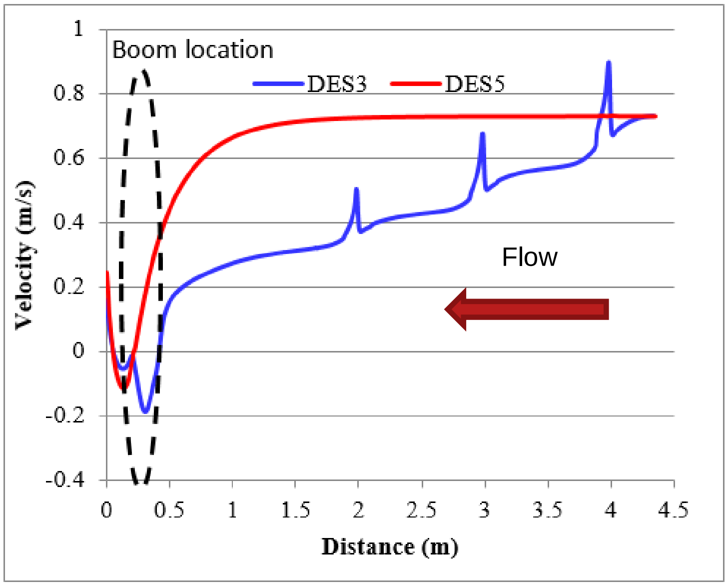


Figure 34. Influence of vertical screens on the flow velocity 10 cm below the surface. Along the main axis of the boom, refer to line MN in Figure 32. Red refers to simulation of the conventional boom (DES5), and blue refers to the simulation with horizontal and vertical screens.

The vertical screens reduce the incident flow velocity by two mechanisms. Each screen obstructs the flow which causes a rapid drop in the flow velocity between the front and back of the screen. Also, eddies are generated when flow passes through each screen. This dissipates the flow's kinetic energy, and decreases the flow velocity gradually between the screens.

In order to investigate the effect of screens on the performance of the Screen-boom system, the first round of simulations were conducted based on a conventional single-skirt boom (in the absence of horizontal and vertical screens). Table 13 summarizes these simulations and the containment ratios predicted for each scenario pertaining to the conventional boom.

Table 13. Test matrix 1 for 3D Screen-boom simulations (with the absence of screens).

Simulation ID	Skirt depth, m (full scale depth, m)	Oil type	Current speed, m/s (full scale speed, knots)	Volume of spilled oil, L/m (of the boom width)	Containment success after 50 s (%)	Containment success after 100 s (%)
DES1	0.21 **(0.95)**	L	0.36 **(1.5)**	20	100	100
DES2			0.49 **(2)**		76.5	50
DES3			0.73 **(3)**		3.4	-
DES4	0.28 **(1.23)**				11.7	-

The conventional boom contained 100% of the light oil at a current speed of 1.5 knots. The containment ratio decreases to 50% when incident current speed increased to 2 knots. The conventional boom was not successful in containing the oil at a current speed of 3 knots even when the skirt depth was increased by 30%. Figure 35 through Figure 38 depict snapshots of the model results after 100 sec of the simulations stated in Table 13.

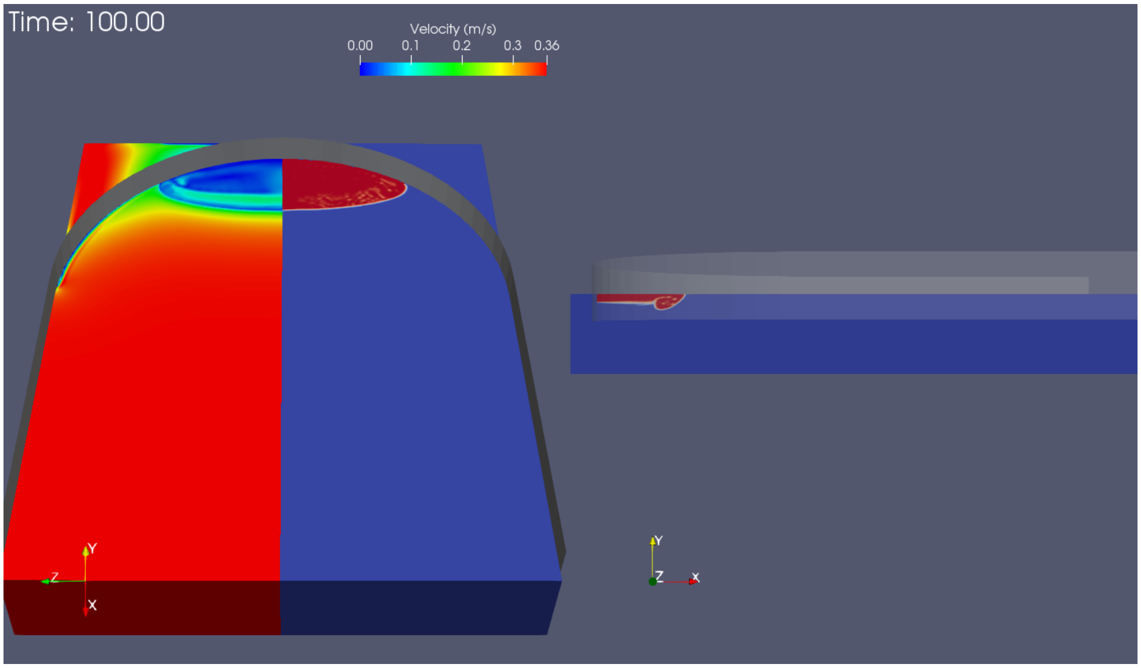


Figure 35. Velocity contours and slick shape after 100 sec of simulation DES1.

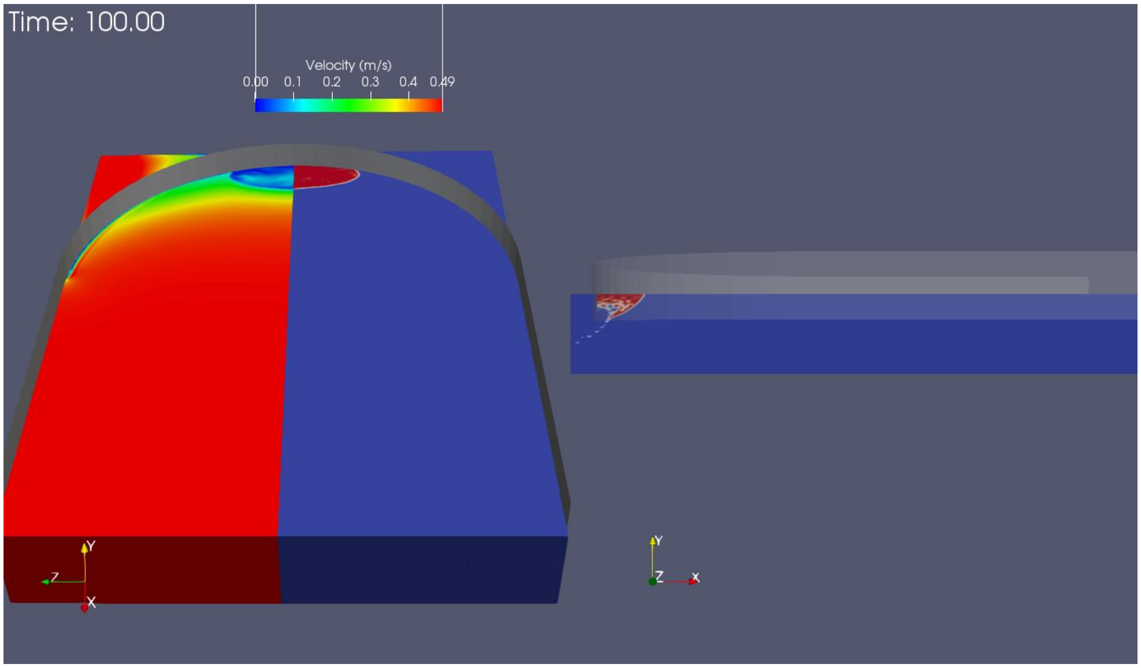


Figure 36. Velocity contours and slick shape after 100 sec of simulation DES2.

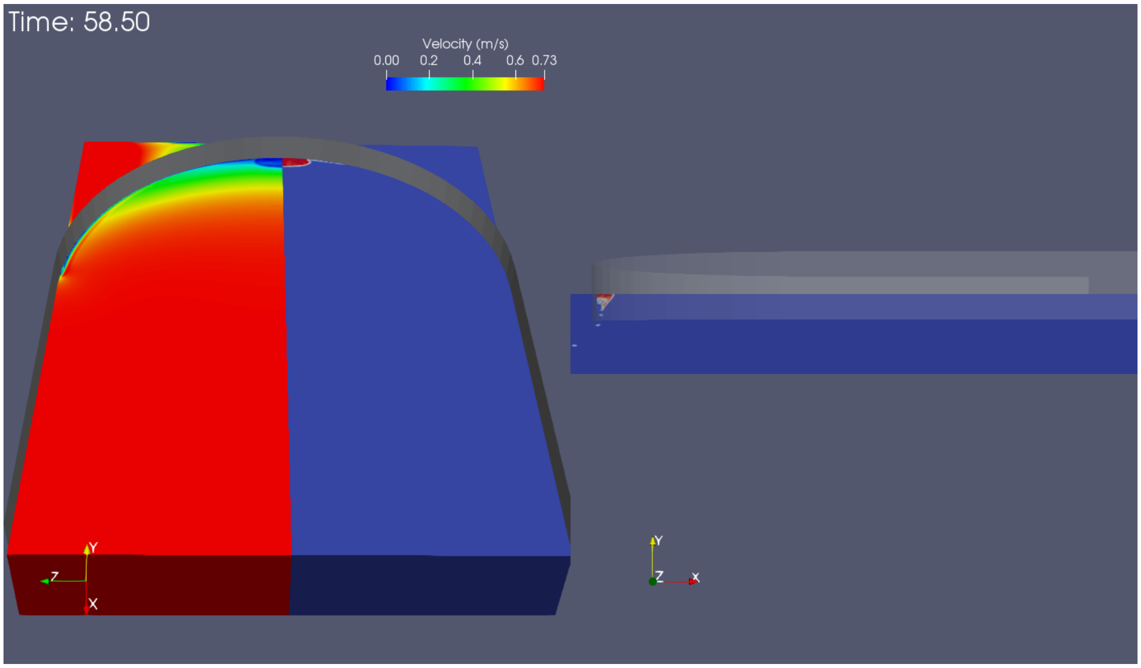


Figure 37. Velocity contours and slick shape after 58.5 sec of simulation DES3.

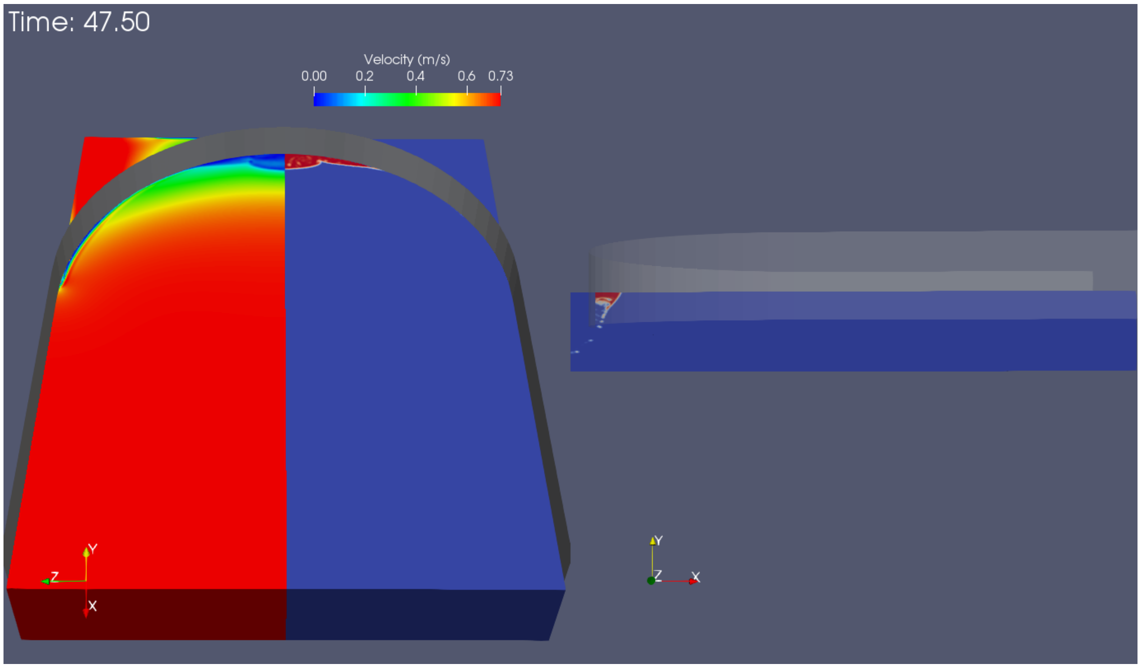


Figure 38. Velocity contours and slick shape after 47.5 sec of simulation DES4.

In the second round of simulations, the horizontal and vertical screens were implemented into the model (refer to Figure 32). The porosity of all screens was 80%. The influence of the horizontal screen on the boom performance was investigated through simulating some of the scenarios without the horizontal screen. Moreover, the effect of the skirt depth was also tested through simulating some of the scenarios when the skirt depth increased by 30% compared with the original Screen-boom design. A summary of the simulations conducted in the second round is provided in Table 14.

Table 14. Test matrix 2 for 3D Screen-boom simulations.

Simulation ID	**Skirt depth, m (full scale depth, m)**	**Oil type**	**Current speed, m/s (full scale speed, knots)**	**Volume of spilled oil, L/m (of the boom width)**	**Porosity (%)**	**Horizontal screen**	**Vertical screens**	**Containment success after 50 s (%)**	**Containment success after 100 s (%)**
DES5	0.21 **(0.95)**	L	0.73 **(3)**	20	80	✕	✓	99	95.5
DES6	0.28 **(1.23)**					✕	✓	99	97
DES7	0.21 **(0.95)**	M				✕	✓	43	35
DES8						✓	✓	65	58
DES9	0.28 **(1.23)**					✕	✓	99	92
DES10	0.21 **(0.95)**	L	0.79 **(3.25)**			✓	✓	97	94
DES11			0.85 **(3.5)**			✕	✓	64	44
DES12						✓	✓	86	74
DES13			0.97**(4)**			✓	✓	38	18
DES14			1.21**(5)**			✕	✓	2	1
DES15	0.28 **(1.23)**					✕	✓	35	26
DES16	0.21 **(0.95)**					✓	✓	1	~0
DES17		M				✕	✓	1	~0
DES18	0.28 **(1.23)**					✕	✓	33	2

The Screen-boom system was able to contain more than 95% of the light oil at a current speed of 3 knots (full scale). This was observed in DES5 wherein the horizontal screen was not modelled. The same configuration contained 35% of the medium oil (DES7) at the same current speed as simulated in DES5. The containment success rate of DES5 (35%) was improved to 58% when the horizontal screen was added in DES8. Increasing the skirt depth by 30% in DES9 compared with DES7 changed the medium oil containment rate at 3-knots current speed from 35% to 95%.

The Screen-boom system was also tested at higher current speeds. The boom contained approximately 94% of the injected light oil at a current speed of 3.25 knots (full speed). In general, adding the horizontal screen improved the containment rate by approximately 30% for the light oil and by approximately 20% for the medium oil. The results also indicate that increasing the skirt depth improved the containment rate of the boom. The impact of skirt depth on the containment ratio was more significant at slower speeds (compare DES7-9 with DES14-15) and for light oil (DES14-15 with DES17-18). Figure 39 through Figure 43 present snapshots of model results after 100 sec of simulations for DES5, DES8, DES9, DES10 and DES12.

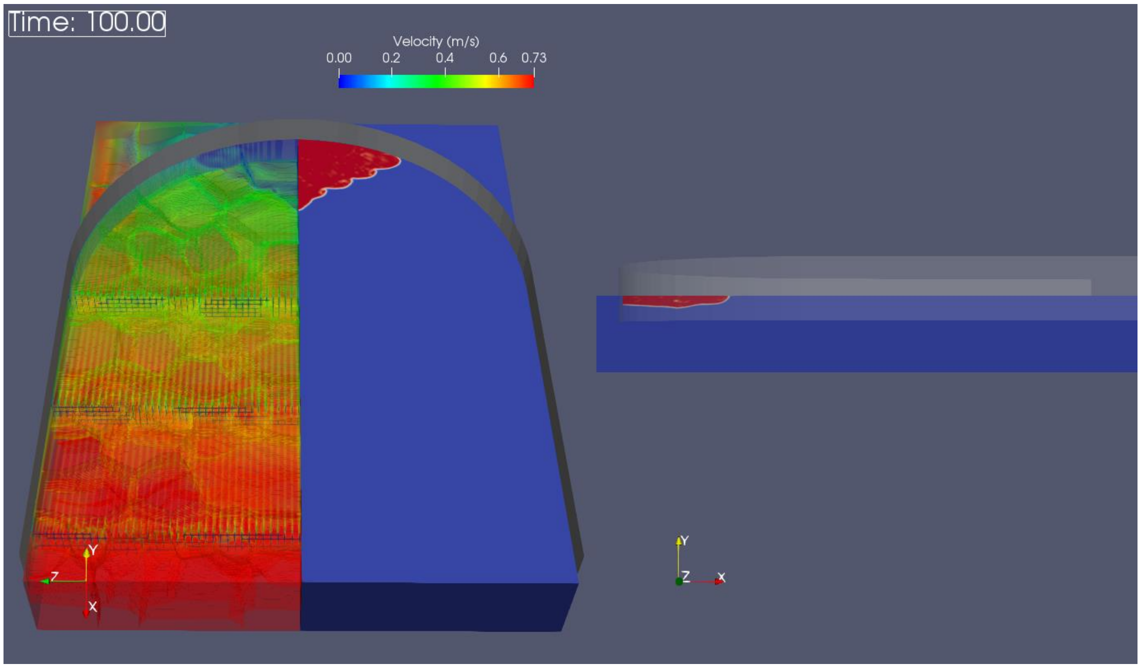


Figure 39. Velocity contours and slick shape after 100 sec of simulation DES5.

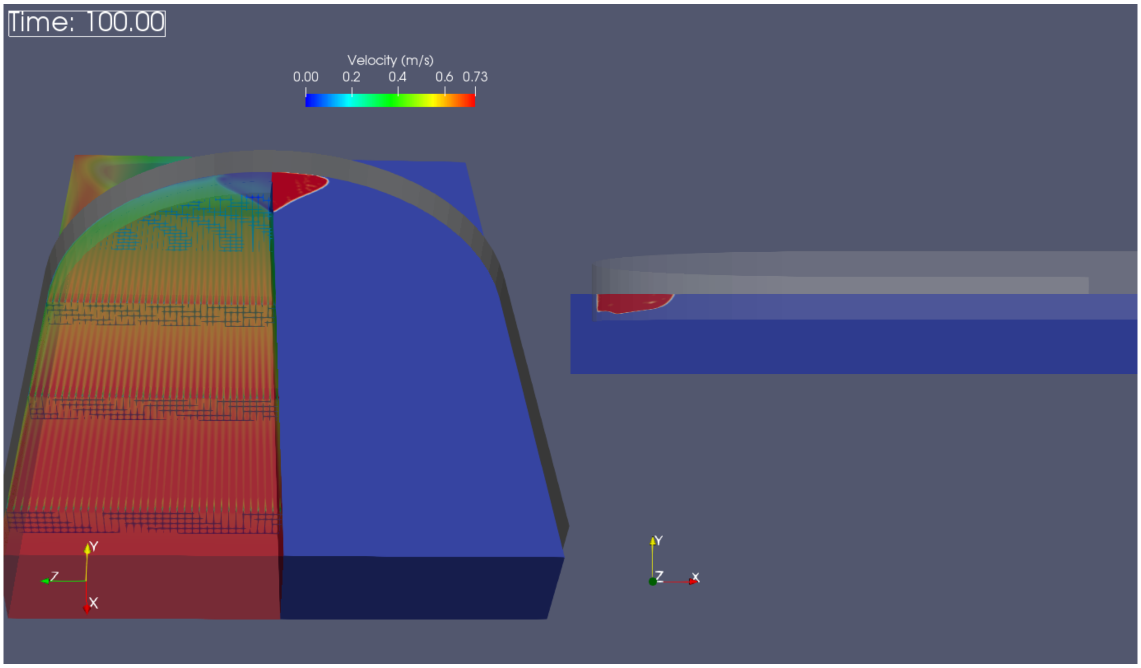


Figure 40. Velocity contours and slick shape after 100 sec of simulation DES8.

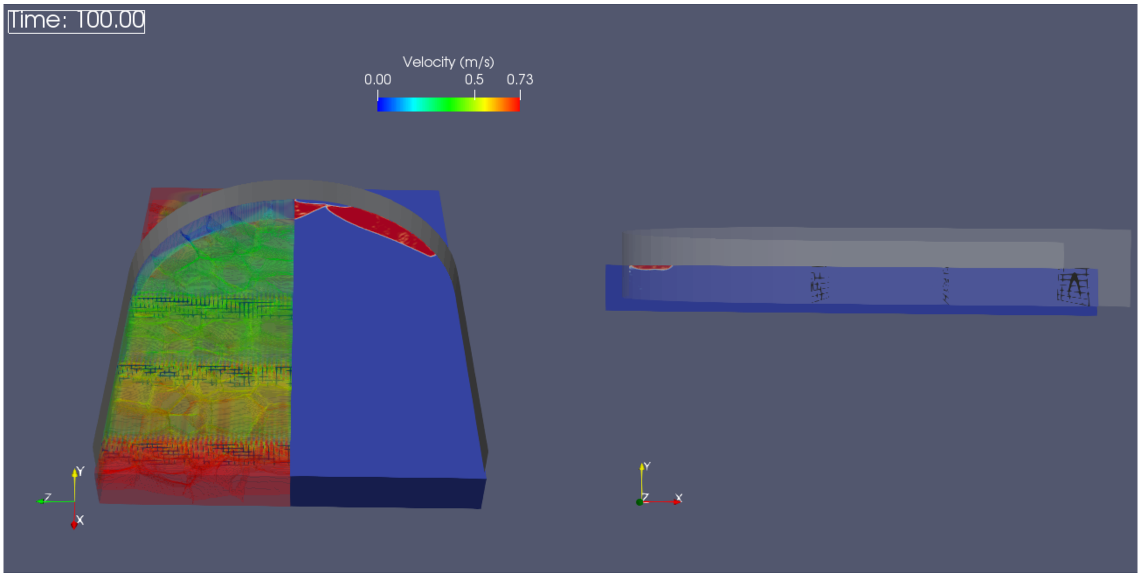


Figure 41. Velocity contours and slick shape after 100 sec of simulation DES9.

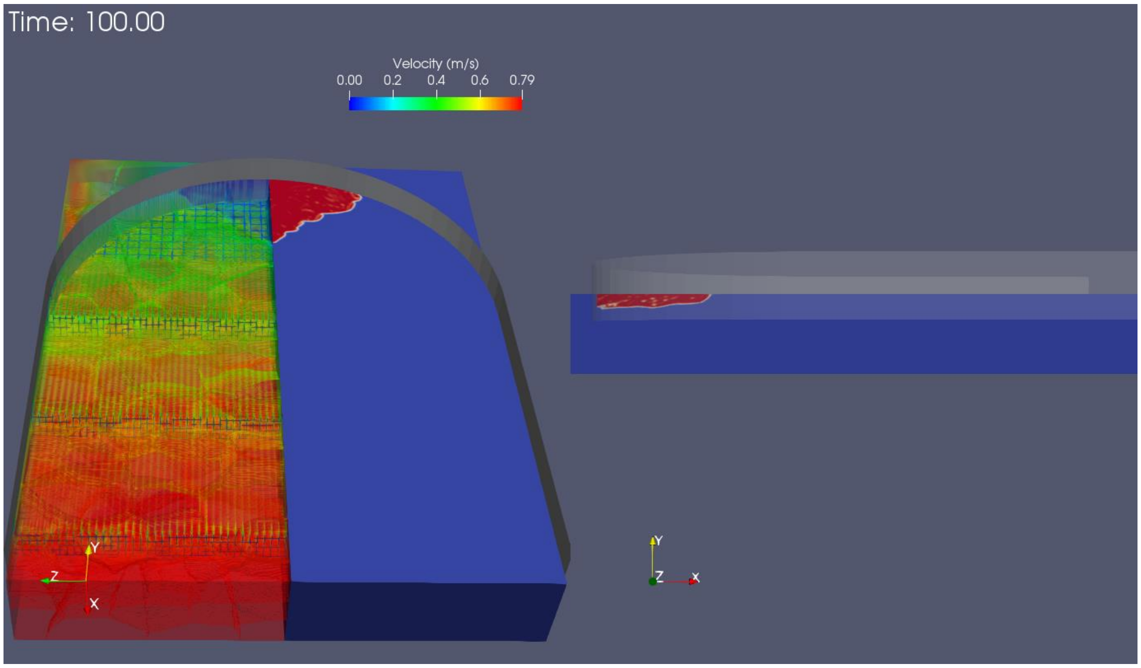


Figure 42. Velocity contours and slick shape after 100 sec of simulation DES10.

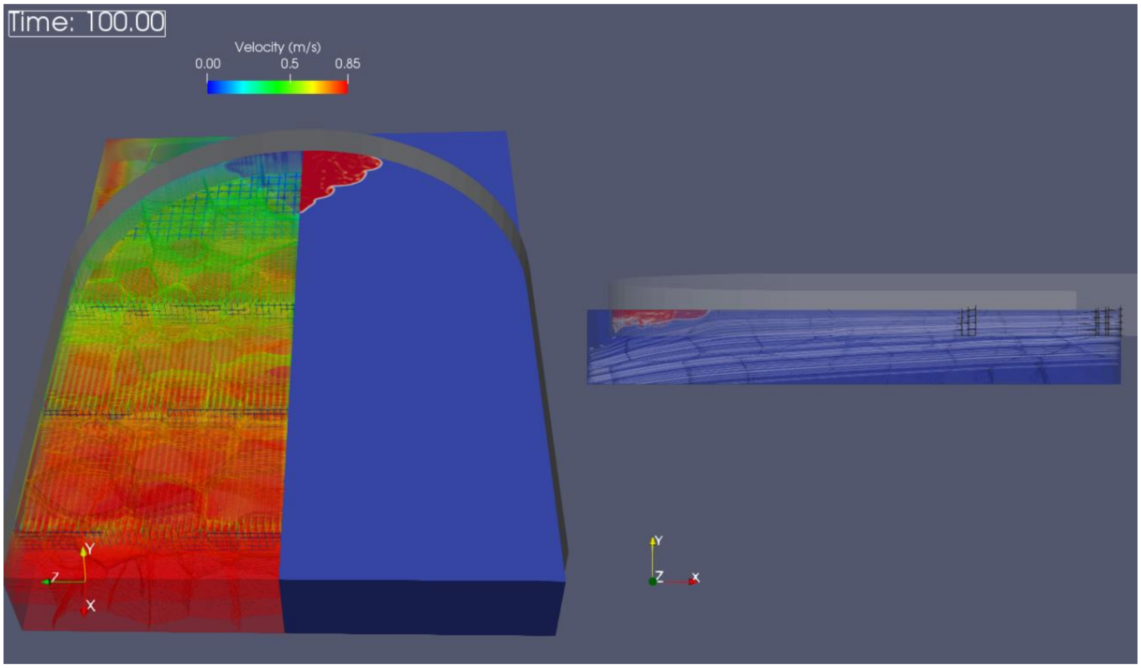


Figure 43. Velocity contours and slick shape after 100 sec of simulation DES12.

Ramped-Boom Systems

In the last round of simulations, a Ramped-boom configuration was modelled (refer to Figure 44). A summary of the simulations conducted in this round is provided in Table 15.

Table 15. Test matrix for 3D Ramped-boom simulations.

Simulation ID	Skirt depth, m (full scale depth, m)	Oil type	Current speed, m/s (full scale speed, knots)	Volume of spilled oil, L/m (of the boom width)	Containment success after 50 sec (%)	Containment success after 100 sec (%)
DES19	0.21 **(0.95)**	L	0.73 **(3)**	20	92	92
DES20			0.79 **(3.25)**		91	91
DES21			0.85 **(3.5)**		81	79
DES22			0.97 **(4)**		79	76
DES23		M	0.73 **(3)**		92	91
DES24			0.97 **(4)**		37	35

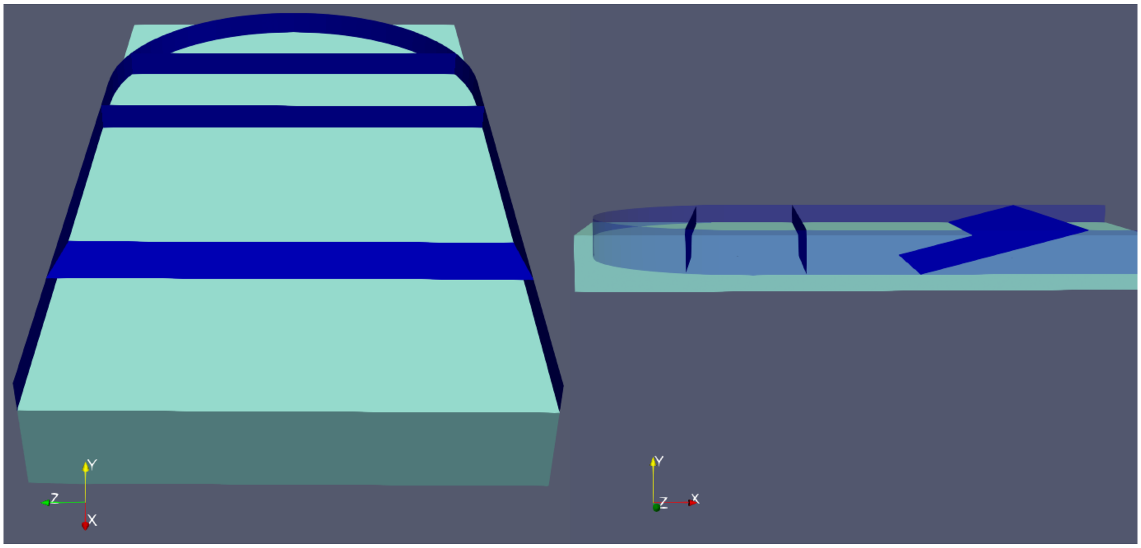


Figure 44. Schematic view of the Ramped-boom system.

The Ramped-boom system contained more than 90% of the light oil at a current speed of 3.25 knots. The results indicate that the system was able contain more than 90% of the medium oil at a current speed of 3 knots. Comparison of the simulation results for DES13-14 (Screen-boom) with DES21-22 (Ramped-boom) shows that the Ramped-boom system had better performance in containing the light oil at current speeds higher than 3 knots. The Ramped-boom system was also able to contain 57% more volume of the medium oil than the Screen-boom system at a current speed of 3 knots (compare DES8 and DES23). Figure 45 through Figure 47 show snapshots of model results after 100 s of simulations DES20, DES21, DES22.

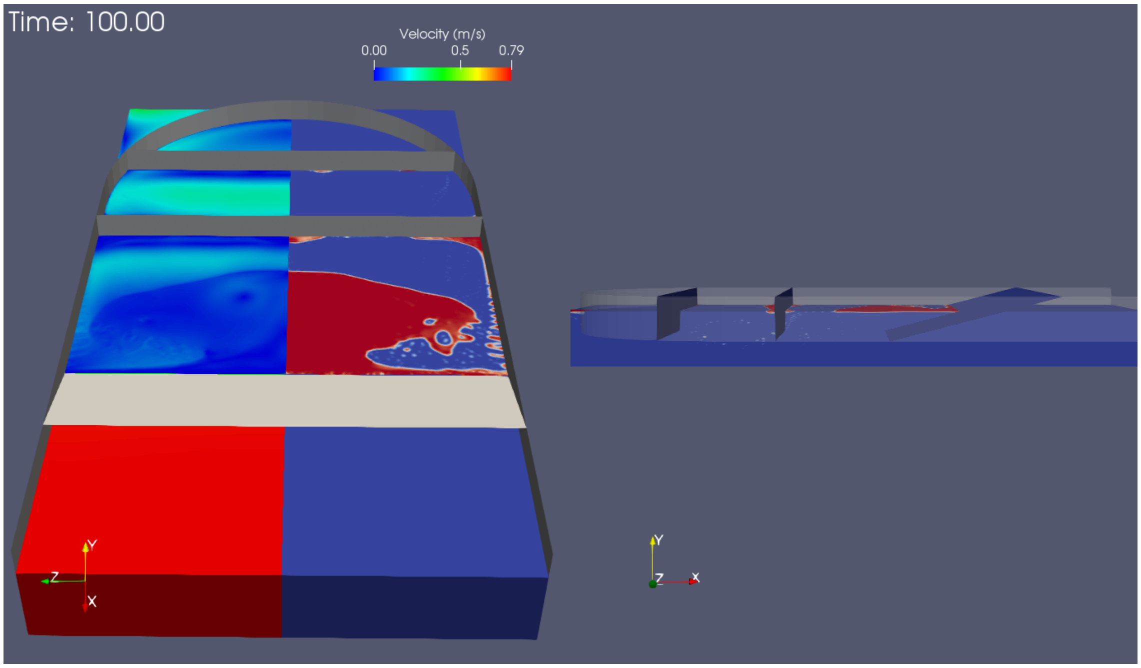


Figure 45. Velocity contours and slick shape after 100 sec of simulation DES20.

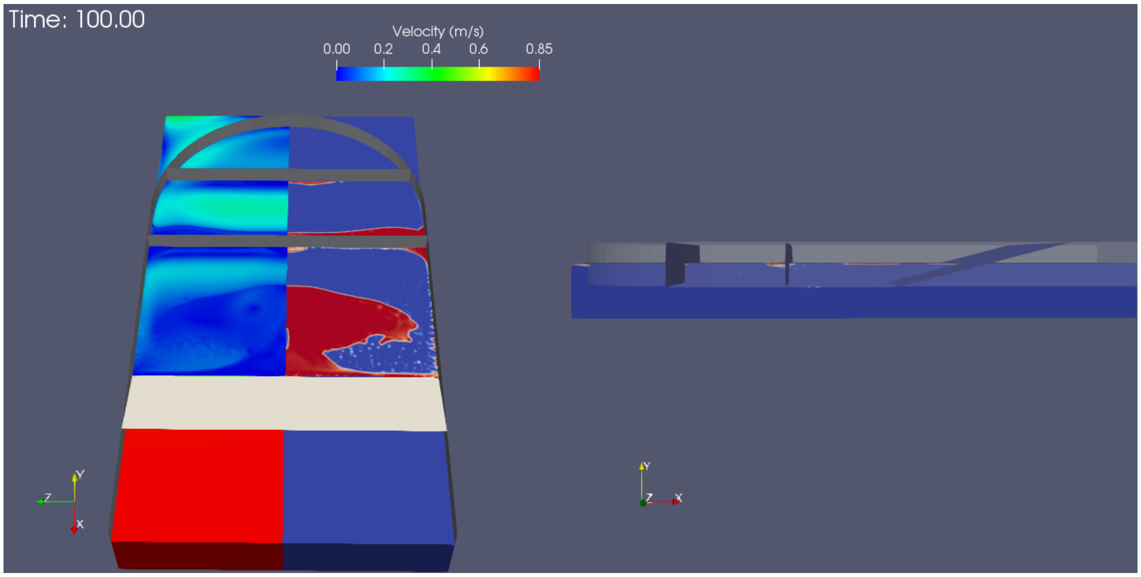


Figure 46. Velocity contours and slick shape after 100 sec of simulation DES21.

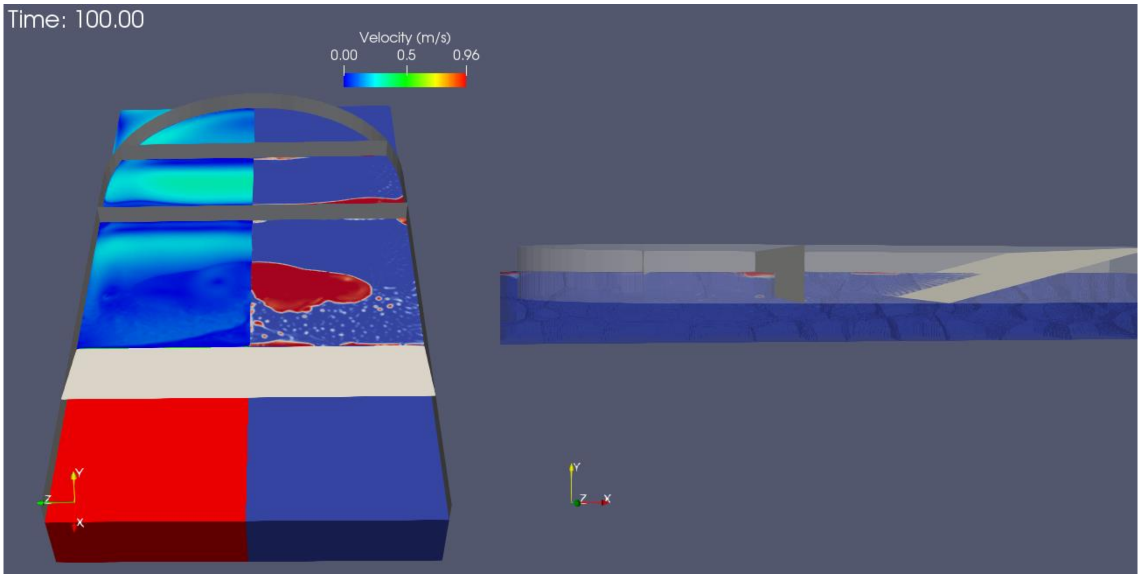


Figure 47. Velocity contours and slick shape after 100 sec of simulation DES22.

4.4. CFD Modelling Summary and Conclusions

A series of two- and three-dimensional CFD simulations were implemented to investigate the oil containment performance characteristics of several high-speed oil spill containment boom concepts for relative speeds of 3 to 5 knots. The problem was modelled as a two-phase incompressible flow past a fixed boom system, using the OpenFOAM CFD Toolbox. Following initial testing of the capability of OpenFOAM to simulate the performance of oil containment booms by comparing simulation results to experimental data, several different boom systems were investigated. CFD simulations were implemented to investigate the containment performance of the boom systems for different oil types (light, medium and heavy). Five main boom concepts were investigated:

- Conventional (single-skirt)
- Ramped, consisting of a ramp followed by three solid vertical skirts
- L-Shaped, consisting of a single vertical skirt connected to a solid horizontal barrier
- Screened, consisting of a conventional boom with horizontal and vertical screens
- V-shaped, consisting of an opening at the apex directing the oil-water mixture to a storage reservoir

The two- and three-dimensional CFD simulation results are generally consistent with each other. It should be noted that some of the 3D simulations could not be approximated as a 2D problem due to the high variability of oil concentration and flow condition across the main flow direction. For such cases, differences between the 2D and 3D simulation results are to be expected. Additionally, even when a problem does warrant a 2D approximation, some differences in the results are to be expected (as compared with the 3D) due to differences in the approaches and the mesh characteristics between the 2D and 3D simulations.

Key findings based on the simulation results are as follows:

- Conventional booms perform poorly in high current speeds, particularly speeds in excess of 2 knots.
- Deeper skirts (larger boom drafts) are generally associated with better performance.
- The performance of the Ramped-boom system is promising. The predicted containment success for light and medium oils in a 3 knot current speeds exceeded 75%.
- The addition of vertical and horizontal screens to conventional booms improves the performance significantly. Particularly for current speeds of 3 knots, light oil is effectively contained with three vertical screens and one horizontal screen. One simulation showed that the performance is reduced when the volume of spilled oil is tripled.
- The V-shaped boom generally performed poorly, although it was more effective with an increase in the draft and opening width at the apex. It should be noted that the CFD simulation results may vary significantly from the observed performance of the NOFI Current Buster 6 since detailed geometry of the prototype were not available.
- The L-shaped boom was more successful than the Ramped-boom system for containment of heavy oil in high current speeds. The performance of the Screen-boom system subject to heavy oil was not studied.

Through this study, CFD techniques (and OpenFOAM in particular) have been shown to be a useful and effective tool for simulating the interaction of oil and water with various styles of oil containment booms, and assessing their relative performance. Recommendations for future CFD investigation are discussed in §6.

5. Phase 3 – Scaled Laboratory Testing

Physical hydraulic modelling is a well-established discipline that has played a pivotal role in the growth of hydraulic engineering as a profession. Physical models have provided great insight into many complex flow problems with hydraulic structures, and they have provided reliable and economical design solutions to support mankind's activities in lakes, rivers, estuaries, and oceans. Many present-day engineering design techniques were developed using laboratory measurements, and numerous theoretical developments have relied on laboratory experiments for validation.

There is relatively little published research regarding the design and evaluation of oil booms using a physical scale modelling approach. Most of the past research has involved very small testing facilities (see Lindenmuth *et al.*, 1970; Swift *et al.*, 1996; Wong & Barin, 2003; Amini *et al.*, 2008b; etc.) where limitations of test equipment and potential scaling effects may be a limiting factor in the overall usefulness of such studies. It is also noteworthy that nearly all of the existing research involves fixed booms in a moving flow field, and virtually no examples of flexible, floating booms that are towed.

A very limited number of full scale test facilities exist around the world (in particular the Oil Spill Response Research & Renewable Energy Test Facility (Ohmsett), located in New Jersey). While these facilities provide as close to real-world simulation as could be expected, the cost of fabricating and modifying various types of booms for assessment, and the cost for operating the facility are impediments towards research in this area. It should also be noted that the Ohmsett facility has an 8 foot depth which limits the boom drafts that can be effectively tested.

This study involves novel experimental research conducted in both two- and three-dimensions, at a notably larger scale and in larger test facilities than nearly all existing research. In the 2D experiments, the water and oil flowed past scale models of the oil containment booms that were fixed in place. In the 3D experiments, the model booms were towed through a tank of water. Some of the 3D experiments were conducted in calm water, while wavy conditions were modelled in others. The 2D experiments are described further in §5.3 while the 3D experiments are discussed in §5.4.

5.1. Scale Modelling Principles

The selection of a suitable geometric scale is a key element in the design of any physical model study. Although many factors are considered, the decision hinges on striking a compromise between two important and sometimes conflicting requirements:

- minimizing scale effects by selecting as large a model scale as possible, and
- faithfully reproducing the environmental conditions with existing facilities and equipment. The dimensions of available facilities and the capabilities of critical equipment (including the current generation system, tow carriage, and wave generator) must be taken into consideration.

A geometric scale of 1:8 was adopted for this study, which means that all lengths in the model were eight times smaller than the corresponding prototype length. This scale was selected so that the model booms could be modelled at as large a scale as possible to ensure maximum realism and reduce potential uncertainties caused by scale effects.

According to Delvigne (1989), there are different scaling rules that need to be considered for different oil containment failure modes. Based on experiments on scaling oil droplet formation (Delvigne, 1991), geometric down-scaling used for small-scale laboratory experiments is unnecessary when modelling the generation of droplets from interfacial instabilities. However, the flow and advection, excluding droplet formation and droplet splitting, can be modelled at a reduced scale by applying Froude similarity rules. Critical accumulation is caused by oil-water interfacial instability. It is also independent of the geometry of the barrier and in particular the draft. Therefore, for critical accumulation, as in droplet entrainment, all involved parameters are simulated at full scale. Since drainage failure depends on the barrier draft and shape, it can be scaled down according to Froude and densimetric Froude numbers. Although the Weber number has also been used by some researchers to scale down the oil droplets being torn from the oil slick, Delvigne (1991) showed this phenomenon to be independent of this number.

As a result, the downscaling law has to be chosen with consideration of the purpose of the particular case under investigation. The formation of droplets is caused by unstable increasing waves on the interface. These interfacial waves and instabilities are influenced only by three oil parameters: the density difference between oil and water, viscosity, and oil-water interfacial tension. Hence, using real oil permits doing full scale experiments to model droplet entrainment failure. Moreover, for experiments in the presence of waves or in modelling of drainage failure, Froude similarities are applied (adapted from Amini *et al.*, 2008a). All of the physical modelling experiments were conducted such that the water depth was at least four times deeper than the skirt depth to respect deep water conditions (Amini *et al.*, 2008a).

In this study, Froude scaling was used to relate conditions in the model to those at full scale. Froude scaling provides a set of scaling laws that dictate the proper relationship between quantities measured in the model, such as velocities and boom dimensions, and the same quantities at full scale. These scaling relationships are derived from similitude of the Froude number (Fr), which represents the relative magnitude of gravitational and inertial forces. Since free surface hydraulics are governed by a balance between the gravitational and inertial forces acting on water particles, similitude of the Froude number in the model and at full scale, together with geometric similitude, ensures that the model provides a reasonable simulation of the interaction of steady free-surface flows with the model oil booms. Scale factors for selected parameters are summarized in Table 16. In this report, measured quantities are expressed as full scale values, unless otherwise noted.

Table 16. Scale relationships for selected parameters at 1:8 scale.

Parameter	**Scale Factor ($\lambda = 8$)**	**Typical value at full scale**	**Corresponding value at model scale**
Length (distance, depth, height)	λ^1	10 m	1.25 m
Time (duration, period)	$\lambda^{1/2}$	5 s	1.77 s
Velocity (length/time)	$\lambda^{1/2}$	1.0 m/s	0.35 m/s
Acceleration (length/time^2)	λ^0	9.81 m/s^2	9.81 m/s^2

The ideal scale law for interfacial tension (σ) of seawater is:

$$\lambda_\sigma = 1.025{\lambda_l}^2$$

which describes how the interfacial tension of the fluid used in the tests ideally should be modelled. Substituting $\lambda_l = 8$, it is evident that these model tests should have been conducted in a fluid that has an interfacial tension roughly 66 times smaller than that of seawater. However, since the test fluid was freshwater having approximately the same interfacial tension as seawater, the interfacial tension scale for these tests was actually close to $\lambda_\sigma = 1$. This implies that the interfacial tension in the model was roughly 66 times too large. Because of this distortion in interfacial tension, physical processes that are sensitive to interfacial tension such as oil droplet formation were not simulated correctly in the model. Unfortunately, it is not possible to establish the precise nature or magnitude of the inaccuracies resulting from these effects.

The Reynolds number (Re) is commonly used to characterize the level of turbulence in a flow and the relative importance of inertial forces and viscous forces. The Reynolds number governs certain flow behaviours such as the development of boundary layers and the drag forces on objects in a flow. Laminar flow occurs at low Reynolds number where viscous forces are dominant, while turbulent flow occurs at larger Reynolds number where inertial forces are dominant. In this study, the Reynolds number in the model was roughly 23 times smaller than at full scale, which is similar enough such that boundary layer formation and drag forces in the model will mirror nature with only very small differences.

5.1.1. Test Oil Properties

Based upon a literature review, consensus among a number of researchers suggested that the best approach to achieve realistic performance assessments would be to assume Froude scaling of the dynamics (tow speed or flow speed) and the geometry of the boom itself, but the viscosity and density of the oil (and water) should not be scaled (Delvigne, 1989). This approach was used in this research study, where fresh water at room temperature was used to represent the water in a lake, river, or ocean, and several commercially available products were used to represent the spilled oil. Based upon discussions with SL Ross and BSEE, Table 5 provides characteristics for representative crude oils that were suggested for the purposes of this study. In consideration for the allowable scope of work and for ease of research, it was decided to focus on the light and medium oils for both the computational and physical modelling simulations.

For health and safety reasons and operational considerations, the use of real crude oil in the test facilities was not possible. Therefore, considerable investigation was undertaken into mineral and vegetable oils that could be used as potential crude oil substitutes. As both the viscosity and density of oil (and water) are controlled by temperature, the substitute oils would ideally have the same characteristics of the prototype light and medium crude oils at the temperature of fresh water used in the test facilities (~19°C).

Based upon analysis by the SL Ross laboratory, *Motomaster ISO AW32 Hydraulic Oil* was selected to represent a light crude oil (with a viscosity of ~87 mm^2/s and density of ~0.853 g/mL at a temperature of 19°C), while *Motomaster 85W-140 Extreme Pressure Gear Oil* was selected to represent a medium crude oil (with a viscosity of ~1,567 mm^2/s and a density of 0.896 g/mL at a temperature of 19°C). Both substitute oils were slightly less dense than the target crude oils; however, they were deemed acceptable alternatives. The measured viscosity and density of the substitute oils at various temperatures is shown in Figure 48 and Figure 49. For comparison, the measured viscosity and density of fresh water at various temperatures is shown in Figure 50. Therefore, the representative light and medium oils were ~85 and ~1,524 times more viscous than fresh water at the same temperature, respectively.

The test oils were coloured using fluorescent red dye in order to improve observation by eye and by the video cameras. The dye had no effect on the density or viscosity of the oils. A vacuum clean-up process was used following each test to remove virtually all the oil from the test facility and provide a similar starting condition for all subsequent tests (it is noted that a slight sheen of oil remained on the surface of the water each time after vacuuming). The vacuum hose was positioned just slightly above the water surface which allowed the oil to be wicked up and removed while at the same time collecting minimal amounts of water. Oil absorbent cloths were also used to wipe down the boom and collect any remaining oil from the water surface. The vacuumed oil (and water) was stored in a large drum where it could settle and separate over a short period. The separated water (with only slight oil contamination) was siphoned from the bottom of the drum while the oil remained at the surface. This water was placed in a secondary drum where further separation could occur over an extended period. The clean water from the secondary drum was pumped back into the test facility, while the remaining oil residue was removed and disposed along with the used absorbent cloths.

Once a sufficient thickness of oil was collected in the main vacuum drum, it was recovered and returned to the original 5 gallon pails. It was noted that the vacuuming process caused a visible change in the test oil, from translucent to a more milky/cloudy appearance, likely due to a change in the air content. Based upon analysis by the SL Ross laboratory, there was effectively no change in the measured density or viscosity of the oil, and it was concluded that the recovered oil could be re-used for subsequent tests. Many of the initial 2D tests used fresh oil, while the remainder of the 2D tests and nearly all of the 3D tests used recovered oil.

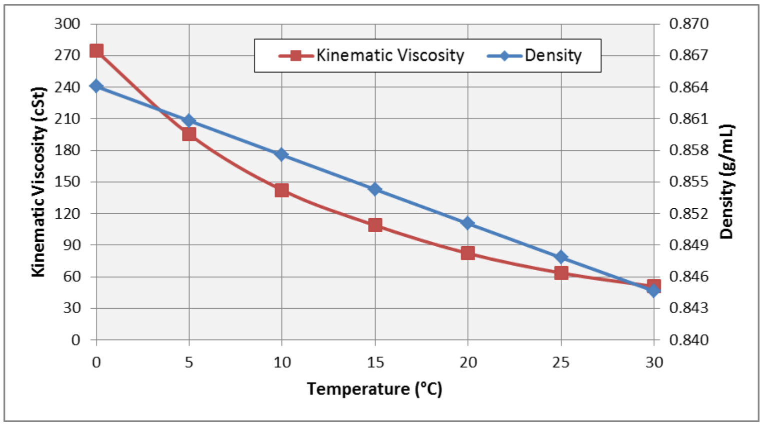


Figure 48. Measured viscosity and density of AW32 Hydraulic Oil at various temperatures.

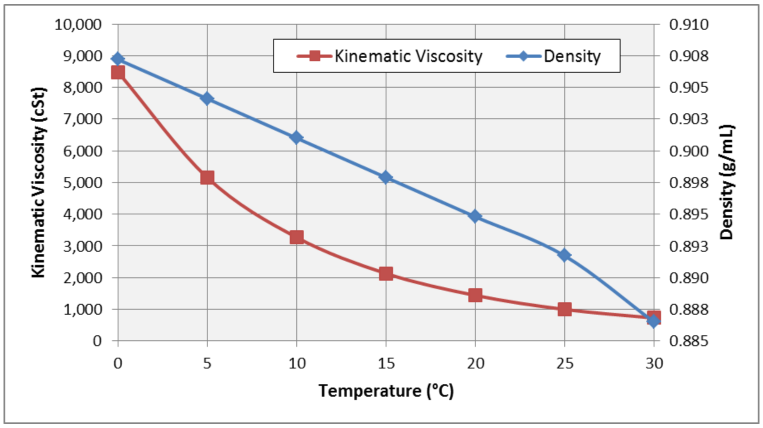


Figure 49. Measured viscosity and density of 85W-140 Gear Oil at various temperatures.

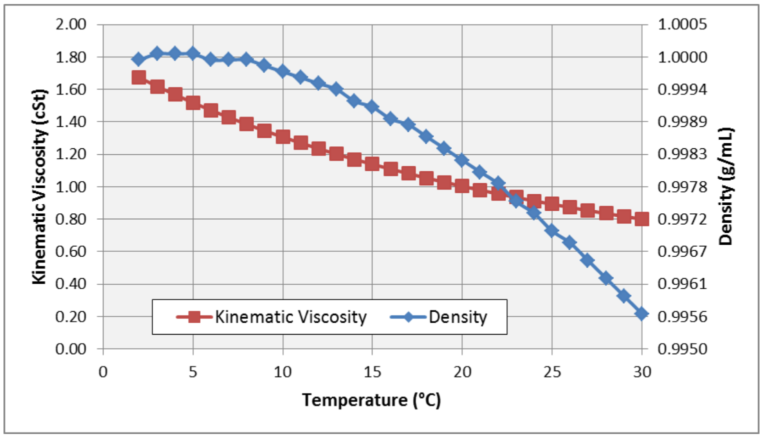


Figure 50. Measured viscosity and density of fresh water at various temperatures.

5.2. Instrumentation Systems and Data Acquisition

5.2.1. Wave Measurements and Analysis

Vertical fluctuations of the free surface (waves) were measured in the 3D physical model using a single high-precision capacitance-wire wave gauge designed by Akamina. The gauge operates by sensing the change in capacitance that occurs as a portion of the insulated wire becomes wetted. The output voltage is directly proportional to the percentage of the wire that is wetted, regardless of whether the wetting is continuous (green water) or intermittent (as in the case of splash or spray). The insulated wire is strung under tension on a bow made of slender metal tubing, and the bow is secured in a vertical orientation. The wave gauge was calibrated by changing its elevation with respect to a fixed water level. The gauge featured a highly linear response, with a calibration error less than 0.5% over a 0.15 m (model scale) calibration range. This error represents an accuracy of better than ± 0.75 mm at model scale, which is equivalent to ± 6 mm at full scale. The calibration constant remained stable throughout the wave calibration process and daily recalibration was not required. The wave gauge output was sampled at a rate of 50 Hz.

NRC-OCRE's GEDAP[1] software was used to analyze all wave conditions measured in the model using standard time-domain and frequency-domain analysis algorithms. Figure 51 shows an example (with results from test WaveCal_4) of the wave analysis plots used in this study. These plots show the measured wave trains and total wave spectra at each wave gauge as well as the wave machine feedback signal, and also list some key summary statistics computed from the measured wave record. The most pertinent derived values and statistics were also collected and summarized in a series of spreadsheets. These analysis plots and spreadsheets were transmitted to SL Ross as part of the project deliverables.

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[1] GEDAP™ software has been developed and used at NRC-OCRE for over 25 years. The current version represents the state-of-the art in wave generation and analysis software. Several leading international hydraulics laboratories, including MARIN in the Netherlands, and the U.S. Army Corps' Coastal Engineering Research Centre at Vicksburg currently use GEDAP software.

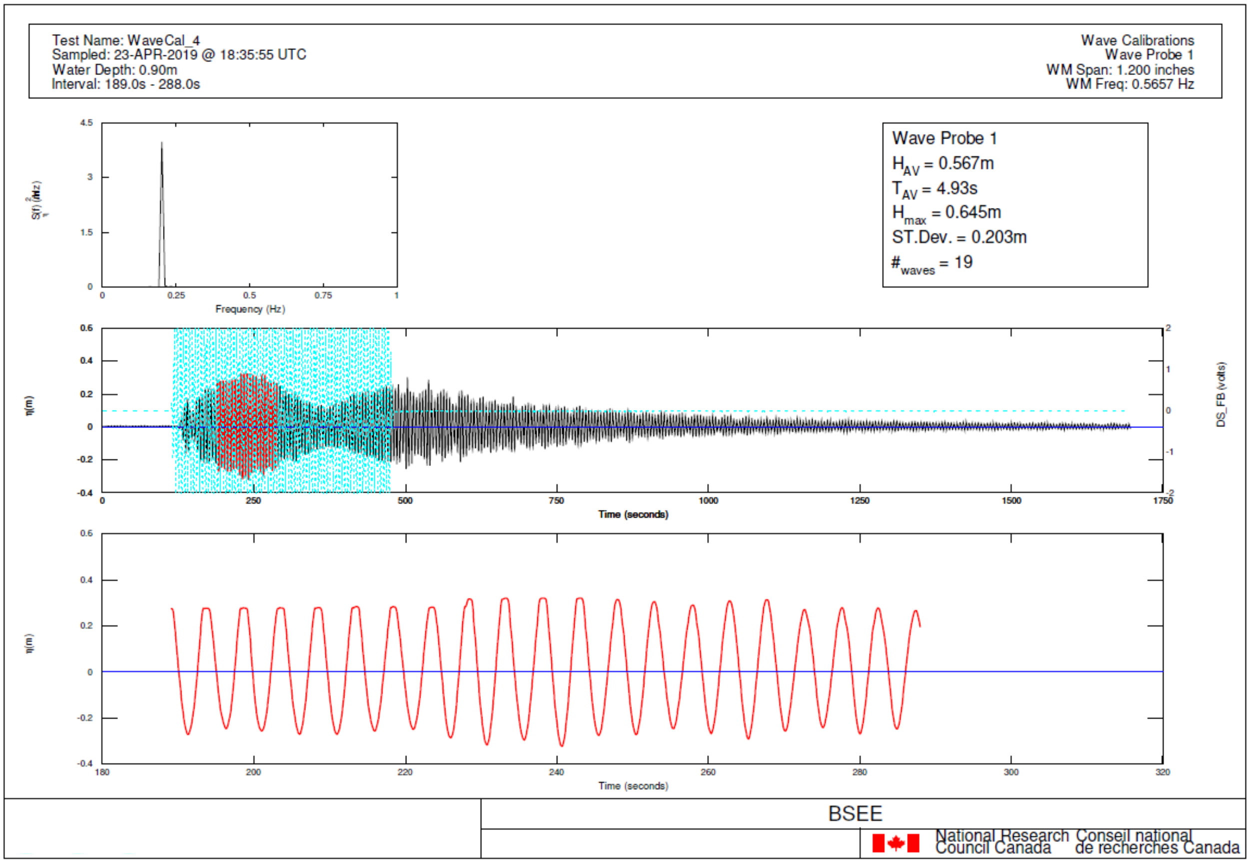


Figure 51. Example of a wave analysis plot showing data from test WaveCal_4.

5.2.2. Current Measurements and Analysis

Currents were measured in the 2D physical model experiments using two 2-axis (*u*,*v*) electromagnetic current meters (CMs), where *u* and *v* are the components parallel to the x- and y-axes. For this study, the velocities were measured in a local coordinate system with the x-axis defined as positive in the direction of flow (towards the north end of the flume), and the y-axis defined as positive towards the west wall of the flume. The vertical velocity component was not measured, but will generally be small in shallow water. In this case, the horizontal velocity vector at a point in space can be defined as: $U_h(t) = (u, v)$.

The measuring principle of the electromagnetic current meter is based on Faraday's Law of electromagnetic induction whereby a voltage is induced by an electrical conductor passing through a magnetic field. In the model, water acts as the electrical conductor when flowing past the sensor, and the induced voltage is proportional to the average flow velocity around the sensor tip. The current meters used a factory pre-calibration and the outputs were sampled at a rate of 50 Hz (model scale). The sensors were mounted to rigid support stands and positioned to measure flow speeds at approximately 5 cm (model scale) below the surface.

The velocity measurements were analyzed to resolve the speed and direction of the low-frequency (current) component of the flow at each sensor. The low-frequency part of each signal was isolated by low-pass filtering with a cut-off frequency of 1/30 Hz (full scale). The velocity magnitude or flow speed was computed as:

$$|U_h(t)| = \sqrt{u^2(t) + v^2(t)}$$

while the direction was obtained as:

$$\theta_{U_h(t)} = \tan^{-1}\left(\frac{v(t)}{u(t)}\right)$$

Figure 52 shows an example (with results from test CAL_60_1) of the velocity analysis plots used in this study. These plots show the measured high- and low-frequency currents and directions at each current meter, and also list some key summary statistics computed from the measured velocity record. The most pertinent derived values and statistics were also collected and summarized in a series of spreadsheets. These analysis plots and spreadsheets were transmitted to SL Ross as part of the project deliverables.

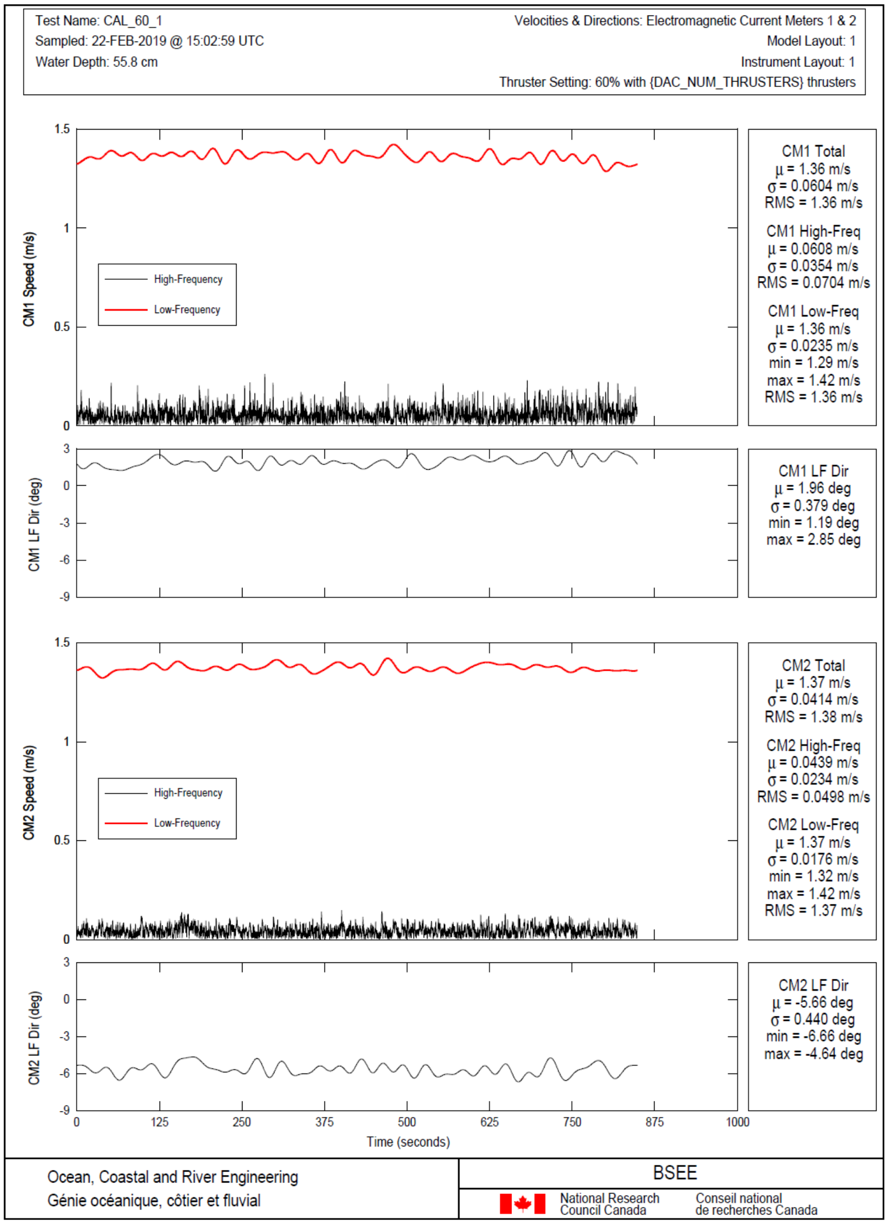


Figure 52. Example of a velocity analysis plot showing data acquired during test CAL_60_1.

5.2.3. Data Acquisition System

A data acquisition system collects signals from the various sensors deployed in the model for storage in a computer data file. An imc CRONOScompact (CRC) system was used to collect the analog voltages and convert them to a digital signal for storage on a PC using NRC-OCRE's GDAC software. The CRC houses a number of modules for different measurement types. The LV-16 was used to convert the wave gauge signals from analog to digital. LV-16 is a measurement amplifier for 16 channels of differential input with 24-bit resolution, configurable low pass filter or Anti-aliasing filter, sample rates up to 20 kHz/channel and a bandwidth of 5 kHz. The velocity signals were collected digitally from the supplier's hardware. The digital signals were processed by a special GDAC server program. The GDAC software is developed and maintained by NRC-OCRE staff and is a suite of applications used for the collection, storage, and viewing of sensor data. The GDAC software is a client/server application in which the client can acquire data from multiple servers and each server can have multiple devices connected to it. In this particular project, each test facility had its own CRC device and one digital service connected to it, and operated at a master rate of 1,000 samples/second with a 5 minute buffer. The data from each test was stored in a single binary data file and was processed with NRC-OCRE's GEDAP software suite.

5.2.4. Video and Photography

Several high-quality video cameras (both automated and manually controlled) were used to document and digitally record all tests during the 2D and 3D physical modelling studies, as detailed in Table 17 and Table 18. The automated digital video feeds were relayed to the control room and recorded directly to hard drive. The automated video cameras also had date/time stamps that were synchronized with the timing clock of the data acquisition computer so that the video images could be correlated with the test data. Videos recorded on the manually controlled cameras (including mounted GoPro cameras and a handheld Canon camera) were collected on internal storage and later transferred to hard drive. Numerous digital photographs were also captured during the study, some of which appear in this report. The entire archive of photo and video recordings has been transmitted to SL Ross as part of the project deliverables.

Table 17. List of video cameras for 2D testing.

Camera #	Field of View	Control	Comments
1	Oblique overhead of entire boom	Automatic	
2	Oblique side view at apex	Automatic	
3	Direct overhead at apex	Manual	GoPro
4	Oblique overhead (view varies)	Manual	Canon handheld
5	Underwater view at apex	Automatic	Not available for all tests

Table 18. List of video cameras for 3D testing.

Camera #	Field of View	Control	Comments
1	Overview of Ice Tank (from North wall)	Automatic	
2	Overview of Ice Tank (from South wall)	Automatic	
3	Direct overhead at boom apex	Automatic	
4	Oblique overhead at boom apex	Automatic	
5	Low-angle oblique from behind boom apex	Manual	GoPro
6	Direct overhead at boom apex (view varies)	Manual	Canon handheld
7	Low-angle oblique side view of entire boom	Manual	GoPro (not available for all tests)

5.3. 2D Physical Modelling Experiments

5.3.1. 2D Test Facility and Model Setup

The 2D portion of the physical modelling study was conducted in NRC-OCRE’s Large Wave & Current Flume (LWCF). The LWCF is 97 m long, 2 m wide, and up to 2.75 m deep (318 ft x 6.5 ft x 9 ft). The LWCF is located indoors, can be rapidly filled and drained, and is serviced by an overhead gantry crane. The facility is equipped with a powerful computer-controlled wave generator with active wave absorption capability that can generate irregular waves with wave heights up to 0.75 m and wave periods from 1.5 to 4 s (note that the wave generation capabilities of this facility were not used for this study). The LWCF is also equipped with a current generation system comprised of 12 electrically-powered variable-speed thrusters installed in a tunnel below the flume sub-floor. When activated, the thrusters generate a steady circulation within the tunnel and in the open space above the sub-floor, and the current speed is regulated by adjusting the rpm of the thrusters. The current can be generated with or without waves, and the direction of the current can also be reversed. Key components of the current generation system are pictured in Figure 53. For these tests, the LWCF was also equipped with flow training walls at the inlet and outlet from the tunnels as well as a flow straightener at the upstream end of the flume. These served to maximize the flow speed and reduce rotational eddies thereby producing a more uni-directional flow throughout the testing section. The flow training walls and flow straightener are shown in Figure 54.

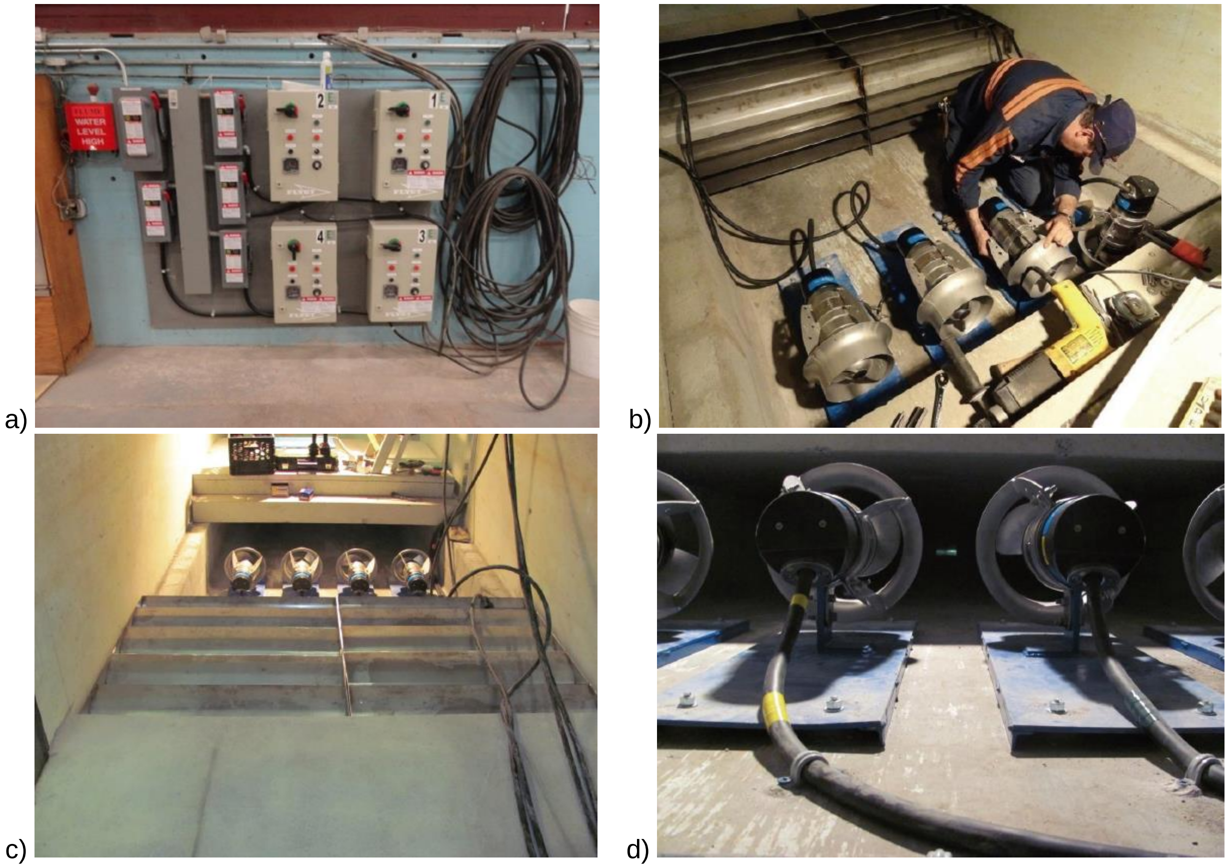


Figure 53. Key components of the current generation system.
a) one of the control panels for adjusting thruster speed;
b) and c) thruster banks and guide vanes being installed in the LWCF;
d) profile view of the thruster tunnel beneath the sub-floor.

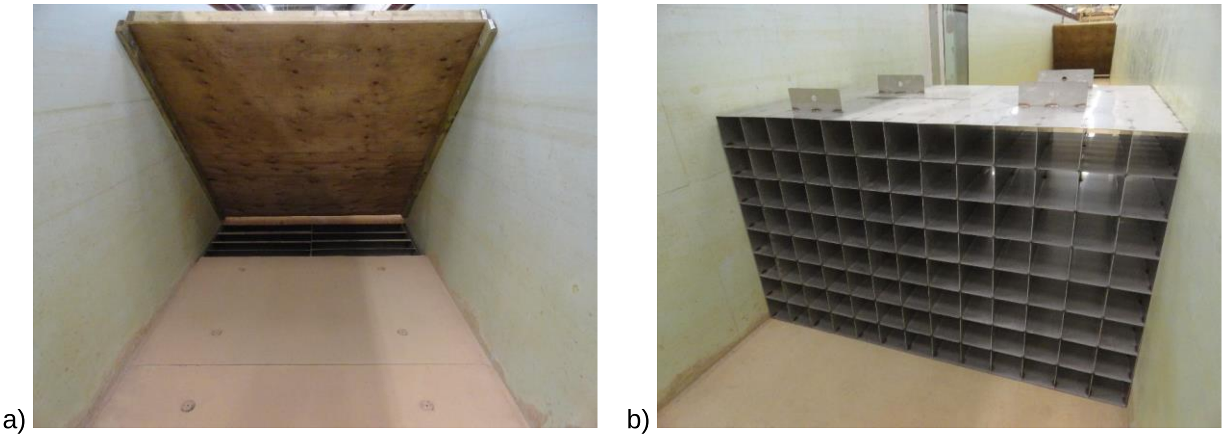

a) b)

Figure 54. Flow training wall (a) and flow straightener upstream of the test section (b).

In these 2D experiments, faithful scale models of several boom designs were fixed (one at a time) to the sides of the flume at the test site, and the thrusters were used to generate a steady current (at various velocities) in the flume. A series of slotted steel angle strips were carefully leveled and mounted to each side of the flume along the test site. These slotted strips provided flexibility to install the various boom components at any desired location and elevation. A measured volume of test oil was added to the flow upstream from the boom that was carried down the flume towards the boom. The interaction of the oil with the boom and the ability of the boom to retain the oil was monitored visually and using video cameras positioned above and beside the boom (looking through large viewing windows located at the test site).

The overall setup of the LWCF is shown in Figure 55. Prior to installing the model booms, a simple bathymetry was constructed using concrete slabs placed on top of concrete blocks (see Figure 55b). The bathymetry included two sloping ramps (one upstream and one downstream) and a 33.6 m long (full scale) flat section where the models were installed. This simple bathymetry produced a shallow water depth of 4.464 m and a deep water depth of 7.544 m. The bathymetry served to locally increase the effective flow speeds that could be generated by the thrusters, while also providing an area of reduced flow speeds in behind the boom for secondary containment of any oil that bypassed the boom itself. The downstream flow training wall was slightly submerged which created a stilling basin on its lee side to further contain any floating oil which bypassed the secondary containment booms.

Test oil was delivered several metres (model scale) upstream of the bathymetry (see Figure 56). The oil was poured at a steady rate from 5 gallon pails onto an inclined ramp whose bottom edge was positioned a few millimetres above the water surface. This minimized any downward velocity of the oil, and allowed ample time for the oil to resurface and naturally spread out to the edges of the flume. Several views of the 2D testing in the LWCF are pictured in Figure 57.

Oil clean-up operations between tests used a vacuum system as described in §5.1.1. After each test, the thruster setting was reduced to a point where the flows kept the test oil trapped against the main boom, but slow enough not to force entrainment and also safe for access by the technicians (see Figure 58).

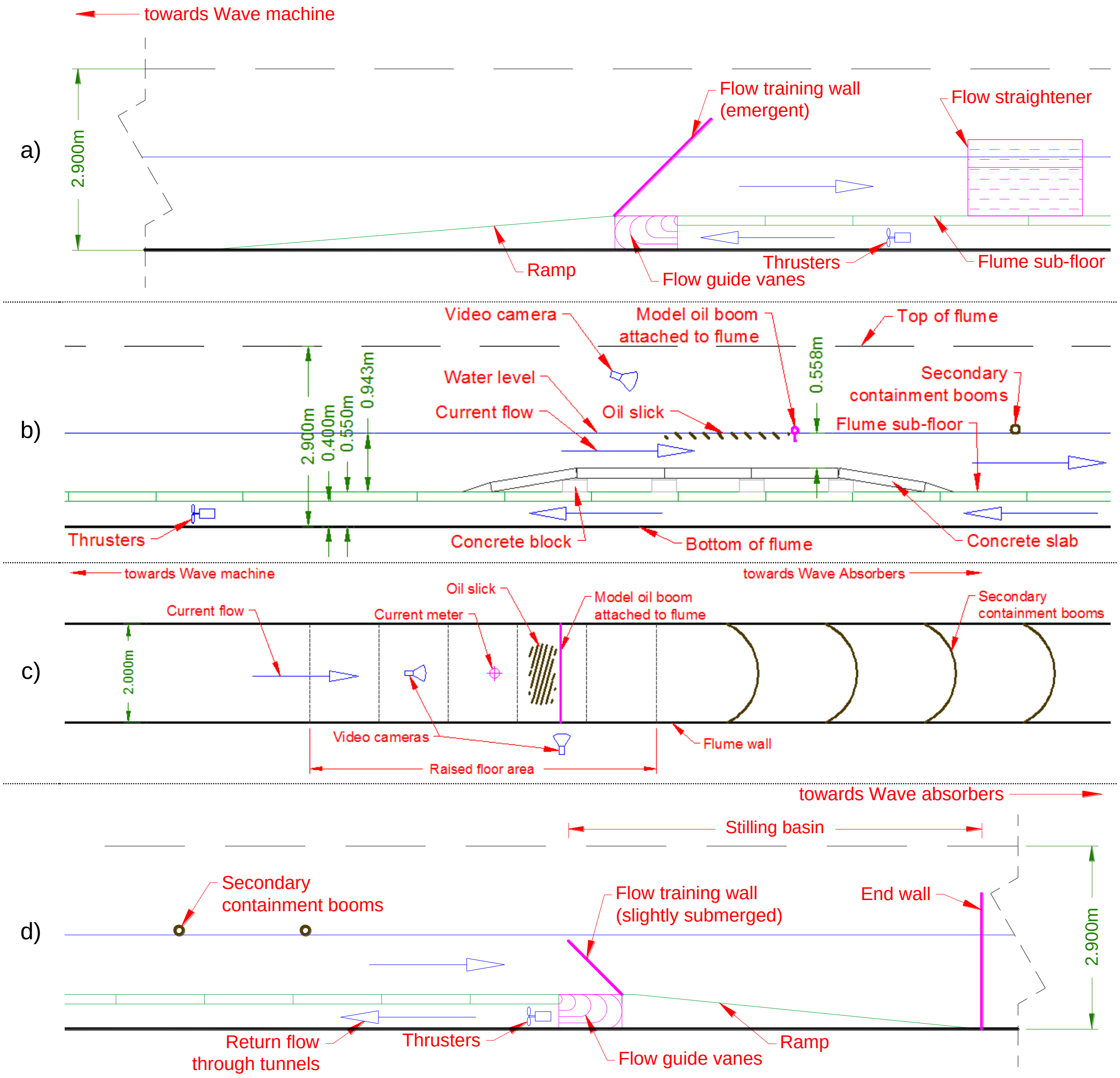


Figure 55. Layout for 2D scale model testing in the LWCF.
a) profile view of south end of flume;
b) profile view of central part of flume with oil boom and viewing windows;
c) plan view of central part of flume;
d) profile view of north end of flume.

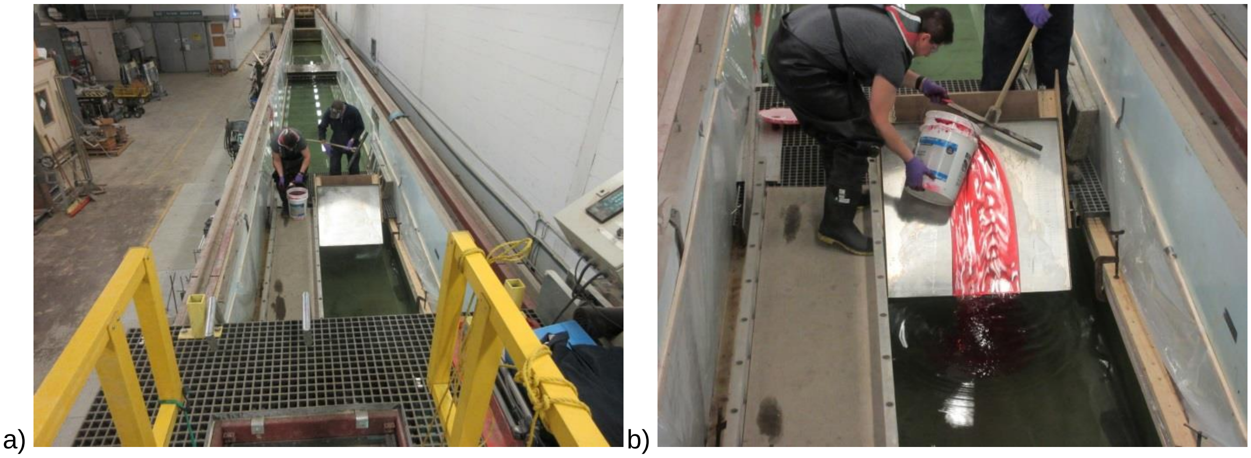


Figure 56. Delivery of test oil upstream of the test section.

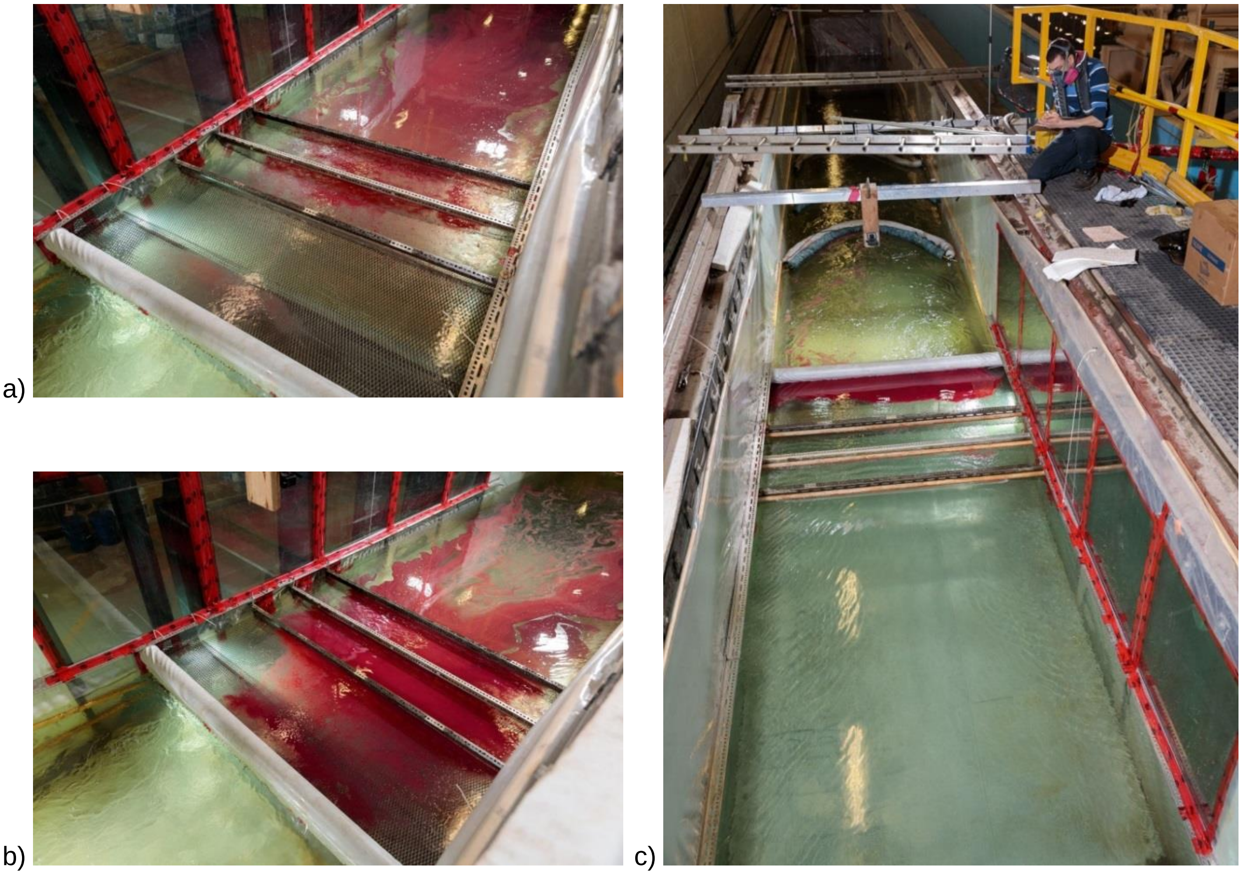


Figure 57. Views of the LWCF during 2D physical model testing.
a) Oil encountering the first upstream skirt of the oil boom model (view looking upstream);
b) The same view a short time later;
c) Oil captured by the downstream model boom after several minutes (view looking downstream).

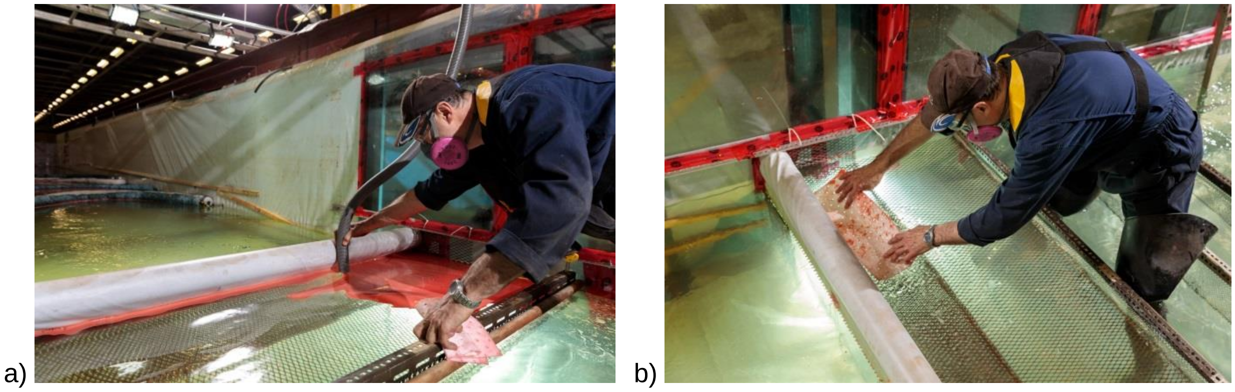

a) b)

Figure 58. Oil clean-up operations between tests in the LWCF.

5.3.2. 2D Flow Calibrations

With the simple bathymetry in place and with the scale model of the conventional boom installed, but prior to any tests with oil, flow calibrations were performed to determine a rating curve describing the relationship between thruster setting and the resulting current at the test site. A five minute ramping period (model scale) was given each time the thruster settings were changed to allow the currents to stabilize. Currents were measured at two locations, side by side, 10.7 m upstream of the boom centerline (approximately three times the clearance depth below the boom), at a depth of ~0.4 m below the surface (see Figure 59). The currents were sampled over a period of five minutes (model scale) and the mean current speed remained quite stable throughout (see Figure 52). Subsequent analysis of the data from the two current meters revealed that the standard deviation from CM1 was twice as high as CM2, and that the data appeared to be less reliable. Therefore, the decision was made to use the data from CM2 only.

Table 19 presents a summary of the velocities recorded at CM2 during the flow calibration tests. The rating curves developed from this data are plotted in Figure 60. The thruster settings required to generate the various current speeds used for testing the oil booms were derived from these rating curves. The relationship between thruster setting and mean current velocity was quite linear across the full range. Eight thrusters were used to generate relatively slow currents (less than ~1.2 knots), while ten thrusters were used to generate faster currents (up to a maximum of ~4.2 knots). At high flow speeds, there was a noted difference in water elevation on the upstream and downstream sides of the boom (see Figure 59b).

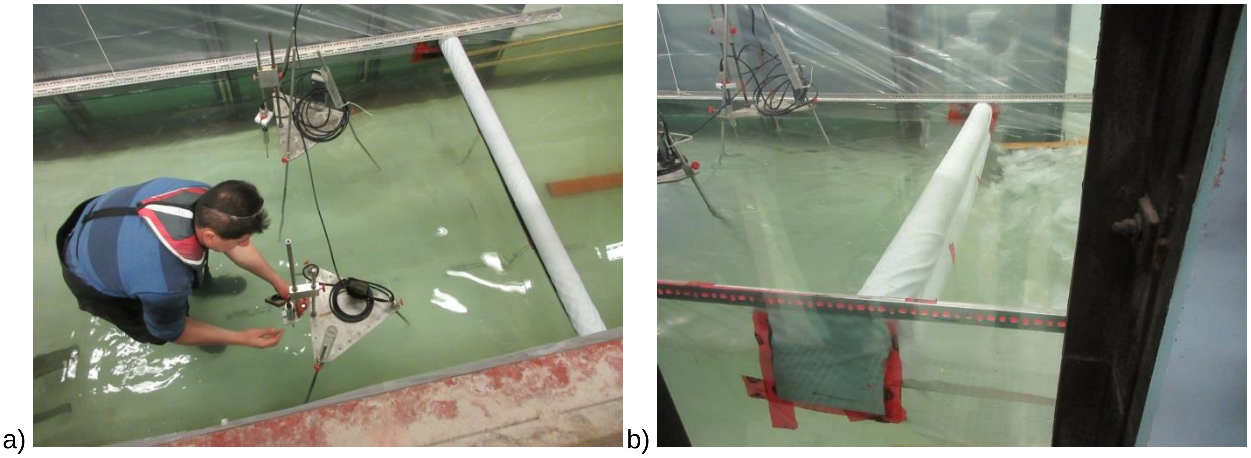

a) b)

Figure 59. Flow calibrations in the LWCF.

Table 19. Summary of velocity measurements during flow calibrations.

Test Name	# of Thrusters	Thruster Setting	Mean Speed (m/s)	Max Speed (m/s)	Standard Deviation (m/s)	Mean Speed (knots)
CAL_25_1	10	25%	0.60	0.67	0.022	1.16
CAL_40_1	10	40%	0.94	1.03	0.027	1.84
CAL_60_1	10	60%	1.37	1.53	0.041	2.67
CAL_80_1	10	80%	1.87	2.13	0.065	3.64
CAL_100_1	10	100%	2.36	2.59	0.076	4.58
CAL8_20_1	8	20%	0.43	0.50	0.017	0.84
CAL8_22_1	8	22.5%	0.50	0.55	0.015	0.97
CAL8_25_2	8	25%	0.55	0.60	0.017	1.06
CAL8_30_1	8	30%	0.67	0.74	0.021	1.30

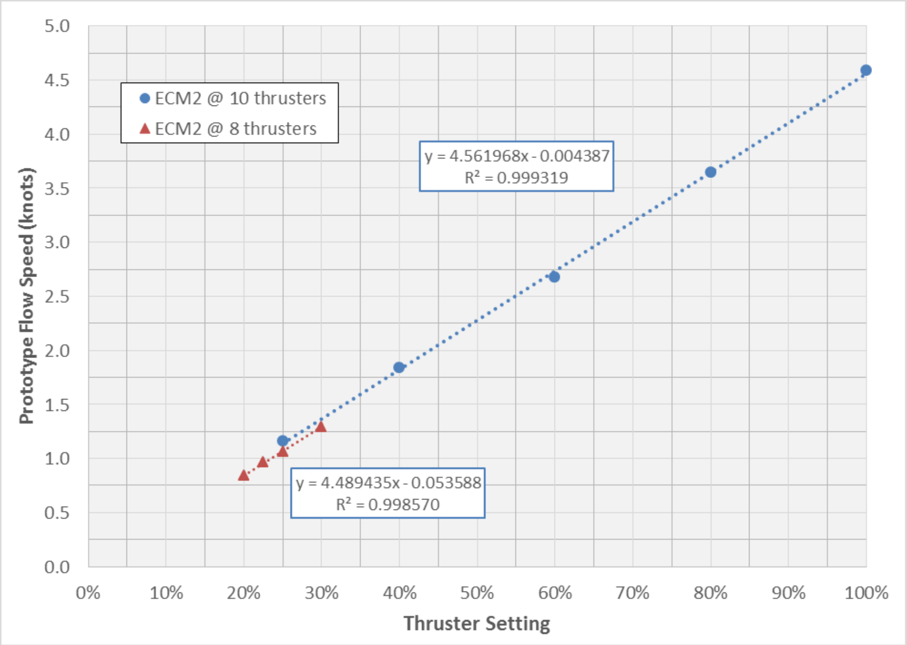


Figure 60. Rating curves with eight and ten thrusters in operation.

5.3.3. 2D Oil Boom Model Fabrication

The first boom model investigated was a conventional boom based on the Ro-Boom 2200. Figure 2 shows the schematic of the nominal prototype design, while Figure 61a shows the schematic of the 2D scale model reproduction. The model boom was fabricated using a 4-inch PVC pipe that was capped at both ends and spanned the full width of the flume. The boom was rigidly secured beneath the slotted steel angle (affixed to the sides of the flume) and the water level was set according to the target draft depth of 0.95 m (in still water). The boom was wrapped with a vinyl sheet to create a skirt that extended down from the centreline of the boom. The base of the skirt included a small fold through which a rigid ¼-inch steel rod was inserted to act as a tensioning chain. The steel rod alone did not provide enough tension to prevent planing of the skirt at higher flow speeds; therefore a set of thin wires with turnbuckles were installed to provide the necessary tension and maintain a near vertical skirt at any flow speed (see Figure 62a). The vinyl skirt was purposely extended beyond the span of the flume, allowing the excess material to be secured to the sides of the flume and prevent any loss of oil from around the sides of the boom (see Figure 62b). This ‘base case’ conventional boom configuration remained in place as the primary boom for all subsequent investigations involving the Screen-boom and Ramped-boom systems.

Figure 61b and c show the two upstream horizontal floor modifications that were investigated as variants of the base case conventional boom. A strip of sheet metal was folded to build the initial 1.52 m long horizontal floor, which was later extended to form a 3.84 m long floor (corresponding to 2D CFD investigations). Figure 63 shows the installation of the first variant.

Figure 61. 2D model scale reproduction of the conventional boom and variants.
a) base model; b) modification #1; c) modification #2.

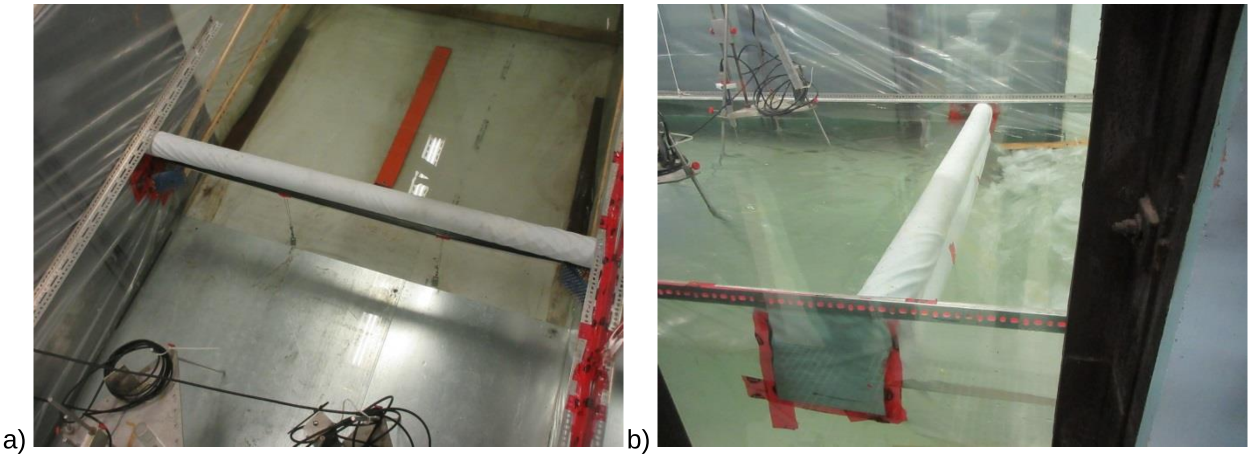


Figure 62. 2D scale model of the conventional boom.

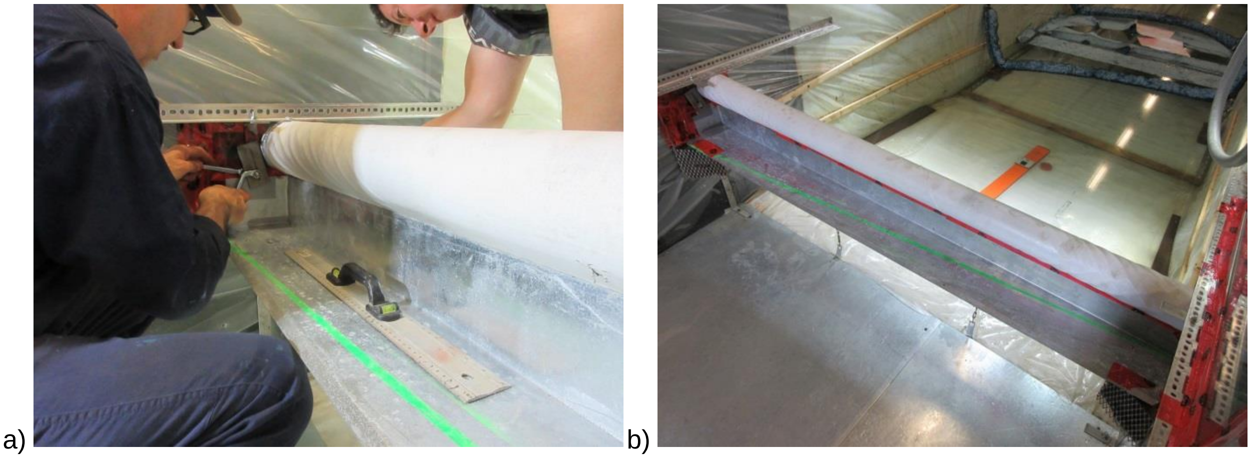


Figure 63. Installation of the upstream horizontal floor (variant of the conventional boom).

The second boom model investigated was a Screen-boom system based on the DESMI Speed-Sweep 2200. Figure 4 shows the schematic of the nominal prototype design, while Figure 64a shows the schematic of the 2D scale model reproduction. Three upstream booms were fabricated by attaching a plastic mesh material (with a porosity of 67%) to a wooden rod that spanned the width of the flume. Similar to the main boom, the wooden rods were rigidly mounted below the slotted steel angle. The draft of the vertical mesh skirts was set to the same depth as the main boom (0.95 m). A 1/8-inch rod was woven through the base of the mesh to provide tension and restrict planing of the upstream skirts. A thin sheet of steel mesh (with a porosity of 62%) was affixed to the bottom edge of the main boom skirt facing horizontally upstream. Two thin rods were installed to prevent sagging of the leading edge of the horizontal skirt (not shown in schematics). The base case for the Screen-boom model is shown in Figure 65a.

Figure 64b, c, and d show the three modifications that were investigated as variants of the base case Screen-boom. For the first modification (see Figure 64b), an additional steel mesh sheet was installed directly atop the existing horizontal skirt creating a double layer. The hole pattern of the doubled mesh sheets was offset to create the maximum possible blockage effect, resulting in a porosity of 38%. For the second modification (see Figure 64c), an additional steel mesh sheet was installed approximately 0.20 m above the lower horizontal skirt (with doubled bottom layer). This new upper layer had a porosity of 62%

and was extended upstream and affixed to the third vertical skirt, as shown in Figure 65b. For the third modification (see Figure 64d), an additional steel mesh sheet (with a porosity of 62%) was installed approximately 0.20 m above the previously added second layer, extending half-way to the third vertical skirt. In each case, these modifications were made based upon the observations of the researchers, in particular on the observed behaviour of the oil droplets and their interaction with the boom components, and discussions as to how to improve performance.

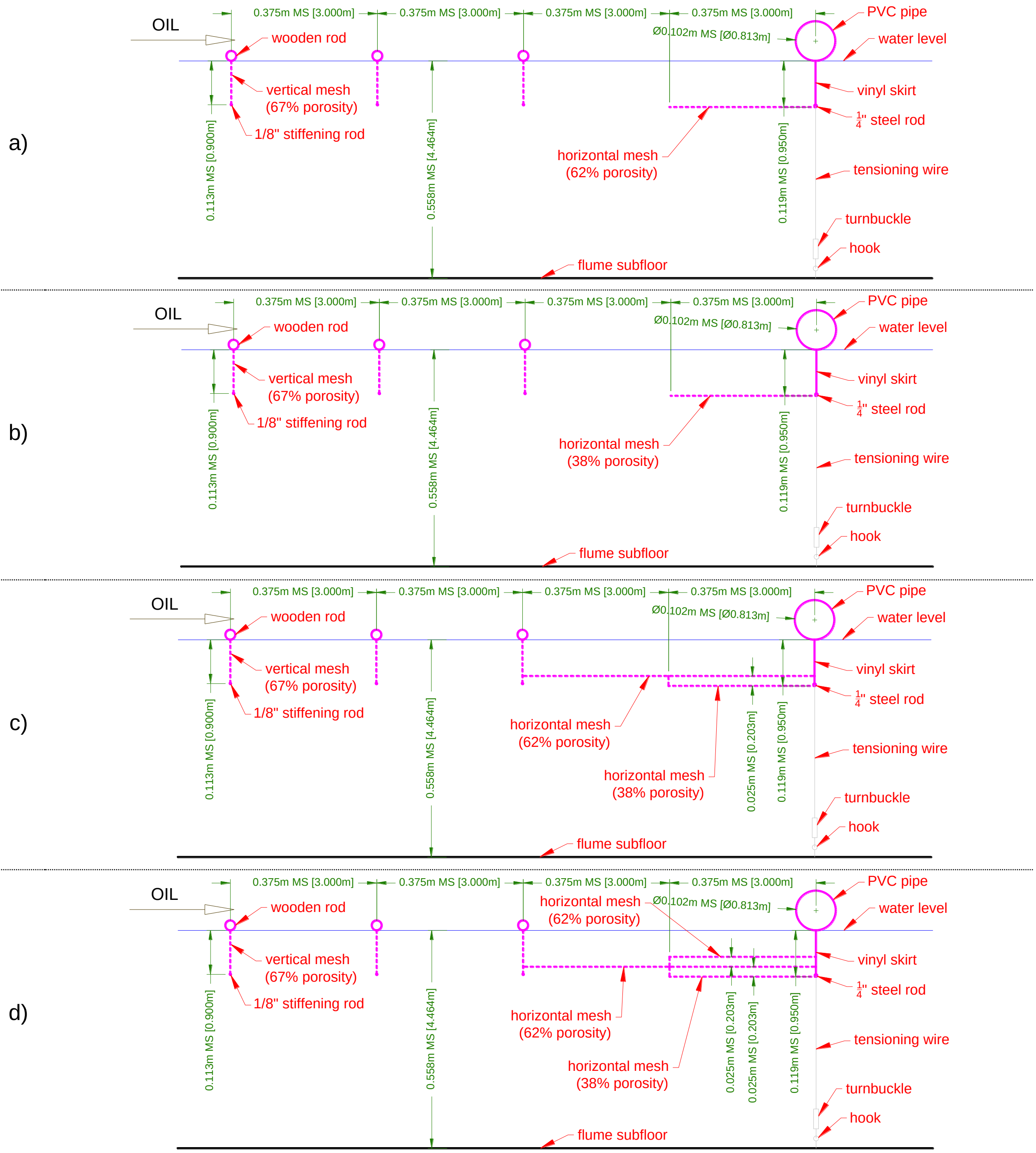


Figure 64. 2D model scale reproduction of the Screen-boom and variants.
a) base model; b) modification #1; c) modification #2; d) modification #3.

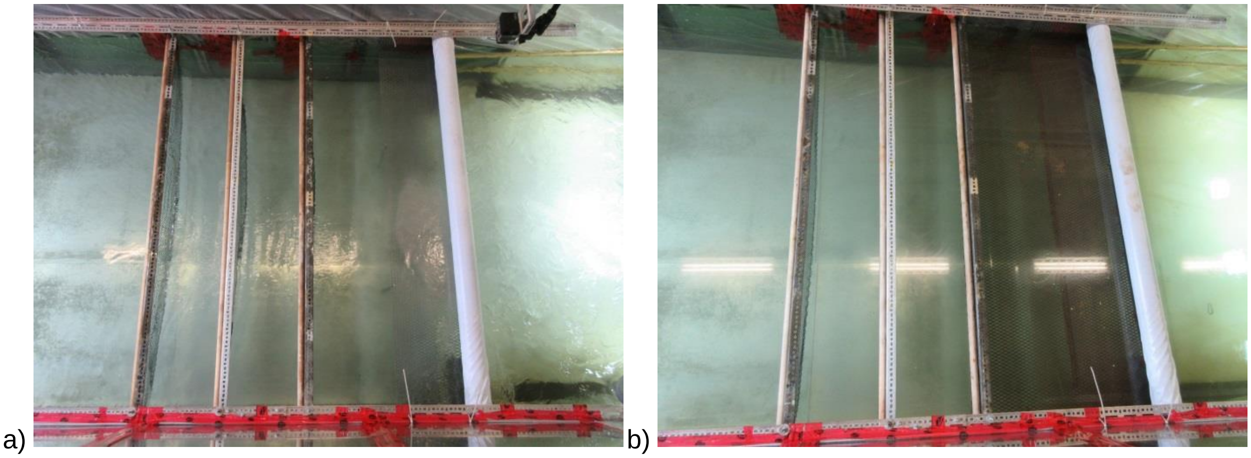


Figure 65. 2D scale model of the Screen-boom system (a) and one of the variants (b).

The third boom model investigated was the Ramped-boom system. Figure 6 shows the schematic of the nominal prototype design, while Figure 66a shows the schematic of the 2D scale model reproduction. The ramp itself was fabricated using a transparent plexiglass sheet, rigidly mounted below the slotted steel angle to create a 15° downward angle. The upstream portion of the ramp extended slightly above the waterline to prevent oil and water from passing over the top of the ramp. The downstream edge of the ramp was set to a draft of 0.61 m, approximately 2/3rds the depth of the main boom skirt. Tape was used at the edges of the flume to prevent any loss of oil from around the sides of the ramp and force all flow to pass beneath. The two inner booms were fabricated by wrapping a vinyl sheet around a wooden rod to create a skirt that extended down from the centreline of the boom. Similar to the main boom, the wooden rods were rigidly mounted below the slotted steel angle. The draft of the inner vertical skirts was also set to 0.61 m. Like the main boom, the base of the skirt included a small fold through which a rigid ¼-inch steel rod was inserted to act as a tensioning chain. The steel rods alone did not provide enough tension to prevent planing of the skirts at higher flow speeds; therefore a set of thin wires with turnbuckles were installed to provide the necessary tension and maintain nearly vertical skirts at any flow speed. As before, the vinyl skirts were also purposely extended beyond the span of the flume, allowing the excess material to be secured to the sides of the flume and prevent any loss of oil from around the sides of the inner booms. The base case for the Ramped-boom model is shown in Figure 67.

Figure 66b and c show the two modifications that were investigated as variants of the base case Ramped-boom. For the first modification (see Figure 66b), the ramp was relocated further upstream, creating a larger gap between the ramp and the first inner boom. For the second modification (see Figure 66c), the ramp was relocated back to its original position, while a series of horizontal steel mesh sheets were installed at the base of the main boom skirt. The bottom featured a doubled layer of sheets with a porosity of 38%, while an upper layer (with a porosity of 62%) was installed approximately 0.20 m above. These horizontal sheets extended approximately 2/3rds of the distance upstream to the second inner boom.

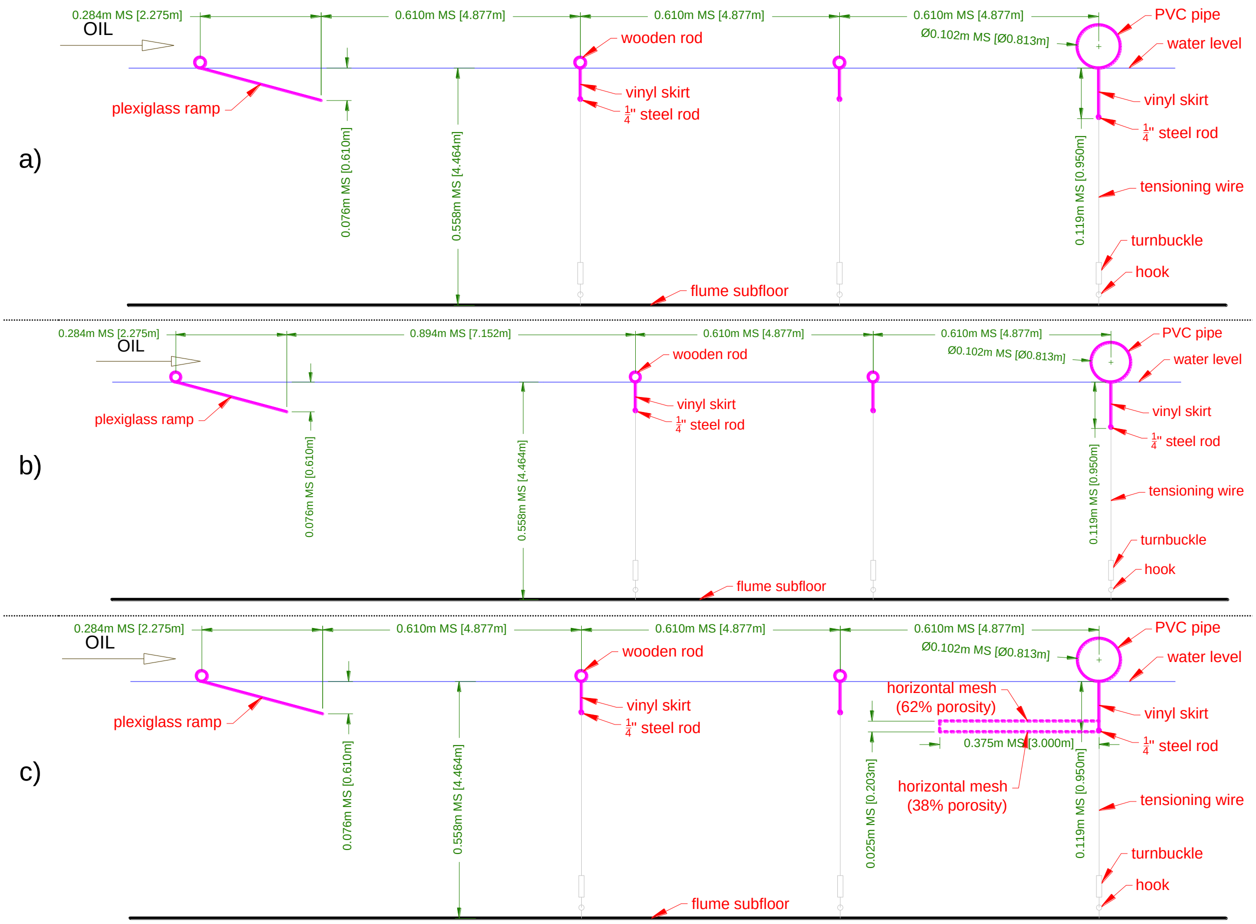


Figure 66. 2D model scale reproduction of the Ramped-boom system and variants.
a) base model; b) modification #1; c) modification #2.

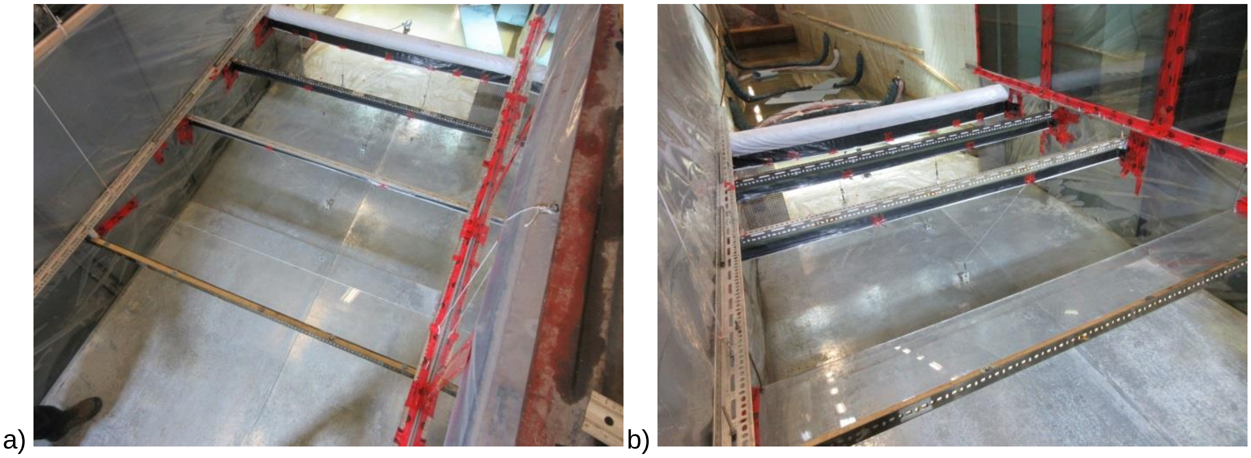


Figure 67. 2D scale model of the Ramped-boom system.

5.3.4. 2D Model Testing

Following the flow calibration phase, several trial tests were performed with small amounts of oil and at relatively slow flow speeds (~0.9 knots) to observe the behaviour of the oil as it interacted with the boom and to determine the ideal setup of the downstream secondary containment booms, video cameras, and overhead lighting. During these trials, it was observed that small vortices were forming at the edges of the boom model (where it met the viewing windows on either side of the flume). Oil collected near the centre of the boom was retained, however oil droplets near the sides were, on occasion, caught into these edge vortices and carried under the skirt. After discussion with SL Ross, it was agreed that these edge vortices were an unrealistic boundary effect which would not occur in a true three-dimensional situation involving a U-shaped boom. In an effort to slightly reduce the flow speeds and resulting vortices along the walls of the flume (and therefore encourage oil entrainment to occur closer to the middle of the flume), a set of flow baffles were installed at each edge of the model which remained in place for the entire testing program. The initial set of flow baffles were small triangular wedges of perforated sheet metal that extended a short distance below the bottom of the skirt (see Figure 62a and Figure 63b). These initial flow baffles were successful at reducing the size and frequency of vortex formation adjacent to the windows at lower flow speeds; however increased vortex formation and some entrainment of oil below the bottom of the baffles was observed as flow speeds increased. The second set of flow baffles consisted of perforated metal sheets that extended further towards the middle of the flume (wider) and extended all the way to the base of the flume (deeper), as seen in Figure 67. The second set of baffles were fabricated and installed following Test_13, and were successful at reducing the size and frequency of edge vortex formation throughout the remainder of the testing program.

As previously mentioned, faithful 2D scale models of several boom designs were fixed (one at a time) to the sides of the flume at the test site, and the thrusters were used to generate a steady current (at various velocities) in the flume. A measured volume of test oil was added to the flow upstream from the boom that was carried down the flume towards the boom. The interaction of the oil with the boom and the ability of the boom to retain the oil was monitored visually and using video cameras positioned above and beside the boom (looking through large viewing windows located at the test site).

While the CFD modelling could provide a precise quantitative value for the percentage of oil contained by the boom after any given time-step, this was effectively impossible in the physical model, and therefore the results described here below are more subjective and qualitative. Each and every physical model test (both 2D and 3D) was observed by the same researcher, who, as much as possible, has attempted to provide an impartial and consistent observation from one test to the next. Initially, the 2D test results were given as a best estimate of the percentage of oil containment (akin to the CFD results), however this proved very difficult to judge, particularly when the amount of oil loss increased. Upon further consideration, it was decided that the physical modelling results would be reported as a percent rating similar to a test score. While this rating was still analogous to the percent of oil containment, it was not meant to be a direct comparison. In terms of the test scoring, high expectations were set in order to develop booms that minimized the loss of oil. A rating of 100% indicates a ‘perfect’ result, in that absolutely no loss of oil was observed throughout the duration of the test. A rating in the high 90’s generally indicates a ‘near perfect’ result, where only minute quantities of oil were lost during course of the test. Ratings in the mid-90’s generally indicate good performance but with a greater loss of oil over the same duration. Ratings in the low-90’s are considered adequate, but on the verge of failure, and could be considered analogous to the definition of first loss (see §1.2). Ratings lower than 90% are considered a failure with an unacceptable level of oil lost over the test duration, and could be considered analogous to the definition of gross loss (see §1.2).

It is noted that the 2D tests were observed over a minimum period of 5 minutes (model scale), equivalent to a little more than 14 minutes at full scale. The observation period was longer in some cases (particularly for the Screen-boom at low flow speeds since it took longer for the oil to make its way through the vertical screens).

Table 20 provides a summary of the 2D physical modelling test results, while Figure 68, Figure 69, and Figure 70 show typical views of oil containment at the end of each test for the various boom models. Tests 1 through 16 involved the conventional boom and variants. At relatively low flow speeds (≤1.2 knots), the base case conventional boom model demonstrated nearly 100% containment of light oil over the test duration. Periodic vortex formation at the face of the boom caused individual globules to entrain and bypass the skirt. As flow speeds increased to ~1.6 knots, the headwave became shorter and thicker, and entrainment of individual globules started to increase, though the boom still captured the vast majority of the oil. Of any escaped oil, most of it resurfaced immediately downstream and remained trapped in the wake of the boom. Continuous entrainment of individual globules of light oil was observed at ~1.8 knots. Tests with medium oil with the base case conventional boom model showed marginally improved results versus the same flow speeds with light oil. It is noted that the headwave region for medium oil was considerably shorter and thicker, and individual oil globules that did bypass the skirt were considerably larger than for the case of light oil.

For Test 9 (with a short upstream horizontal floor), large globules of oil were entrained by strong sporadic vortices, and a large portion of the bypassed oil was observed to be carried away further downstream (rather than trapped immediately in the wake of the boom). This modification was clearly a reduction in performance compared with the base case conventional boom. Additional tests with a longer upstream horizontal floor showed an improvement over the shorter floor variant, but ultimately no notable improvement compared with the base case conventional boom performance.

It is noted the boom configuration and conditions in Tests 14 and 15 were identical and demonstrated that the 2D physical model testing results were highly repeatable, thereby providing confidence in the 2D modelling setup and subsequent judgement of the boom performance.

Tests 17 through 37 involved the Screen-boom system and variants. At relatively low flow speeds (≤1.4 knots), it was noted that the upstream screens provided a considerable reduction in the surface flow speeds, and it took several minutes for all the oil to collect immediately upstream of the main boom. The base case Screen-boom model demonstrated nearly 100% containment of light oil over the test duration. Periodic vortex formation at the face of the boom was observed, however these vortices were sometimes prevented from fully developing by the horizontal screen, which helped reduce entrainment of individual globules. As flow speeds increased to ~1.8 knots, the headwave became shorter and thicker, and entrainment of individual globules started to increase, though the boom still captured the vast majority of the oil. Of any escaped oil, some of it resurfaced immediately downstream and remained trapped in the wake of the boom, though some also bypassed the wake zone and continued downstream. Continuous entrainment of individual globules of light oil was observed at ~2.4 knots. Similar results were observed at the same flow speeds with medium oil.

Comparing Tests 22 and 27 (which had triple the volume of oil), it was noted that the headwave was considerably longer and thicker, and the entrainment of individual oil globules was more continuous, suggesting that the greater volume of oil had a somewhat negative impact on the boom performance.

Tests with variations to the horizontal screens showed a minor improvement over the base case, where continuous entrainment of individual globules of light oil was observed at ~2.8 knots. It was noted that, in most cases, there was a notable amount oil entrainment that occurred upon the initial build-up of the headwave region, but often this rate of loss decreased or nearly stopped altogether a short while later.

Tests 38 through 48 involved the Ramped-boom system and variants. Even at relatively high flow speeds (≤2.6 knots), the base case Ramped-boom model demonstrated nearly 100% containment of light oil over the test duration. The vast majority of oil passing under the ramp quickly resurfaced into the area behind the ramp and before the first inner boom, and was subsequently conveyed upstream into the 'dead zone' above the ramp where it effectively remained trapped. Trace amounts of oil were carried downstream from the bottom edge of the ramp, some resurfacing in between the first and second inner booms, some between the second inner and main boom, and some again on the downstream side of the main boom. As flow speeds increased, it was observed that increasing amounts of oil bypassed the main containment zone. Much of this oil was still trapped by the second inner and main booms, though increasing amounts were also lost downstream. Nearly all of the observed oil loss occurs upon the initial encounter with the oil slick (oil that resurfaces within the boom footprint generally remains contained). Similar results were observed at the same flow speeds with medium oil. The Ramped-boom demonstrated adequate performance even up to ~3.4 knots flow speed, which was approaching the practical limit of flow speeds that could be tested in the flume.

Comparing Tests 41 and 42 (which had triple the volume of oil), it was noted that there was a negligible difference in the performance of the boom, suggesting the Ramped-boom likely has a larger oil containment capacity compared with the conventional boom or Screen-boom models.

A slight reduction in performance was observed when the ramp was relocated further upstream, as the zone between the ramp and the first inner boom became increasingly turbulent. A slight improvement in performance was observed upon adding a horizontal screen to the main boom.

Table 20. 2D physical modelling test results.

Test #	Boom Design	Flow Speed (knots)	Oil Type	Volume of spilled oil (L/m of the boom width)	% Rating
1	Conventional boom	0.98	Light	9.5	100
2	Conventional boom	1.20	Light	9.5	100
3	Conventional boom	1.41	Light	9.5	98
4	Conventional boom	1.59	Light	9.5	95
5	Conventional boom	1.82	Light	9.5	85
6	Conventional boom	1.59	Medium	9.5	99
7	Conventional boom	1.82	Medium	9.5	92
8	Conventional boom	2.00	Medium	9.5	55
9	CB Modification #1	1.82	Medium	9.5	85
10	CB Modification #2	1.59	Medium	9.5	97
11	CB Modification #2	1.82	Medium	9.5	60
12	CB Modification #2	1.41	Light	9.5	80
13	CB Modification #2	1.41	Light	9.5	93
14	CB Modification #2	1.41	Light	9.5	98
15▲	CB Modification #2	1.41	Light	9.5	98
16	CB Modification #2	1.59	Light	9.5	90
17	Screen-boom	1.20	Light	9.5	100
18	Screen-boom	1.41	Light	9.5	100
19	Screen-boom	1.59	Light	9.5	99
20	Screen-boom	1.82	Light	9.5	95
21	Screen-boom	2.00	Light	9.5	93
22	Screen-boom	2.19	Light	9.5	91
23	Screen-boom	2.41	Light	9.5	85
24	Screen-boom	2.60	Light	9.5	75
25	Screen-boom	2.19	Medium	10.0	95
26	Screen-boom	2.41	Medium	10.0	85
27	Screen-boom	2.19	Light	28.4	90
28	SB Modification #1	2.19	Light	9.5	98
29	SB Modification #1	2.41	Light	9.5	95
30	SB Modification #1	2.60	Light	9.5	90
31	SB Modification #1	2.60	Medium	9.5	75
32	SB Modification #2	2.19	Light	9.5	100
33	SB Modification #2	2.41	Light	9.5	99
34	SB Modification #2	2.60	Light	9.5	92
35	SB Modification #2	2.78	Light	9.5	85
36	SB Modification #2	2.60	Medium	9.5	70
37	SB Modification #3	2.78	Light	9.5	90
38	Ramped-boom	1.59	Light	9.5	100
39	Ramped-boom	2.19	Light	9.5	100
40	Ramped-boom	2.60	Light	9.5	99
41	Ramped-boom	3.01	Light	9.5	95
42	Ramped-boom	3.01	Light	28.4	95
43	Ramped-boom	3.01	Medium	9.5	95
44	Ramped-boom	3.19	Light	9.5	95
45	Ramped-boom	3.42	Light	28.4	95
46	RB Modification #1	3.19	Light	9.5	93
47	RB Modification #2	3.19	Light	9.5	97
48	RB Modification #2	3.19	Medium	10.0	92

▲ Repeatability test

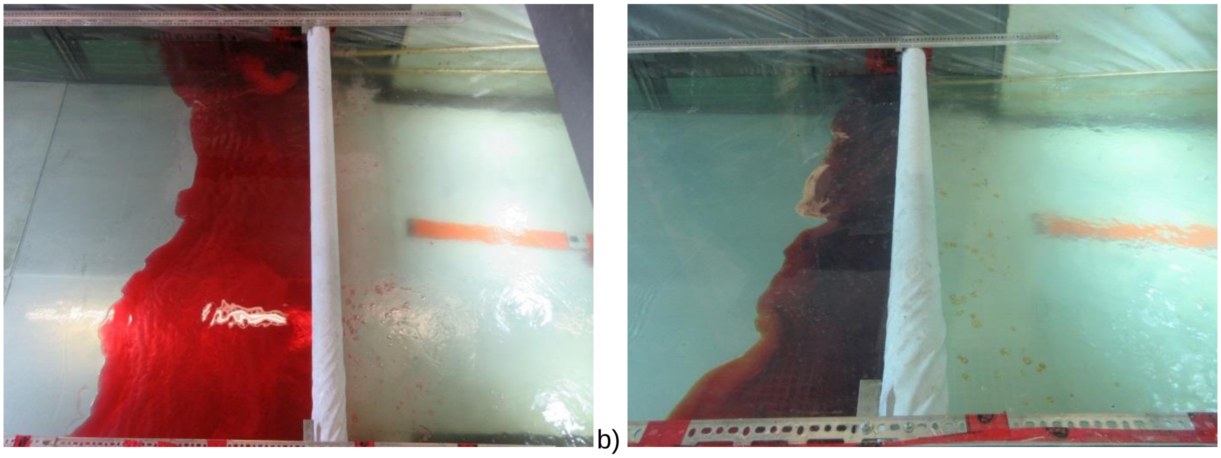
a)  b)

Figure 68. Containment of light and medium oil after tests with the conventional boom.
a) results from Test_3; b) results from Test_6. Flow is from left to right.

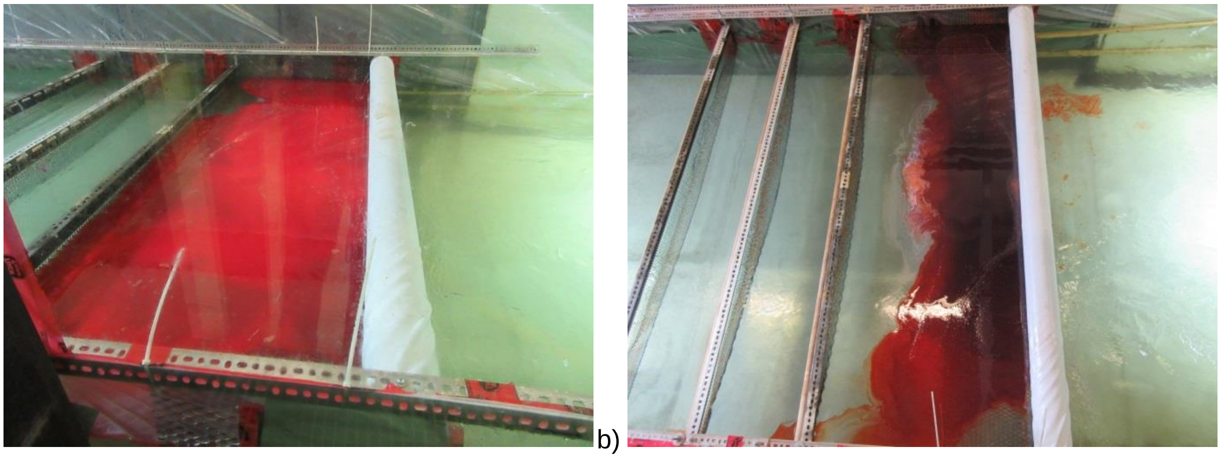
a)  b)

Figure 69. Containment of light and medium oil after tests with the Screen-boom system.
a) results from Test_32; b) results from Test_25. Flow is from left to right.

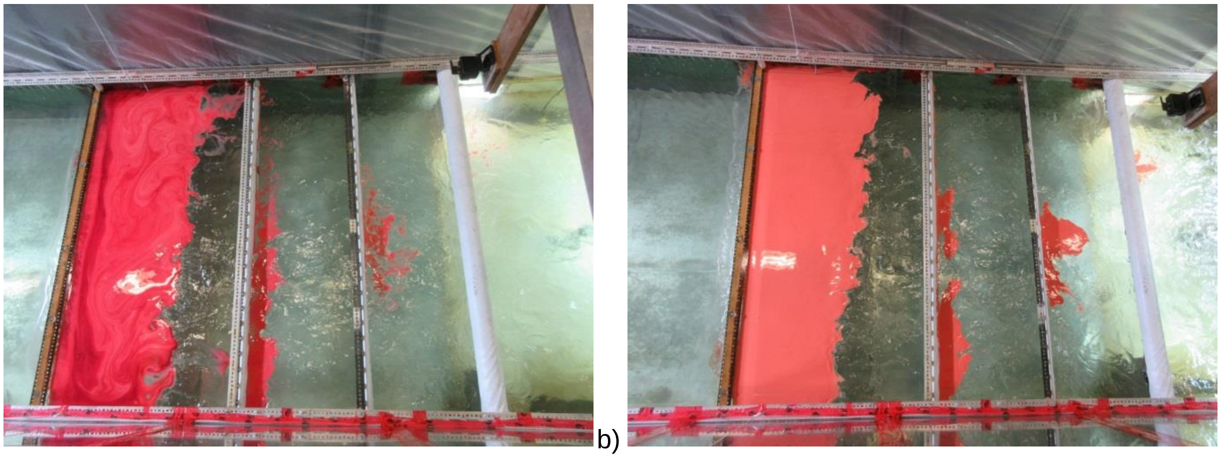
a)  b)

Figure 70. Containment of light and medium oil after tests with the Ramped-boom system.
a) results from Test_40; b) results from Test_43. Flow is from left to right.

5.4. 3D Physical Modelling Experiments

5.4.1. 3D Test Facility and Model Setup

The 3D portion of the physical modelling study was conducted in NRC-OCRE's Ice Tank (IT). The Ice Tank is 21 m long, 7 m wide, and up to 1.1 m deep (69 ft x 23 ft x 3.6 ft). The Ice Tank is equipped with a sturdy tow carriage and is located indoors within a cold room that can be chilled down to ~−20°C. Both freshwater ice and model ice (with low strength to simulate the behaviour of real ice in a scale model) can be grown with thickness up to ~0.6 m (note that the ice-growing capabilities of this facility were not used for this study). For these tests, the Ice Tank was outfitted with a portable wave generator and a simple wave absorber, shown in Figure 71.

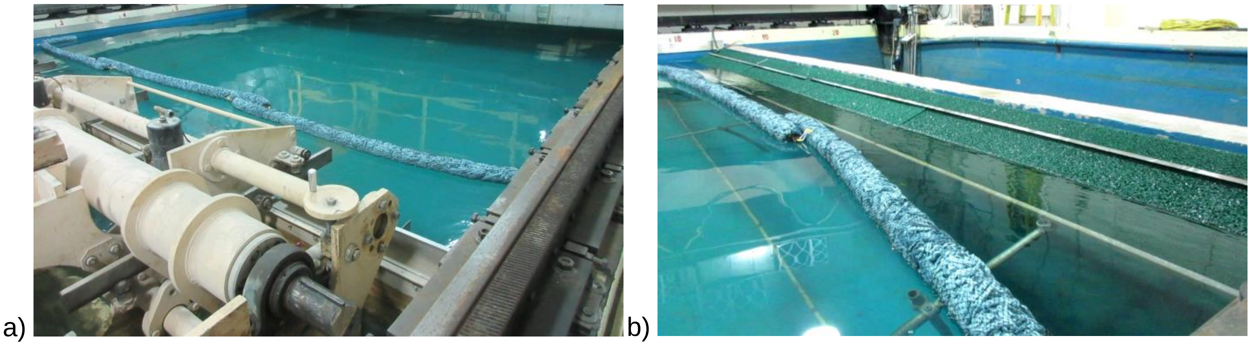

a) b)

Figure 71. Portable wave generator (a) and wave absorber (b).

In these 3D experiments, faithful scale models of several U-shaped boom designs were connected (one at a time) to the tow carriage so that they could be towed down the length of the tank at various speeds. A measured volume of test oil was added to the water upstream from the boom. The interaction of the oil with the boom and the ability of the boom to retain the oil was monitored visually and using video cameras positioned above, beside, and behind the boom. Some tests were conducted in calm water, while wave conditions were simulated in others.

The length scale for these experiments was 1:8, the same as for the 2D experiments described in the previous section. The overall setup of the Ice Tank is shown in Figure 72. The water depth was set to 0.9 m at model scale or 7.2 m at full scale for all tests (a significant increase in draft clearance as compared with the 2D physical model tests). Test oil was released just upstream from the mouth of the boom by two different delivery systems. For the first system (see Figure 73a and b), test oil was pre-loaded into a tilting drum installed ahead of the tow carriage. As the tow carriage began to move, the drum was tilted which poured the contents at a steady rate onto a sloping ramp whose bottom edge was positioned a few millimetres above the water surface (similar to the process used in the 2D testing). Two upstream fins were installed to confine the initial spread of the delivered oil and ensure it all entered into the mouth of the boom. The first oil delivery system was used up to and including Test3D_17. As tow speeds increased, there was concern that the oil delivered from the inclined ramp did not have sufficient time to resurface by the time the boom was passing by, and this led to discussions on how to modify the oil delivery system. The second system (see Figure 73c and d) involved pre-loading oil into a partially submerged drum whose top and bottom were removed. The drum was raised by a winch on the jib crane as the tow carriage began to move, which gently released the oil at the water surface. The second oil delivery system was used for all but a few of the remaining 3D tests. For a select few tests, oil was delivered directly into the boom apex in order to maximize the length of time that oil could potentially pass beneath the skirt from the boom apex at high-speed (see Figure 73e and f). Several views of the 3D testing are pictured in Figure 74.

A vacuum system as described in §5.1.1 was used to clean up the oil between tests. After each test, technicians used a portable secondary containment boom spanning the full width of the basin to collect all the oil over the surface of the entire basin and concentrate it in one location close to the vacuum (see Figure 75).

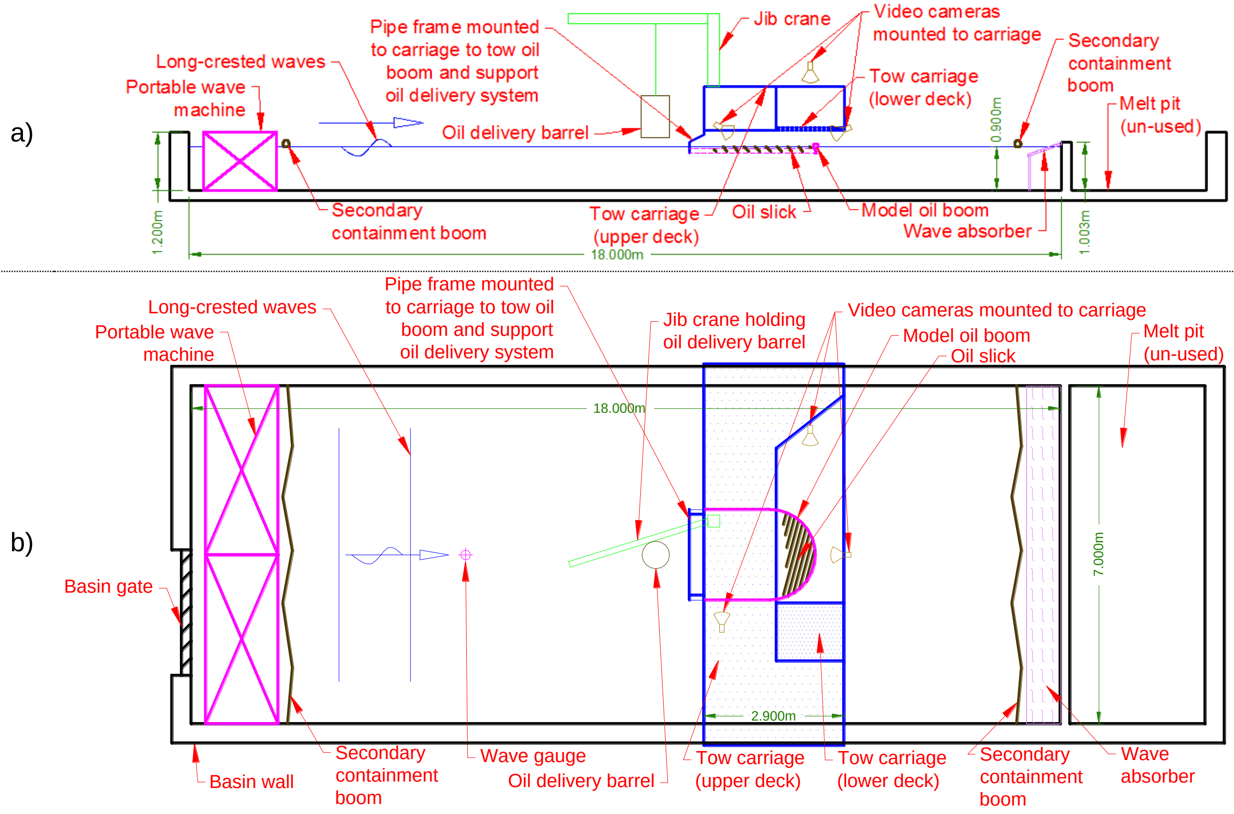


Figure 72. Layout for 3D scale model testing in the Ice Tank.
a) profile view; b) plan view.

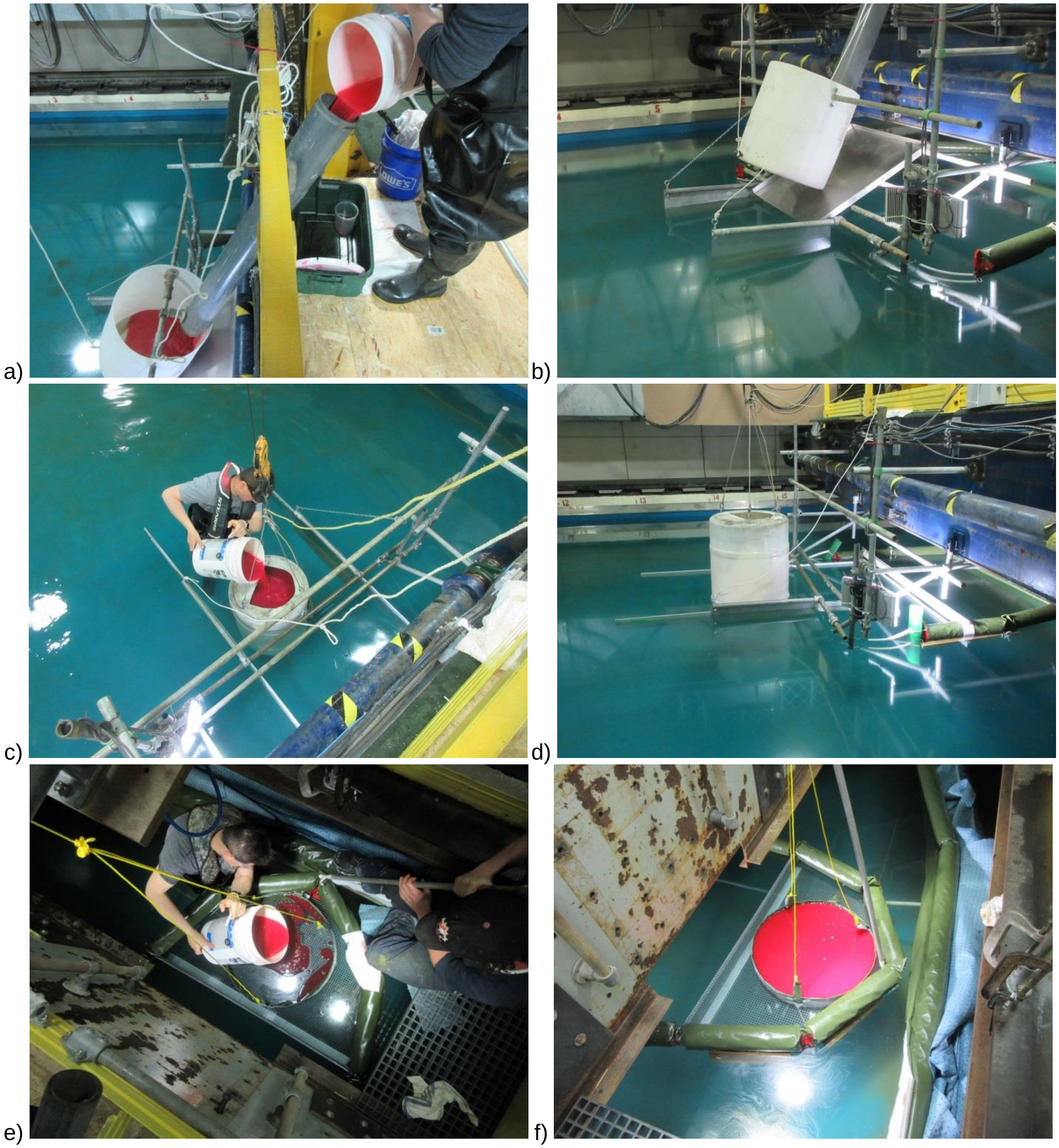


Figure 73. Oil delivery systems used in the 3D testing.
a) and b) initial oil delivery system using an inclined ramp and guide fins;
c) and d) second oil delivery mechanism using a cylindrical container and guide fins;
e) and f) oil delivery directly into boom apex (for selected tests only).

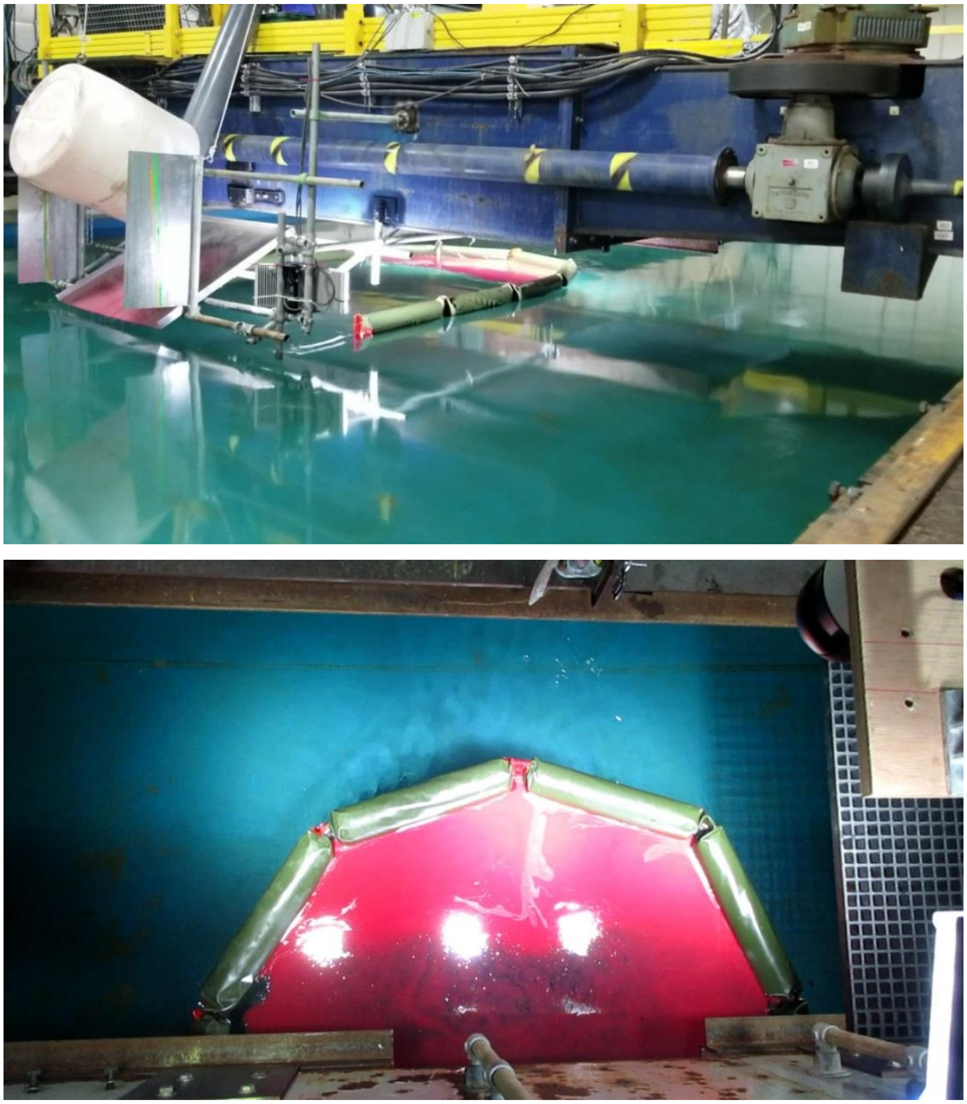


Figure 74. Views of the Ice Tank during 3D physical model testing.
(Top) oblique side view of the entire boom model; (Bottom) overhead view of boom apex.

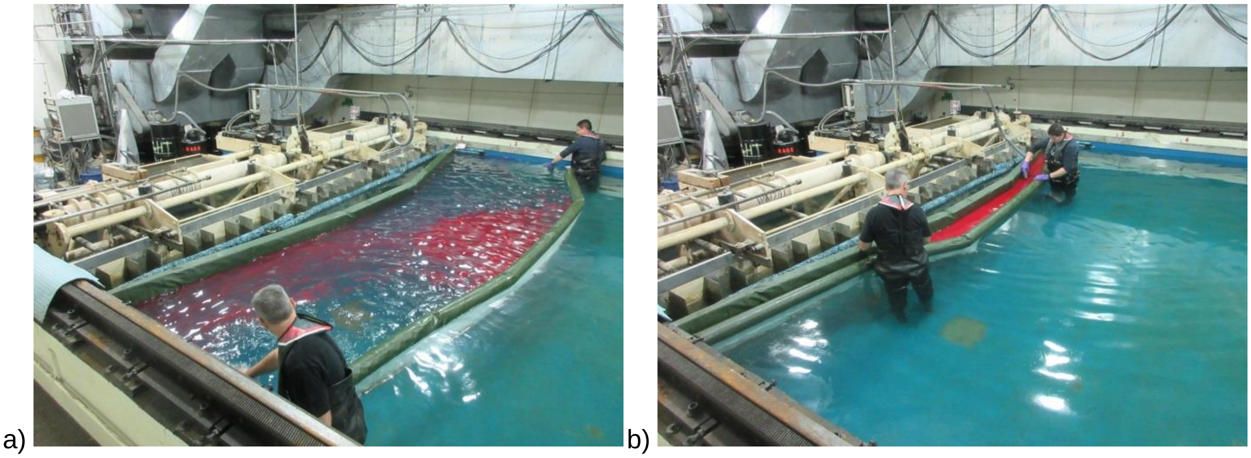


Figure 75. Oil clean-up operations between tests in the Ice Tank.

5.4.2. Wave Calibrations

Wave calibrations were performed to determine the relationship between the stroke of the wave machine paddle and the resulting wave height near the centre of the basin. Only regular wave conditions were generated in this study, which implies that each wave in the wave train had the same height and period. While the simple wave absorber was effective at removing small wave disturbances from the basin, it was less effective at damping the relatively long period waves investigated in this study. While waves were being generated, a significant portion of the incident wave energy was reflected by the tank wall resulting in the development of a partial standing wave field across the length of the basin after a short period of time. A time-selection window was used to perform the wave height analysis, ignoring the first portion of the wave gauge signal before the partial standing wave had developed. The wave heights remained relatively stable upon development of the partial standing wave pattern, and all attempts were made to perform tests with booms during this same time period.

Table 21 presents a summary of the wave analysis from the calibration tests. The rating curve developed from this data is plotted in Figure 76. For waves with a period of 5 sec (at full scale), the wave machine settings required to generate the various wave heights used for testing the oil booms were derived from this relationship, which was reasonably linear across a range of wave heights. The wave height at full span was 0.57 m (full scale). Mid-way through the oil boom testing program, the decision was taken to generate and test in larger, more energetic wave conditions than those pre-calibrated beforehand. Due to restrictions on the paddle slew rate, it was not possible to generate higher waves at the same 5 sec period. Therefore, a larger wave condition with a period of 8 sec and an estimated wave height of ~1.04 m was informally calibrated mid-way through the testing program.

Table 21. Summary of wave calibration results.

Test Name	WM Span (inches)	WM Freq. (Hz)	Avg. Wave Height (m)	Avg. Wave Period (s)	StDev. Wave Height (m)	# of Waves
WaveCal_2	0.2900	0.5657	0.135	4.93	0.050	30
WaveCal_1	0.3399	0.5657	0.156	4.93	0.058	30
WaveCal_5	0.5972	0.5657	0.293	4.93	0.106	25
WaveCal_3	0.7001	0.5657	0.333	4.93	0.121	24
WaveCal_6	0.9170	0.5657	0.404	4.93	0.148	21
WaveCal_4	1.1999	0.5657	0.567	4.93	0.203	19

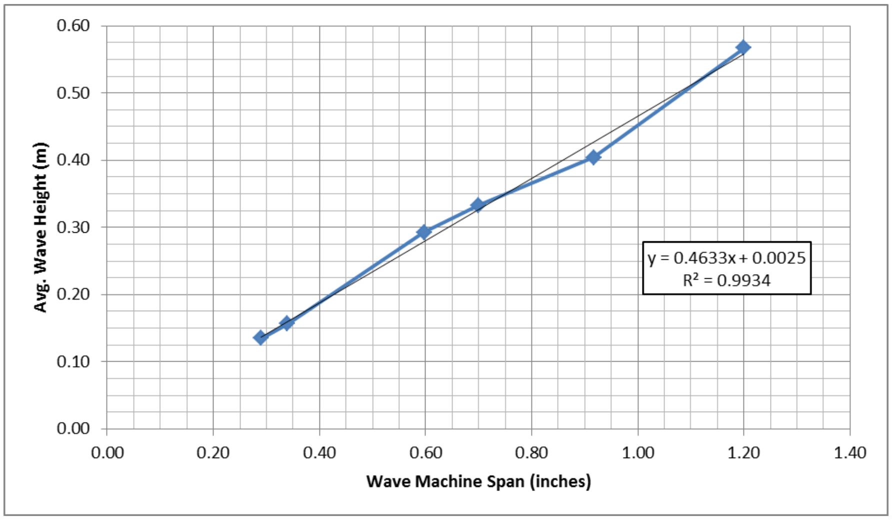


Figure 76. Wave machine span versus wave height for 5 sec period.

5.4.3. 3D Oil Boom Model Fabrication

The first boom model investigated was a conventional boom based on the Ro-Boom 2200. Figure 2 shows the schematic of the nominal prototype design, while Figure 77 shows the schematic of the 3D scale model reproduction. The model boom was fabricated using a series of 4-inch PVC pipes that were capped at each end. The PVC pipes were spaced apart to provide a flexible watertight joint between each segment. The boom was wrapped with a vinyl sheet to create a skirt that extended down from the centreline of the boom. The base of the skirt included a small fold through which a rigid steel chain was inserted to provide tension and prevent planing of the skirt at higher flow speeds. Since the 3D scale model actually floated (and was not supported from the sides and above like in the 2D model), the skirt length was shortened accordingly such that the base of the skirt was at the correct depth while the boom floated in calm water. Figure 78 shows the fabrication and floatation of the 3D scale model.

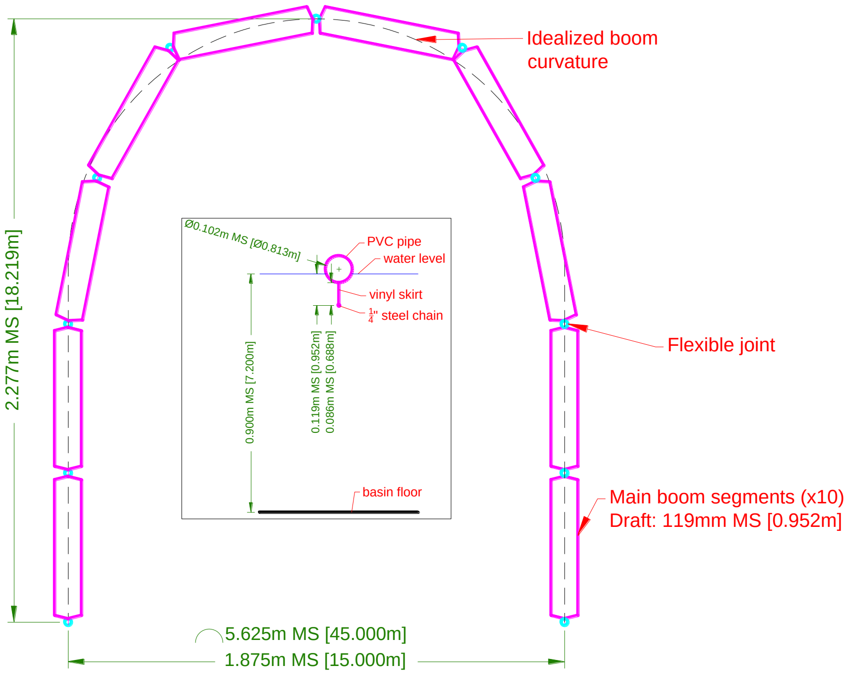
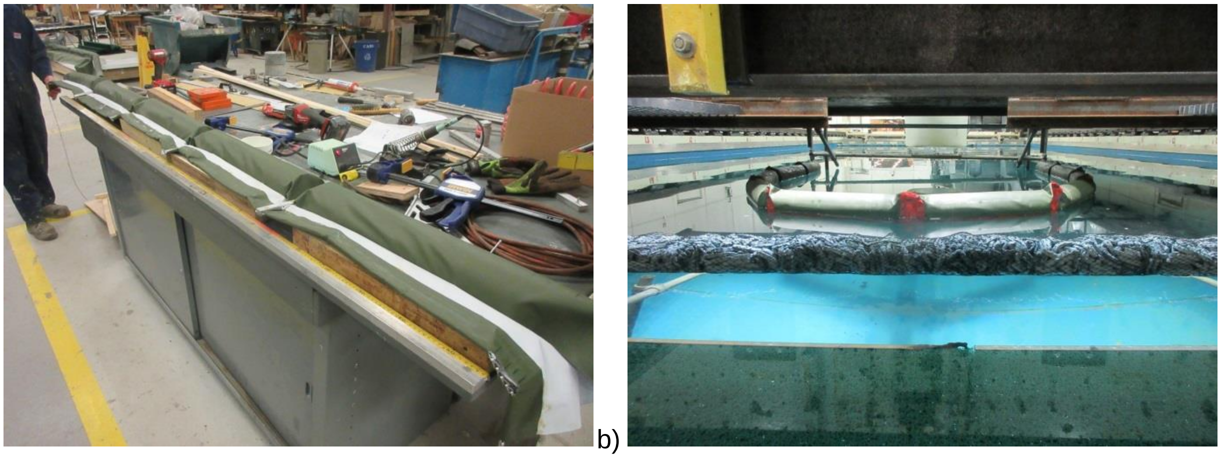


Figure 77. 3D model scale reproduction of the conventional boom.



a) b)

Figure 78. 3D scale model of the conventional boom.

The second boom model investigated was the Ramped-boom system. Figure 6 shows the schematic of the nominal prototype design, while Figure 79 shows the schematic of the 3D scale model reproduction, which used the conventional boom model as a basis. For simplicity and ease of construction, the inner skirts and ramp were positioned to align with the existing flexible joints, and therefore the spacing between the inner components does not exactly match the configuration tested in the 2D physical modelling. The ramp itself was fabricated using a transparent plexiglass sheet, rigidly mounted between the U-shaped boom to create a 15° downward angle. The upstream portion of the ramp extended slightly above the waterline to prevent oil and water from passing over the top of the ramp. The downstream edge of the ramp was set to a draft of 0.61 m, approximately two-thirds the depth of the main boom skirt. A thin foam gasket was used at the edges of the ramp to prevent any loss of oil from around the sides and force all flow to pass beneath the ramp. The two inner booms were fabricated in a similar fashion to the main boom, but with their skirts set to the same shallower draft of 0.61 m. The base of the inner booms included a small fold through which a rigid ¼-inch steel rod was inserted to act as a tensioning chain. Small L-shaped brackets were used to create a watertight attachment of the inner booms to the joints of the main boom. The width of the ramp and the inner booms was customized to maintain a similar curvature to the base case conventional boom. After initial floatation of the assembled model, it was observed that the bottom edge of the ramp sat lower in the water than it should due to the added weight of the plexiglass sheet. Therefore, some additional floats were temporarily added to the outside of the main boom, which had minimal impact on the overall performance. Figure 80 shows the fabrication and floatation of the 3D scale model.

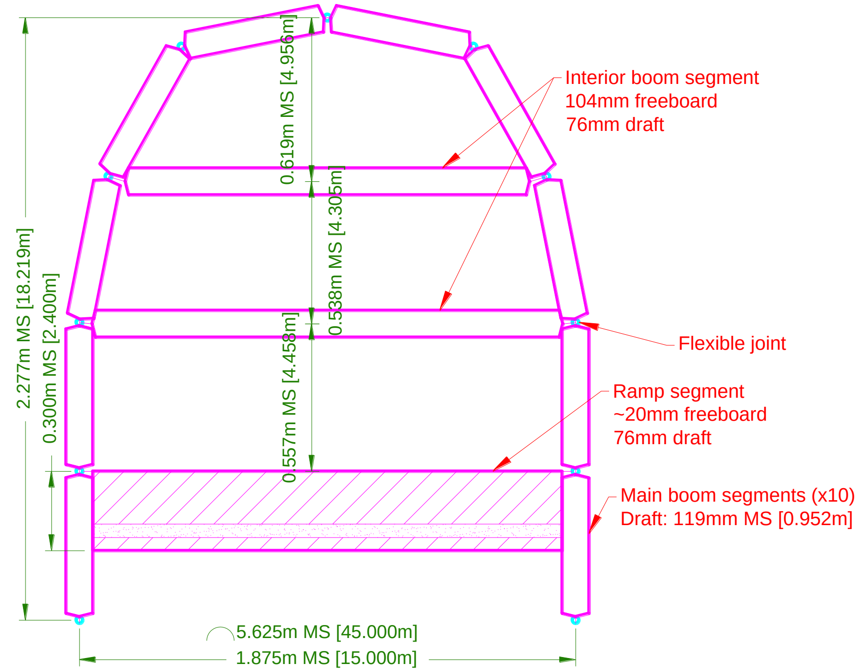


Figure 79. 3D model scale reproduction of the Ramped-boom system.

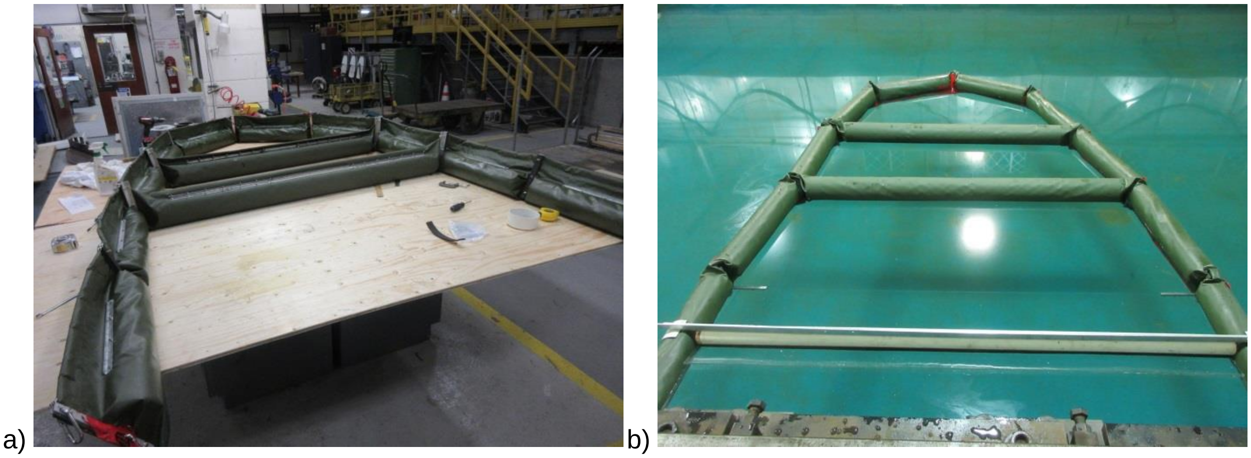


Figure 80. 3D scale model of the Ramped-boom system.

The third boom model investigated was a Screen-boom system based on the DESMI Speed-Sweep 2200. Figure 4 shows the schematic of the nominal prototype design, while Figure 81 shows a schematic of the 3D scale model reproduction which used the conventional boom model as a basis. For simplicity and ease of construction, the vertical screens were positioned to align with the existing flexible joints, and therefore the spacing between the inner components does not exactly match the configuration tested in the 2D physical modelling. It should also be noted that the 3D version incorporated a horizontal mesh that extended all the way to the third vertical screen, which is a combination of the configurations tested as modifications to the initial 2D model. The porosity of the vertical and horizontal screens in the 3D model (79%) was higher than those investigated in the 2D models, which was more in-line with the porosity used for the CFD modelling (which had shown promising results). The width of the vertical screens and plan shape of the horizontal screen was customized to maintain a similar curvature and plan shape as the base case conventional boom. The vertical screens were given a small fold on their upper edge (above water) to provide stability and maintain tension. After initial floatation of the assembled model, it was observed that the model (particularly the apex section) sat lower in the water than it should due to the added weight of the screens. Therefore, some additional floats were temporarily added to the underside of the screens, which had minimal impact on the performance of the boom. It is noted that the skirt depth at the apex was approximately 13 cm (model scale), which was ~1 cm lower than the target draft. Figure 82 shows the fabrication and floatation of the 3D scale model.

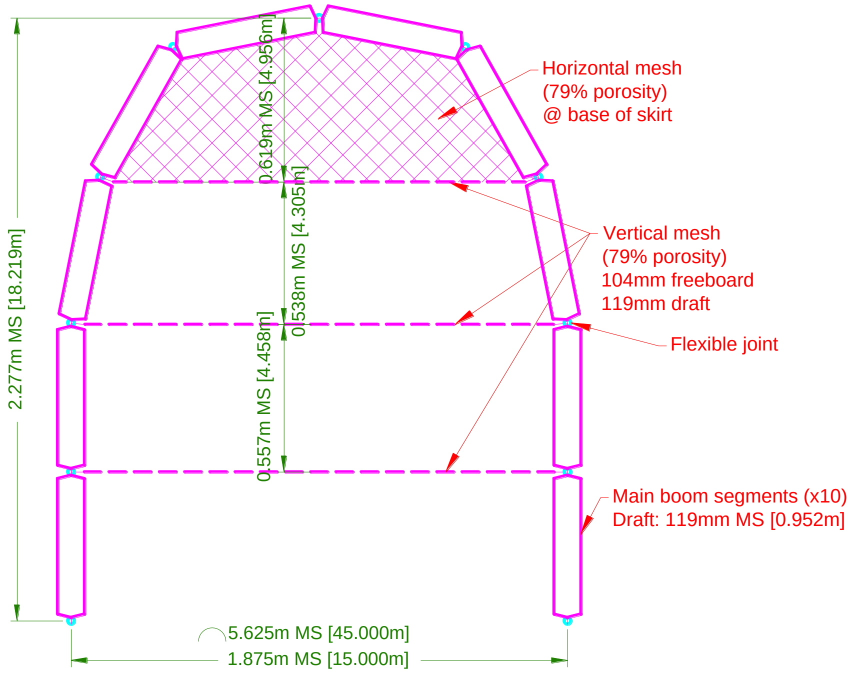


Figure 81. 3D model scale reproduction of the Screen-boom system.

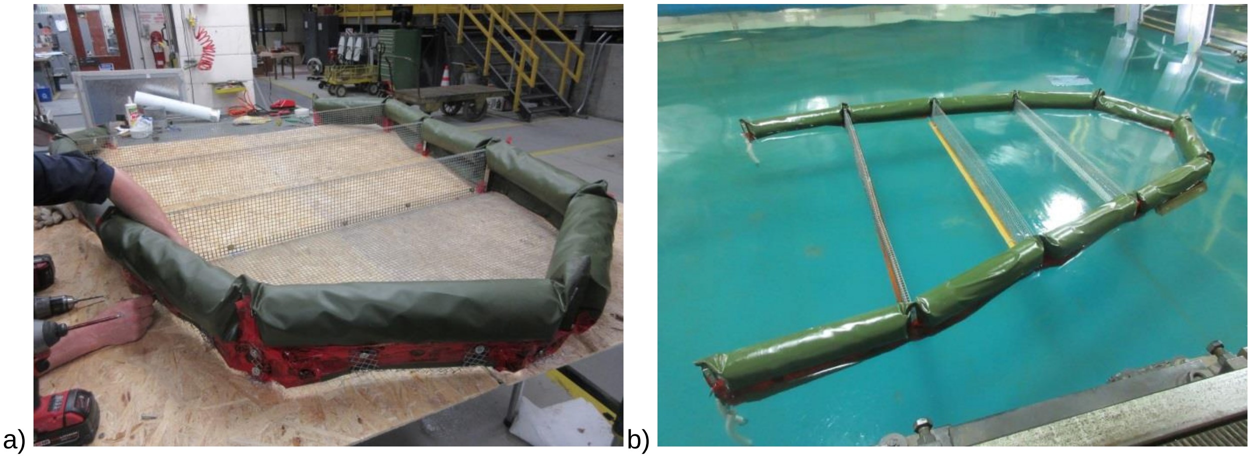


Figure 82. 3D scale model of the Screen-boom system.

5.4.4. 3D Model Testing

Following the wave calibration phase, several trial tests were performed with oil at relatively slow tow speeds (~1.2 knots) to observe the behaviour of the oil as it interacted with the boom and to determine the ideal setup of the oil delivery systems, video cameras, and overhead lighting. As previously mentioned, faithful 3D scale models of several U-shaped boom designs were connected (one at a time) to the tow carriage so that they could be towed down the length of the basin at various speeds. A measured volume of test oil was added to the water upstream from the boom. The interaction of the oil with the boom and the ability of the boom to retain the oil was monitored visually and using video cameras positioned above, beside, and behind the boom.

As discussed in §5.3.4, it was not possible to establish a precise quantitative value for the percentage of oil contained by the boom in these experiments, and therefore the results described here below are more subjective and qualitative in nature, and are based mainly on observation by an experienced researcher. As in the 2D experiments, the performance of the boom in each test was given a grade that was inversely proportional to the amount of oil observed to escape from the boom pocket. A rating of 100% indicates a 'perfect' result, in that absolutely no loss of oil was observed throughout the duration of the test. A rating in the high 90's generally indicates a 'near perfect' result, where only minute quantities of oil were lost during course of the test. Ratings in the mid-90's generally indicate good performance but with a greater loss of oil over the same duration. Ratings in the low-90's are considered adequate, but on the verge of failure, and could be considered analogous to the definition of first loss (see §1.2). Ratings lower than 90% are considered a failure with an unacceptable level of oil lost over the test duration, and could be considered analogous to the definition of gross loss (see §1.2).

In addition, it is critical to note that, while the 3D scale model tests were much more realistic than the 2D tests, the duration of the oil–boom interaction was very short due to the relatively fast tow speeds investigated and the relatively short length of the Ice Tank facility. Depending on the tow speed, the 3D scale model tests had a duration of only ~30 seconds (model scale), equivalent to ~85 seconds at full scale. In some cases, this duration may have been insufficient for the headwave to fully develop and for oil entrainment to occur and/or worsen compared with what was observed during the 2D experiments, where the test duration was much longer.

Table 22 provides a summary of the 3D scale model test results, while Figure 83, Figure 84, and Figure 85 show typical views of oil containment at the end of each test for the various boom models.

3D Tests 1 through 15 investigated the performance of the conventional boom. The base case conventional boom model demonstrated nearly 100% containment of light oil over the test duration at tow speeds of ≤1.6 knots, similar to the results from the 2D testing (and perhaps even slightly better than seen previously). Entrainment failure was observed to commence at ~1.7 knots. Tests with medium oil with the base case conventional boom model showed slightly worse results versus the same flow speeds with light oil. This result is more in line with the CFD results, which also concluded that medium (and heavy) oils were more difficult to contain than light oils. It is noted that the headwave region for medium oil was somewhat shorter and thicker, and individual oil globules that did bypass the skirt were larger than for the case of light oil.

Tests with relatively small to moderate wave heights (<0.6 m) and relatively short wave periods (~5 sec) indicated a slight deterioration in performance (compared with calm water conditions), as the boom effectively rode the waves with the oil, and as such, the relative movement between the oil and boom was not much different with waves than without waves. A similar result was observed in test #13, conducted with a more energetic wave condition (1.04 m wave height and 8 sec period), though it was noted that the motion of the boom became increasingly jerky, which would undoubtedly place more stress on the various components of the boom and likely increase oil leakage over time.

The boom configuration and test conditions in 3D Tests 4 and 5 were identical and the results from these tests demonstrated that the 3D scale model test results were highly repeatable, thereby providing confidence in the 3D experimental setup, test methodology, and subsequent judgement of the boom performance.

Comparing Tests 13 and 15 (which had triple the volume of oil), it was noted that the headwave was considerably longer and thicker and that the greater volume of oil appeared to have only a small negative impact on boom performance.

3D Tests 16 through 29 involved testing and assessment of the Ramped-boom system. Similar to what was observed in the 2D experiments, the Ramped-boom model demonstrated nearly 100% containment of light oil over the short test duration up to and including relatively high speeds (≤2.6 knots). The vast majority of oil passing under the ramp quickly resurfaced into the area behind the ramp and ahead of the first inner skirt, and was subsequently conveyed upstream into the ‘dead zone’ above the ramp where it remained trapped. Trace amounts of oil were carried downstream from the bottom edge of the ramp, some resurfacing in between the first and second inner booms, some between the second inner and main boom, and some again on the downstream side of the main boom. As flow speeds increased, it was observed that increasing amounts of oil bypassed the main containment zone immediately behind the ramp. Much of this oil was still trapped by the second inner and main booms, though increasing amounts remained submerged and were lost downstream. Nearly all of the observed oil loss occurred during the initial encounter with the oil slick; oil that resurfaces within the boom footprint generally remained contained. The upper tow speed limit for the Ramped-boom in calm water (where loss of oil remained below an acceptable threshold) was judged to be ~3.4 knots. Tests with medium oil again showed slightly worse results compared with equivalent tests with light oil, suggesting that medium oil is slightly more difficult to retain than light oil at higher speeds. Comparing 3D Tests 19 and 22 (which had triple the volume of oil), it was again noted that the performance of the boom was similar in both cases.

Tests with waves suggested that the small waves had a small negative impact on boom performance, and that the impact worsened (performance deteriorated) as the wave heights and wave periods increased. In particular, during the most severe wave condition (3D Test 25), oil in the main containment zone (above the ramp) was observed sloshing back-and-forth, contributing to oil entrainment beneath the first inner skirt (and possible subsequent entrainment beneath the main boom). It is noted that all tests with waves were conducted at a tow speed of 3.0 knots, and how the performance of the Ramped-boom in waves is affected by tow speed remains unconfirmed.

3D Tests 30 through 43 involved the Screen-boom system. The Screen-boom model demonstrated nearly 100% containment of light oil over the short test duration at relatively high speeds (≤2.5 knots). As previously observed, the vertical screens acted to reduce the relative near-surface velocity between the boom and the water (and oil), thus increasing the time it took for all the oil to collect in the pocket immediately upstream of the main boom. This good performance at relatively high speeds was a significant improvement compared with results from the 2D experiments. Three possible reasons for this improvement are: a) the fact that the boom apex was sitting slightly deeper (~1 cm model scale) into the water; b) the change to a less porous (more open) screen; and c) the much shorter test duration. The short test duration may not have provided enough time for the headwave to fully build up at the boom apex, and for entrainment failure to occur. Subsequent tests were conducted with the oil pre-loaded into the boom’s apex region (instead of at the boom mouth); and results from these tests confirmed minimal oil loss at speeds of ~2.5 knots, and deteriorating performance as speeds increased towards 3.0 knots. Similar results were observed at the same flow speeds with medium oil. Like the conventional boom, the performance of the Screen-boom was only slightly worse in the presence of relatively large waves in these short-duration tests. Unfortunately, the performance of all the booms over longer durations, with or without waves, remains unknown.

Table 22. 3D physical modelling test results.

Test #	Boom Design	Tow Speed (knots)	Oil Type	Volume of spilled oil (L/m of the boom width)	Wave Height (m) and Period (s)	% Rating
1	Conventional boom	1.21	Light	10.1	n/a	100
2	Conventional boom	1.59	Light	10.1	n/a	99
3	Conventional boom	1.79	Light	10.1	n/a	90
4	Conventional boom	1.70	Light	10.1	n/a	95
5▲	Conventional boom	1.70	Light	10.1	n/a	95
6	Conventional boom	1.79	Medium	10.1	n/a	85
7	Conventional boom	1.70	Medium	10.1	n/a	85
8	Conventional boom	1.59	Medium	10.1	n/a	85
9	Conventional boom	1.40	Medium	10.1	n/a	95
10	Conventional boom	1.70	Light	10.1	0.15 / 5	94
11	Conventional boom	1.70	Light	10.1	0.45 / 5	94
12	Conventional boom	1.70	Light	10.1	0.57 / 5	94
13	Conventional boom	1.70	Light	10.1	1.04 / 8	94
14	Conventional boom	1.70	Light	30.2	n/a	95
15▲	Conventional boom	1.70	Light	30.2	n/a	93
16*	Ramped-boom	2.20	Light	10.1	n/a	95
17▲*	Ramped-boom	2.20	Light	10.1	n/a	98
18	Ramped-boom	2.61	Light	10.1	n/a	99
19	Ramped-boom	3.00	Light	10.1	n/a	95
20	Ramped-boom	3.19	Light	10.1	n/a	93
21	Ramped-boom	3.41	Light	10.1	n/a	90
22	Ramped-boom	3.00	Light	30.2	n/a	95
23	Ramped-boom	3.00	Light	10.1	0.57 / 5	92
24	Ramped-boom	3.00	Light	10.1	0.15 / 5	93
25	Ramped-boom	3.00	Light	10.1	1.04 / 8	90
26	Ramped-boom	2.61	Medium	10.1	n/a	95
27	Ramped-boom	2.42	Medium	10.1	n/a	99
28	Ramped-boom	2.80	Medium	10.1	n/a	95
29	Ramped-boom	2.80	Medium	10.1	0.57 / 5	92
30	Screen-boom	1.59	Light	10.1	n/a	100
31	Screen-boom	1.70	Light	10.1	n/a	100
32	Screen-boom	1.90	Light	10.1	n/a	100
33	Screen-boom	2.20	Light	10.1	n/a	100
34	Screen-boom	2.50	Light	10.1	n/a	100
35	Screen-boom	3.00	Light	10.1	n/a	95
36	Screen-boom	3.41	Light	10.1	n/a	90
37	Screen-boom	3.00	Light	30.2	n/a	85
38•	Screen-boom	3.00	Light	10.1	n/a	92
39•	Screen-boom	2.50	Light	10.1	n/a	99
40	Screen-boom	2.50	Light	10.1	1.04 / 8	98
41	Screen-boom	2.50	Medium	10.1	n/a	n/a
42•	Screen-boom	2.50	Medium	10.1	n/a	99
43•	Screen-boom	3.00	Medium	10.1	n/a	92

▲ Repeatability test

* Submergence depth at bottom of ramp was too deep

• Oil delivered directly into the boom apex

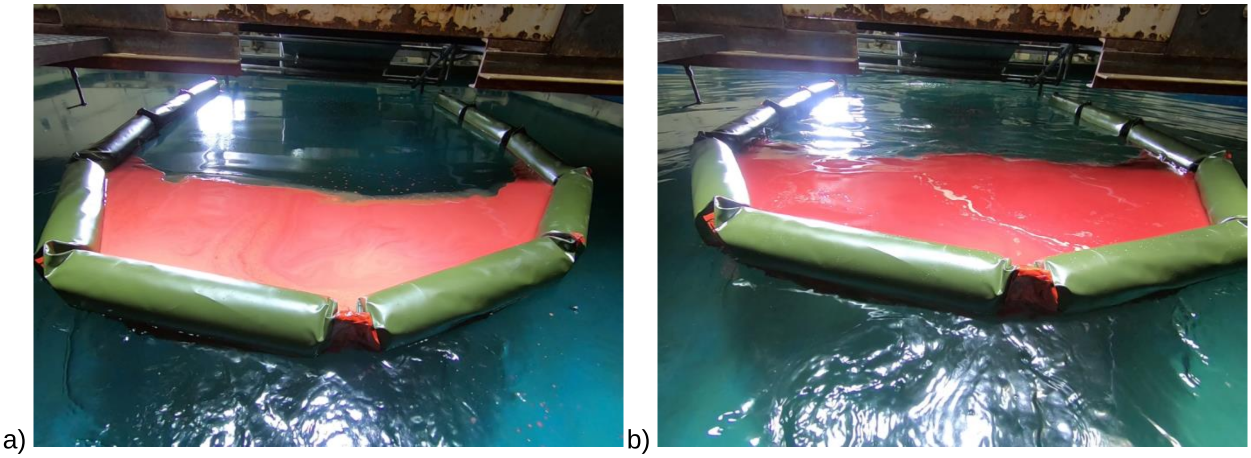


Figure 83. Containment of light oil in calm water and waves with the conventional boom.
a) results from Test3D_3; b) results from Test3D_13.

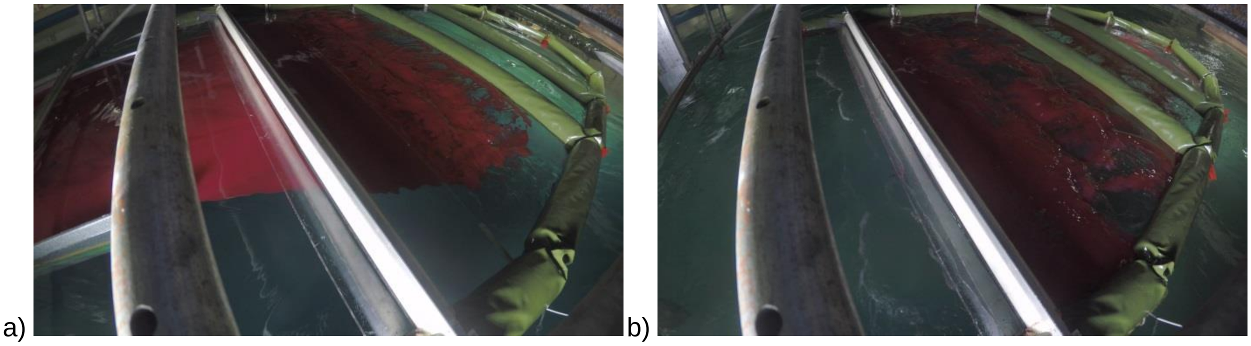


Figure 84. Containment of light oil in calm water and waves with the Ramped-boom system.
a) results from Test3D_22; b) results from Test3D_25.

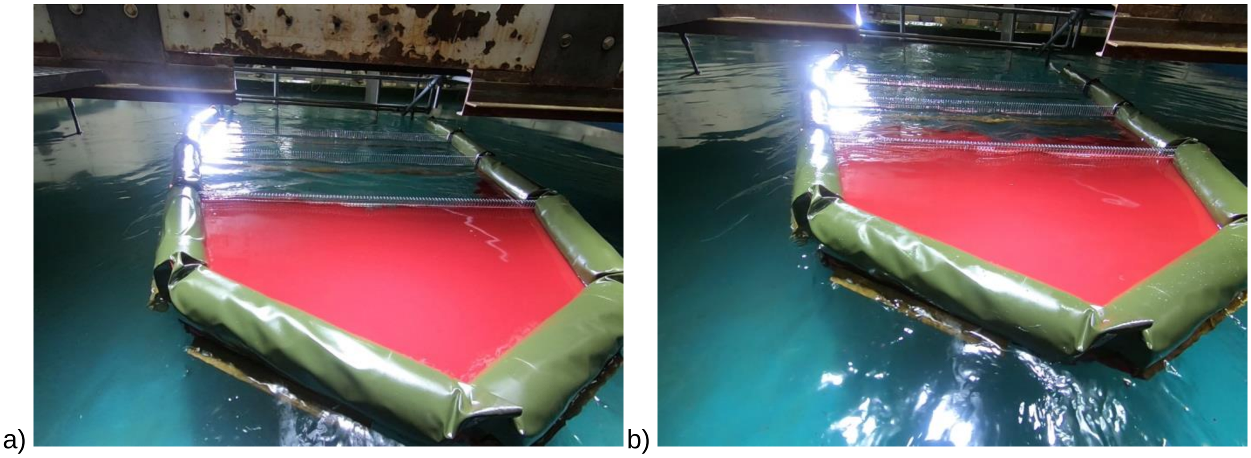


Figure 85. Containment of light oil in calm water and waves with the Screen-boom system.
a) results from Test3D_34; b) results from Test3D_40.

5.5. Physical Modelling Summary and Conclusions

A series of two- and three-dimensional physical scale model experiments were conducted to investigate the oil containment performance characteristics of three oil spill containment boom concepts (and several variations thereof) at high speeds. The 2D testing featured fixed boom models with water (and oil) flowing past at high speeds, whereas the 3D testing featured more realistic, flexible, and floating boom models that were towed at high speeds through both calm water and wavy conditions.

From the literature review (conducted as Phase 1 of this project), it is clear that there has been a limited number of laboratory studies regarding the design and performance of oil boom concepts. Many of these experimental studies have involved trying to understand the behaviour of oil in response to booms; however these were experiments investigating small sections/parts of a full-size boom conducted in relatively small test facilities. Much of the true research and development of oil boom concepts has occurred through experiments at a full scale test facility (like Ohmsett). There is almost no literature on the topic of large-scale model testing and development of oil booms, making this research project rather unique.

Through this study, scaled hydraulic experiments have been shown to be a useful and cost-effective means for studying the interaction of oil and water with various styles of oil containment booms, assessing their performance, and developing modifications to improve performance. The 2D testing setup made it relatively easier to modify and test multiple variations to the boom designs for indefinite lengths of time, and permitted excellent observation from both overhead and a side-view. The 3D testing setup was ultimately more realistic in terms of modelling the interaction of the boom with calm or moving water and with oil.

As expected, the Screen-boom and Ramped-boom systems performed better than the conventional boom, capturing the vast majority of spilled oil at tow speeds up to and just over 3 knots. It should be noted that the Ramped-boom has a significant practical advantage in the fact that the captured oil is completely contained within the confines of the boom, so that the oil would remain contained, even if the tow vessel came to a complete stop or the ambient current changed direction. In addition, the thickness of the oil slicks encountered in these experiments (particularly during the 3D experiments) is likely much greater than would be expected in a real-world oil spill situation. A thinner layer of oil may be beneficial to counteract the initial (minor) loss of oil seen with the Ramped-boom design.

Recommendations for future physical modelling investigation are discussed in §6.

6. Recommendations for Future Work

Through this study, both CFD techniques (and OpenFOAM in particular) and scaled hydraulic experiments have been shown to be a useful and cost-effective means for studying the interaction of oil and water with various styles of oil containment booms, assessing their performance, and developing modifications to improve performance.

Future CFD simulation efforts could focus on investigating other high-speed boom concepts reported in literature, e.g., (Brown *et al.*, 1999; Swift *et al.*, 1996), proposing entirely new containment concepts based on what was learned in the present phase of the project, and studying how oil containment is impacted if the floatation and movements of booms and their interaction with waves are accounted for.

As previously discussed in §5.4.4, the duration of the 3D scale model experiments was limited due to the length of the tow facility, and thus a longer towing tank would be required to confirm the observations made during that part of this research study.

Although all reasonable efforts were made to minimize possible errors, scaling effects may not be fully understood and it is possible that the performance observed in these physical modelling experiments may not be fully repeatable at full scale. Ideally, the scale model testing completed as part of this research could be replicated at ~1:2 or even 1:1 scale to verify the results and determine how model and scale effects may have affected the present research.

The results of this study indicate that the Ramped-boom design appears very promising and should be further investigated and developed in future research.

7. Acknowledgements

Many NRC employees made important contributions to the success of this research project, and their efforts are hereby acknowledged with gratitude, including Dr. Andrew Cornett for his oversight of the project. In particular, Mr. Michel Brassard, Mr. Yvan Brunet, Mr. John Marquardt, and Mr. Amanj Rahman warrant special recognition for their dependable technical support throughout the physical modelling testing program.

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Appendix A

Contents

1. Summary of Internet Literature Review

Year	Authors	Title	Summary	Status
2014	Gong, Tkalich, Xu	The Numerical Investigation on Oil Slick Behavior behind the Oil Boom	The dynamics of contained oil spills is investigated based on multiphase CFD (Computational Fluid Mechanics) model. The oil slick shape behind the oil boom under water current is studied. The velocity field in the oil slick is compared with the velocity field in pure water flow. The thickness of the oil slick is studied quantitatively. It is found that there is a fixed linear relationship between the oil slick relative thickness and the Froude number for different oil, different current velocity, different boom draft and different volume of oil.	Have pdf
2013	Yang, Liu	Numerical modelling of oil spill containment by boom using SPH	The ocean environment is protected from oil pollution usually by using floating booms, which involves water-oil two-phase flow and strong fluid-structure interaction. In this paper, a modified multi-phase smoothed particle hydrodynamics (SPH) method is proposed to model oil spill containment by using a moving boom. Four major influencing factors including oil type, moving velocity and skirt angle of the boom, and water wave are investigated. The SPH simulation results demonstrate different typical boom failure modes found in laboratory experiments. It is shown that the ability of a boom in containing oil is not only affected by its own characteristics, but also closely related to external environmental factors. It is found that boom failure is more likely to happen for heavy oil, high boom velocity, negative skirt angle, and/or in the presence of water waves.	S
2017	Muttin, Campbell, Ouansafi, Benelmostafa	Numerical Modelling and Experimentation of Oil-Spill Curtain Booms: Application to a Harbor	Oil-spill curtain booms are an important response device dedicated to containing and deviating floating pollutants. The hydrodynamic and structural limitations of curtain booms necessitate numerical modelling for efficient usage assessment. A four-step model is proposed and applied during an exercise performed in the Galician region of Spain. Experimental results are used to produce a re-analysis of the model and improve contingency planning.	Have pdf
2011	Xing, Wanqing, Wefeng	Numerical Simulation Technology of Oil	The development of the numerical simulation technology of oil containment by boom is introduced here and the vital role of oil boom on clearing up the spilled oil is elaborated. Based on the numerical wave tank using the momentum source method,	Have pdf

		Containment by Boom	oil containment by boom in waves and currents is numerically analyzed here utilizing the commercial CFD software FLUENT. Finally, the relationship between wave parameters and loss rate is investigated.	
2014	Shi, Meng, Dao, Dong	Numerical Simulation and Structural Analysis of Oceanic Oil Containment Booms in Towing Condition	The oil containment boom made by canvas is a kind of typical flexible structure. It will ruin when the towing speed is too fast. Stress and deformation plays an important role in working performance of oil containment boom. Analyses are conducted by finite element software "ANSYS" in this paper. A number of finite element models for a typical oil boom section are built up, selected the different working conditions, to verify structure’s displacement, strain, stress and tensile strength under arbitrary wave-to-course angle. This study provides a more reasonable analytical method and gets some useful conclusions which will guides evaluation of oil containment boom system.	O
2009	Amini, Scleiss	Numerical Modelling of Oil-Water Multiphase Flow Contained by an Oil Spill Barrier	To enhance the understanding of hydrodynamics of oil spill containment booms, numerical simulations of different booms were carried out using the state-of-the-art Computational Fluid Dynamics program, FLUENT. Single and double barriers containing oil over water surface were modeled and the flow characteristics in the vicinity of rigid and flexible barriers with different drafts were studied. The numerical results were compared with experimental observations and measurements. The simulated velocity field was in good agreement with precise experimental measurements. The extension of turbulence wake was discussed for single and double barriers. Finally, using a multiphase flow model the effect of oil on flow pattern was studied.	Have pdf
2001	Fang, Johnson	Oil Containment by Boom in Waves and Wind. I: Numerical Model	The effectiveness of a boom is associated with the hydrodynamics in the vicinity of the oil slick that it is attempting to contain, especially under open-sea conditions. A comprehensive investigation of oil containment is provided under various current, wave, and wind conditions. In this paper, a local two-phase nonlinear hydrodynamic numerical model is developed to simulate oil containment by a fixed boom under open-sea conditions. The shape of an oil slick is a function of time, and unstable waves may develop along the oil-water interfacial boundary. This paper describes a simulation of the behavior of the oil slick and deals with important interfacial boundary conditions. A	ASCE

			non-hydrostatic pressure is introduced to accommodate the complicated local flow near the oil slick and a successive over-relaxation method is used to solve the pressure equation. A comparison is made of the oil slick shape with and without the hydrostatic pressure assumption. Some simple simulations of free-surface elevations under a number of wave conditions are performed to verify the numerical model. The computed results are in general agreement with those obtained from previous experiments.	
2001	Fang, Johnston	Oil Containment by Boom in Waves and Wind. III: Containment Failure	The numerical simulation of interfacial waves and waves on the free surface of an oil slick under combined current and wave conditions is presented in a companion paper. The present paper focuses on the application of a numerical model developed by Fang and Johnston that numerically predicts the relationship between oil containment failure velocity and wave/wind parameters. Comparative laboratory experiments have been undertaken in a 24 m long, 0.4 m wide, 0.4 m- deep wave flume. Detailed comparisons and discussions of the computed and experimental results are provided. The effects of oil viscosity and density on oil containment failure velocity receive particular attention, and the influences of other parameters such as oil volume and boom draft are also quantified. It is concluded that the developed numerical model provides an economic, convenient, and effective method of predicting oil containment failure under various sea conditions.	ASCE
2013	XiuFeng, MouBin	Numerical modelling of oil spill containment by boom using SPH	The ocean environment is protected from oil pollution usually by using floating booms, which involves water-oil two-phase flow and strong fluid-structure interaction. In this paper, a modified multi-phase smoothed particle hydrodynamics (SPH) method is proposed to model oil spill containment by using a moving boom. Four major influencing factors including oil type, moving velocity and skirt angle of the boom, and water wave are investigated. The SPH simulation results demonstrate different typical boom failure modes found in laboratory experiments. It is shown that the ability of a boom in containing oil is not only affected by its own characteristics, but also closely related to external environmental factors. It is found that boom failure is more likely to happen for heavy oil, high boom velocity, negative skirt angle, and/or in the presence of water waves.	S

2014	Kristiansen, Faltinsen	A Numerical Study on Stratified Shear Layers with Relevance to Oil-Boom Failure	Interface dynamics of two-phase flow, with relevance for leakage of oil retained by mechanical oil barriers, is studied by means of a two-dimensional (2D) lattice-Boltzmann method (LBM) combined with a phase-field model for interface capturing. A multi-relaxation-time (MRT) model of the collision process is used to obtain a numerically stable model at high Reynolds number flow. In the phase-field model, the interface is given a finite but small thickness, where the fluid properties vary continuously across a thin interface layer. Surface tension is modeled as a volume force in the transition layer. The numerical model is implemented for simulations with the graphic processing unit (GPU) of a desktop personal computer. Verification tests of the model are presented. The model is then applied to simulate gravity currents (GCs) obtained from a lock-exchange configuration, using fluid parameters relevant for those of oil and water. Interface instability phenomena are observed, and obtained numerical results are in good agreement with theory. This work demonstrates that the numerical model presented can be used as a numerical tool for studies of stratified shear flows with relevance to oil-boom failure.	ASME
2017	Shi, Li, Chen, *et al.*	Improved SPH simulation of spilled oil contained by flexible floating boom under wave-current coupling condition	A multi-phase Smoothed Particle Hydrodynamics (SPH) method is developed to model the failure process of a flexible oil boom. An algorithm is proposed based on the dynamic boundary particles (DBPs) for preventing the particle disorders during the multi-fluid particle movement around the solid boundary. The improved multi-phase SPH model is firstly validated by the experimental data of a wedge falling into a two-layer oil-water fluid. Then a numerical wave-current flume is established with an active absorbing piston-type wave generator and a circulating current system. The model reliability is validated against the measured vertical profiles of velocity. Simulation of the flexible floating boom movement is implemented by introducing a Rigid Module and Flexible Connector (RMFC) multi-body system. The model is finally applied to the simulation of movement of a flexible floating boom in containing industrial gear oil under the combined waves and currents. Good agreements are obtained between the SPH modelling results and the experimental data in terms of the ambient wave-current field, hydrodynamic responses of the floating body and evolution process of the oil	Have pdf

			slick for the flexible boom. The hydrodynamic responses and containment performances of the flexible floating boom are also compared with those of the rigid one. It is found from both the experimental and numerical results that two vortices of the water phase exist in the front and rear of the boom skirt and the size of the front vortex decreases with an increase of the current velocity while the wake vortex is reversed. It is also found that the skirt of the flexible boom has a larger magnitude of the swaying and rolling than the rigid one and the maximum quantity of the escaped oil of a flexible boom within one wave cycle is about 5% more than a rigid one under the present test conditions.	
2006	Fang, Wong	An advanced VOF algorithm for oil boom design	In this paper, an accurate interface convection technique based on the volume-of-fluid (VOF) scheme is presented and the concepts of interface basis and three types of fluxes are introduced to handle two-layer fluid flow in complex geometric situations. The scheme was tested and the results proved to be accurate. We then compared the computational simulation and the laboratory experiment of an innovative boom arrangement. Satisfactory results indicate the potential for using the computational technique developed in this paper to aid in oil boom design as well as in other multilayer immiscible flow applications.	I
2015	Lu, Xu, Xu, Xie, Wu, Yang, Liu	Experimental and numerical investigations on reliability of air barrier on oil containment in flowing water	Air barriers have been recently developed and employed as a new type of oil containment boom. This paper presents systematic investigations on the reliability of air barriers on oil containments with the involvement of flowing water, which represents the commonly-seen shearing current in reality, by using both laboratory experiments and numerical simulations. Both the numerical and experimental investigations are carried out in a model scale. In the investigations, a submerged pipe with apertures is installed near the bottom of a tank to generate the air bubbles forming the air curtain; and, the shearing water flow is introduced by a narrow inlet near the mean free surface. The effects of the aperture configurations (including the size and the spacing of the aperture) and the location of the pipe on the effectiveness of the air barrier on preventing oil spreading are discussed in details with consideration of different air discharges and velocities of the flowing water. The research outcome provides a	SD

			foundation for evaluating and/or improve the reliability of an air barrier on preventing spilled oil from further spreading.	
		Numerical Simulation of the Flow Channel in the Curved Plane Oil Skimmer	Oil spills at sea can cause severe marine environmental damage, including bringing huge hazards to living resources and human beings. In-situ burning or chemical dispersant methods can be used to handle the oil spills sometimes, but these approaches will bring secondary pollution and fail in some situations. Oil recovery techniques have also been developed to recover oil using oil skimmer equipment installed on ships, while the hydrodynamic process of the oil flowing through the oil skimmer is very complicated and important for evaluating the recovery efficiency. Based on this, a two-dimensional numerical simulation platform for simulating the hydrodynamic process of the oil flowing through the oil skimmer is established based on the Navier-Stokes equations for viscous, incompressible fluid. Finally, the influence of the design of the flow channel in the curved plane oil skimmer on the hydrodynamic process of the oil flowing through the oil skimmer is investigated based on the established simulation platform.	Have pdf
	Borri, Lugni, Greco, Faltinsen	Experimental study of water-oil-boom interaction and failure events	Oil spill caused by maritime accidents can damage valuable ecosystems and have a huge economic impact on fishing and tourism industries. In order to minimize the damage it is important to predict the trajectory of the spilt oil slick and use an effective clean-up strategy. Oil booms represent a valid solution, but their performance has a limitation in sufficiently strong currents and high sea waves. This motivated research efforts in the development of suitable prediction tools useful for the design and for setting the operative limits of these devices. Experiments are instead more difficult to perform. However some relevant studies have been documented along the years, most of them in 2D conditions, with fixed boom and in steady current. For example, Delvigne (1989) studied a scaled boom interacting with different types of oil and identified the failure mechanisms involved. A comprehensive documentation of full- and model-scale tests in 2D and 3D conditions is provided e.g. by Grilli *et al*. (2000). Here a physical investigation is ongoing based on dedicated model tests to be used for gaining further insights on the phenomena involved and as reference data for	Have pdf

			numerical-tools development. The experimental set-up and some of the results of the analysis are discussed in the following.	

A: available for purchase from AIP Conference proceedings
ASCE: available for purchase from ASCE library
ASME: available for purchase from ASME library
I: available for purchase from International Journal of Modelling and Simulation

O: available for purchase from OnePetro proceedings
S: available for purchase from SpringerLink
SD: available for purchase from ScienceDirect

2. **Summary of Highly Ranked Papers: CFD list**

Rel	Year	Title	Authors	Summary
1	1999	Development of containment booms for oil spills in fast flowing water	Brown, Goodman, An	Two double-boom systems designed to contain oil at high water currents were developed and prototype sections of these tested in a flowing channel. Computational fluid dynamics modelling was used to determine the feasibility of these designs. Tests with three oils, whose viscosities varied from 10 to 10,420 cs and whose densities varied from 834 to 964 kg/cu m, indicated that the designs or modifications were successful in containing oil. These oils were contained at twice the current speeds at which a simple flat barrier failed. The presence of oleophilic fibres attached to the upstream boom skirt increased the effectiveness of the multiple booms by slowing the water entering the oil trapping region and by providing and oil-attracting pathway into the trapping area. Bottom nets between the booms decreased the water velocity within the boom system and improved oil trapping.
1	2008	Dynamics of low-viscosity oils retained by rigid and flexible barriers	Amini, Bollaert, Boillat, Schleiss	Oil spills are of major environmental concern in coastal regions. Experience shows that even the best efforts have not prevented the occasional occurrence of major accidents on the sea. As long as massive oil spills are probable, special techniques and equipment will remain essential for facilitating spill cleanup in coastal regions. Mechanical oil barriers, or "booms", are used to contain or divert oil spills on water and are key tools in oil spill response. Recently, an anti-pollution boom, called the Cavalli system, was designed with the intention of preventing the spread of spilled oil by trapping it inside a flexible floating reservoir and improving the pumping operation by decreasing the reservoir surface, consequently increasing the oil layer thickness. The main aim of the present study is to investigate the response of barriers of different types (rigid/flexible) in oil slick containment and to evaluate the capability of a trapping reservoir, i.e., the Cavalli system, as a particular case. For this purpose, both experimental and numerical approaches were pursued. Two-dimensional experiments with rigid and flexible barriers containing a low-viscosity oil were conducted in a laboratory flume. To enhance the understanding of the mechanisms associated with oil containment, numerical simulations were also carried out. The slick shape evolution

				and dynamics, failure initiation, and rate of oil loss under different conditions were examined and analyzed. An empirical relationship was suggested in order to assess the maximum permissible oil-water relative velocity as a function of barrier draft and oil characteristics. Equations were also proposed to predict the slick length and headwave thickness as a function of contained oil volume.
1	1998	Flow around oil containment barriers	Brown, Goodman, An	Computational fluid dynamics (CFD) modelling was validated by reproducing experiments on boom failure reported in the literature and by comparison with measurements in a flowing channel. All three failure mechanisms which occur at the boom center-line were accurately simulated by two-dimensional CFD modelling. Studies of the containment capability of a more realistic flexible boom configuration showed that its behavior is not significantly different from that of a simple flat boom. Measurements around a porous boom system showed that it is capable of oil containment at higher flow velocities than a single boom and were used to validate a CFD model of the system. This is an abstract of a paper presented at the 21st Arctic and Marine Oil Spill Program, AMOP Technical Seminar (Edmonton, Alberta, Canada 6/10-12/98).
1	2005	Fluid dynamics of floating oil containment by mechanical barriers in the presence of water currents	Wicks	Experiments on oil containment by mechanical barriers have led to identification of the important physical phenomena controlling the extent of an oil slick and have illustrated flow conditions leading to failure of the barrier. A mathematical model has been developed to generalize the experimental results. Three regions in the oil layer are identified. 1. a gravity wave region near the upstream end of the slick, which leads to oil droplet formation if water flows faster than a certain critical speed, 2. a boundary layer region where drag of the flowing water causes gradual thickening of the oil, and 3. a skirt region where the flowing water causes oil droplets still present to be swept under the barrier. Another mechanism of failure is discussed whereby oil could escape under the boom by a kind of draining action. Example calculations and design charts are presented which may be useful in deciding whether stationary mechanical barriers would work at all in given cases, and in selecting the proper depth of skirt and length of boom, required in those cases where mechanical barriers, are feasible. Where

				stationary barriers are not feasible, the results can be used to establish minimum boom drift velocity to prevent oil from escaping.
1	2014	Oil containment by floating boom under wave-current coupling conditions. III: Prediction on failure velocity	Feng, Wu, Yu	The numerical simulation of oil containment by floating boom under wave-current coupling conditions is presented in a companion paper. The present paper focuses on the use of the numerical experimental platform developed by FENG and WU for the prediction of oil containment failure velocity of floating boom under wave-current coupling conditions. Detailed derivation processes about the containment failure velocity formula are provided. The effects of oil parameters, wave parameters and oil boom parameters on oil containment failure velocity receive particular attention, and the influences of some of these parameters such as oil density, boom draft are quantified. The prediction model can provide an economic, convenient method for oil spill response. © (2014) Trans Tech Publications, Switzerland.
1	1998	Trapping of leaked oil with tandem oil fences with Lagrangian analysis of oil droplet motion	Lee, Kang, Cho	The effectiveness of two oil fences deployed in tandem to maximize the containment of oil is investigated. To assess the effectiveness of the tandem fences, the viscous flow field around the fences in tandem are analyzed numerically. Then, the trajectories of oil droplets which escaped beneath the fore fence are computed applying the Lagrangian particle-tracking method, to check under what conditions the droplet can be contained between the tandem fences. The validity of the calculated trajectories is checked experimentally by using spherical beads made of paraffin and droplets of kerosene, and the model fence of draft of 4 cm. The numerically predicted trajectories of the droplets show fairly good agreement with the experimental results. The method is applied to predict the motion of the weathered oil. It is shown, numerically, that most of the leaked oil can be trapped between tandem fences, when the distance between the fences is about 10 times the draft of the fore fence.
1 (2)	1996	Boom failure mechanisms: Comparison of channel experiments with	Brown, Goodman, An, Bittner	A large outdoor flowing water channel has been used to obtain experimental data on boom failure mechanisms. Oil containment and failure around a simple barrier has been observed for oil viscosities from 10 to 5600 cSt at relatively low flow velocities from 0.10 to 0.20 m/s. The centre line profiles of stable contained slicks have been measured and underwater videos of escaping oil have been made when the barrier

		computer modelling results		failed. These experiments have been duplicated with a computational fluid dynamics model of the channel and barrier, and satisfactory agreement between the simulated and the experimental measurements has been obtained. The study indicates that computer simulations of these complex processes can be used to obtain data about failure mechanisms that would be difficult to measure experimentally.
1 (2)	1993	Can oil slicks be contained?	Fitzmaurice, Johnston	Oil booms are the primary device for the containment of oil spills. Booms may fail to contain low viscosity oil slicks because of drainage or entrainment failure. These failures, where the oil has low viscosity, have been identified in the technical literature both experimentally and theoretically. These results suggest that containment of low viscosity oil slicks can be successful. Delvigne (1) introduced the phenomena of critical accumulation which was a failure that is unique to the containment of high viscosity oil. His experimental results suggested that oil spill containment was impossible where current speeds exceeded ≈ 0.15 m/s. This paper presents the observations of an experimental program assessing the containment of high viscosity oils. Details of a numerical model developed to predict the failure behaviour of high viscosity oil is presented. A multiple boom system is suggested as a means of avoiding critical accumulation failure and thus achieving the goal of enhanced oil slick containment high viscosity oil.
1 (2)	2004	Experimental, numerical and optimisation study of oil spill containment boom	Muttin, Guyot, Nouchi, Variot	The oil spills consecutive to the shipwrecks of ERIKA and PRESTIGE, showed the efficiency limits of oil spill booms. It is admitted that a stream higher than 1 knot causes oil flight. This study presents a physical modelling upon complementary aspects. The objective is to reinforce the boom efficiency. Firstly, numerical and experimental tests in a vertical 2D section are described. The tests are made on a reduced scale model in fresh water, with plant oils. Secondly, a simplified structural model for the boom is presented. The equilibrium of a chain, with articulated bodies, gives the equilibrium equations in 3D. This provides the equilibrium shape of the boom and the possible flight of the boom in terms of stream velocity. Finally, an optimisation procedure of the boom plan is described. It takes into account the barrage handling, the oil containment

				efficiency, and the barrage storage. This work is done with the support of the French research group RITMER.
1 (2)	2004	Investigation of the effectiveness of tandem oil fences under currents	Lee, Han, Kang, Lee	The behavior of the flow passing a tandem oil fence, and the performance of the fence, were investigated by experimental and numerical methods. The flow characteristics between tandem fences were measured by the particle image velocimetry (PIV) method for the rigid and open free surface between the two fences in order to gather reference data for numerical investigations. A method of assessing a tandem fence by tracing the movement of an oil droplet around the fence is introduced. The effect of the current speed, the separation distance between the two fences, the relative draft of the two fences, and the water depth on the oil containment between the fences was investigated.
(1) 2	2013	A numerical study on the wind effect on the oil containment by boom	Kang, Lee, Jung	We numerically investigate the effect of wind on the oil containment by boom. The numerical simulations are carried out by using commercial computational fluid dynamics software, FLUENT with Volume of Fluid method. A boom containment of high viscosity oil in real scale is simulated, where the lengths of boom and simulated domain size are practical. It is found that the effect of wind becomes significant above the threshold velocity of 10 m/s. At wind velocity of 35 m/s, the leakage rate is twice larger than the leakage rate at 10 m/s.
(1) 2	1969	Fluid dynamics of floating oil containment by mechanical barriers in the presence of water currents	Wicks	Experiments on oil containment by mechanical barriers have led to identification of the important physical phenomena controlling the extent of an oil slick and have illustrated flow conditions leading to failure of the barrier. A mathematical model has been developed to generalize the experimental results. 3 regions in the oil layer are identified. (1) A gravity wave region near the upstream end of the slick, which lead to oil droplet formation if water flows faster than a certain critical speed. (2) a boundary layer region where drag of the flowing water causes gradual thickening of the oil, and (3) a skirt region where the flowing water causes oil droplets still present to be swept under the barrier. Another mechanism of failure is discussed whereby oil could escape under the boom by a kind of draining action. Example calculations and design charts are presented which may be useful in deciding whether stationary mechanical barriers

				would work at all in given cases, and in selecting the proper depth of skirt and length of boom required in those cases where mechanical barriers are feasible. Where stationary barriers are not feasible, the results can be used to establish minimum boom drift velocity to prevent oil from escaping.
(1) 2	2017	Improved SPH simulation of spilled oil contained by flexible floating boom under wave–current coupling condition	Shi, Li, Chen, He, Shao	A multi-phase Smoothed Particle Hydrodynamics (SPH) method is developed to model the failure process of a flexible oil boom. An algorithm is proposed based on the dynamic boundary particles (DBPs) for preventing particle disorders of multi-phase fluid particle movement around solid boundary. The improved multi-phase SPH model is firstly validated by the experimental data of a wedge falling into a two-layer oil–water fluid. Then a numerical wave–current flume is established with a piston-type active absorbing wave generator and a circulating current system. The model reliability is validated against the measured vertical profiles of velocity. Simulation of the flexible floating boom movement is implemented by introducing a Rigid Module and Flexible Connector (RMFC) multi-body system. The model is finally applied to the simulation of movement of a flexible floating boom in containing industrial gear oil under the action of combined waves and currents. Good agreements are obtained between the SPH modelling results and the experimental data in terms of the ambient wave–current field, hydrodynamic responses of the floating body and evolution process of the oil slick for the flexible boom. The hydrodynamic responses and containment performances of the flexible floating boom are also compared with those of the rigid one. It is found from both the experimental and numerical results that two vortices of the water phase exist in the front and rear of the boom skirt and the size of the front vortex decreases with increase of the current velocity while the wake vortex is reversed. It is also found that the skirt of the flexible boom has a larger magnitude of swaying and rolling than the rigid one and the maximum quantity of escaped oil of a flexible boom within one wave cycle is about 5% more than a rigid one under the present test conditions.
(1) 2	2010	Numerical experimental set-up of oil	Feng, Wu, Zhang	Based on the Navier-Stokes equations for viscous, incompressible fluid and VOF method, the numerical experiment platform of oil containment by rigid floating boom in wave is established, utilizing the commercial CFD software FLUENT, and the waves

		containment by rigid floating boom in wave		are generated by defining the velocity of water particle on the inlet boundary. The volume of fluid (VOF) model is used to distinguish the three immiscible fluids (air, oil and water) and to track the interface between them. In this paper, a second order Stokes-wave with the relative wave height of 0.16 is selected as the incoming wave to simulate the shape of the oil slick and analyze the oil containment by rigid floating boom under this wave. The numerical simulation of the oil containment of the spilled oil on the sea under wave conditions is achieved. Numerical results of oil containment by boom in wave agree well with the corresponding researches and the real conditions. Compared with the traditional physics model experiment, the numerical experiment platform can be carried out with the advantages of low cost, easy reconstruction, unlimited to the model scale, high measuring accuracy and so on. It is shown that the present numerical platform is effective, reliable and accurate and can be applied to simulate the oil containment by booms in wave conditions.
(1) 2	2017	Numerical modelling of floating oil boom motions in wave-current coupling conditions	Shi, Li, Zhang, Peng, Chen, Zhou, Mao	Containment booms are commonly used in collecting and containing spilled oil on the sea surface and in protecting specific sea areas against oil slick spreading. In the present study, a numerical model is proposed based on the N-S equations in a mesh frame. The proposed model tracks the outline of the floating boom in motion by using the fractional area/volume obstacle representation technique. The boom motion is then simulated by the technique of general moving object. The simulated results of the rigid oil boom motions are validated against the experimental results. Then, the failure mechanism of the boom is investigated through numerical experiments. Based on the numerical results, the effects of boom parameters and dynamic factors on the oil containment performance are also assessed.
2	2002	A Numerical Model for the Confinement of Oil Spill with Floating Booms	Zhu, Strunin	Zhu and Strunin (Appl. Math. Model., 2001) presented a simple mathematical model for the confinement of oil spills, through the use of floating barriers such as booms, in an open ocean. In that paper, solutions with an indirect approach to solve the nonlinear integral equation system were discussed. In this paper, we shall present some recent results of the model obtained with a direct approach. This direct solution procedure enables us to quantitatively discuss the relationship among three important physical

				parameters, the Froude number, F, the barrier submergence depth, l, and the amount of oil trapped by the barrier, q. Although a further upgrading of our model to somehow incorporate the shear stress on the oil-water interface appears to be necessary, the complexity involved in such upgrading warrants the current model as an initial step in our modelling exercises of this complicated flow phenomenon.
2	1996	Dynamic modelling of oil boom failure using computational fluid dynamics	Goodman, Brown, An, Rowe	The common response to an oil spill on water is to contain the oil with booms and recover it with skimming devices. In some situations, however, the booms cannot hold the oil and the oil will escape underneath the boom due to hydrodynamic forces. Computational fluid dynamics (CFD) is a powerful modelling tool combining fluid dynamics and computer technology. We have utilized a commercial CFD program, Fluent, to simulate the oil-water flow around a boom. The studies accurately model channel experiments conducted in recent years. The studies show that the flow patterns around booms are modified by the presence of oil and, therefore, suggest that towing and wave-conformity tests of booms will not be meaningful unless they are undertaken with the presence of oil.
2	2015	Experimental and numerical investigations on reliability of air barrier on oil containment in flowing water	Lu, Xu, Xu, Xie, Wu, Yang, Liu	Air barriers have been recently developed and employed as a new type of oil containment boom. This paper presents systematic investigations on the reliability of air barriers on oil containments with the involvement of flowing water, which represents the commonly-seen shearing current in reality, by using both laboratory experiments and numerical simulations. Both the numerical and experimental investigations are carried out in a model scale. In the investigations, a submerged pipe with apertures is installed near the bottom of a tank to generate the air bubbles forming the air curtain; and, the shearing water flow is introduced by a narrow inlet near the mean free surface. The effects of the aperture configurations (including the size and the spacing of the aperture) and the location of the pipe on the effectiveness of the air barrier on preventing oil spreading are discussed in details with consideration of different air discharges and velocities of the flowing water. The research outcome provides a foundation for evaluating and/or improve the reliability of a air barrier on preventing spilled oil from further spreading.

2	2013	Numerical modelling of oil spill containment by boom using SPH	Yang, Liu	The ocean environment is protected from oil pollution usually by using floating booms, which involves water-oil two-phase flow and strong fluid-structure interaction. In this paper, a modified multi-phase smoothed particle hydrodynamics (SPH) method is proposed to model oil spill containment by using a moving boom. Four major influencing factors including oil type, moving velocity and skirt angle of the boom, and water wave are investigated. The SPH simulation results demonstrate different typical boom failure modes found in laboratory experiments. It is shown that the ability of a boom in containing oil is not only affected by its own characteristics, but also closely related to external environmental factors. It is found that boom failure is more likely to happen for heavy oil, high boom velocity, negative skirt angle, and/or in the presence of water waves.
2	1997	Numerical modelling of the dynamics of an oil slick spilled on flowing water	An, Brown, Goodman, Rowe, Zhang	Numerical modelling of oil slick dynamics behind a containment boom has been conducted based on experiment in a flowing channel. The modelling results are obtained using a commercial computational fluid dynamics (CFD) software. Fluent, and are in a good agreement with the channel experiment. The oil slick movement around the boom observed in the channel experiment has been accurately modeled. For the case of successful oil containment, the predicted and measured oil slick profiles are consistent with each other. For the case of oil loss, the predicted and measured critical velocities are identical. Therefore, the numerical modelling is well verified and validated by the channel experiment and can be used to guide the design of new booms.
2	2001	Oil containment by boom in waves and wind. III: Containment failure	Fang, Johnston	The numerical simulation of interfacial waves and waves on the free surface of an oil slick under combined current and wave conditions is presented in a companion paper. The present paper focuses on the application of a numerical model developed by Fang and Johnston that numerically predicts the relationship between oil containment failure velocity and wave/wind parameters. Comparative laboratory experiments have been undertaken in a 24-m-long, 0.4-m-wide, 0.4-m-deep wave flume. Detailed comparisons and discussions of the computed and experimental results are provided. The effects of oil viscosity and density on oil containment failure velocity receive particular attention, and the influences of other parameters such as oil volume and boom draft

				are also quantified. It is concluded that the developed numerical model provides an economic, convenient, and effective method of predicting oil containment failure under various sea conditions.
2	2013	Oil Containment by Floating Boom under Wave-current Coupling Condition. I : Numerical Experimental Platform	Feng, Zheng, Wu	
2	2013	Oil containment by floating boom under wave-current coupling condition. II: Containment failure	Zheng, Feng, Wu	The numerical experimental platform of oil containment by floating boom under combined wave and current conditions was presented in a companion paper. The present paper focuses on the application of the platform that numerically predicts the relationship between oil containment failure velocity and wave parameters, oil parameters and boom drafts. The effects of oil density and wave parameters on oil containment failure velocity receive particular attention, and the influence of other parameters such as initial oil volume and boom draft are also quantified.
2	2009	Velocity profiles and interface instability in a two-phase fluid: investigations using ultrasonic velocity profiler	Amini, Ceasre, Schleiss	In the present study the velocity profiles and the instability at the interface of a two phase water-oil fluid were investigated. The main aim of the research project was to investigate the instability mechanisms that can cause the failure of an oil spill barrier. Such mechanisms have been studied before for a vast variety of conditions (Wicks in Fluid dynamics of floating oil containment by mechanical barriers in the presence of water currents. In: Conference on prevention and control of oil spills, Although the velocity field in the region behind the barrier can influence the failure significantly, it had not been measured and analyzed precisely. In the present study the velocity profiles in the vicinity of different barriers were studied. To undertake the experiments, an oil layer was contained over the surface of flowing water by means of a barrier in a laboratory flume. The ultrasonic velocity profiler method was used to measure velocity

				profiles in each phase and to detect the oil-water interface. The effect of the barrier geometry on velocity profiles was studied. It was determined that the contained oil slick, although similar to a gravity current, cannot be considered as a gravity current. The oil-water interface, derived from ultrasonic echo, was used to find the velocity profile in each fluid. Finally it was shown that the fluctuations at the rearward side of the oil slick head are due to Kelvin-Helmholtz instabilities.

3. **Summary of Highly Ranked Papers: Scale Modelling list**

Rel	Year	Title	Authors	Summary
1	1996	Oil containment performance of submergence plane barriers	Swift, Coyne, Celikkol, Doane	Submergence plane oil containment systems are investigated in a laboratory study using large scale physical models in a recirculating flume. Though submergence plane systems have the potential for retaining oil at higher current speeds than conventional oil booms, comparatively little previous research has been done on their operating mechanisms and capabilities. This need is addressed by considering a system consisting of a submergence plane, a containment region and a conventional vertical barrier. The system functions by trapping oil in the quiescent containment region protected by the submergence plane. Faster currents are tolerated because, unlike standard booms, the oil is not collected in a position exposed to the incident current. In initial experiments using oil substitutes and oils, an effective generic cross-section configuration was identified. Oil retention tests were then conducted using oils having a wide range of viscosities and densities. Incident flow speed was 0.772 m/s (1.5 knots) which is nearly 3 times the critical leakage velocity for a single vertical barrier under the same flume conditions. Retention results above 80% for all tests and above 90% for several experiments indicated very good to excellent performance. To explore fluid dynamic processes further, velocity distribution measurements were made using a laser Doppler velocimeter.
1 (2)	1974	Development of a novel high velocity oil slick skimmer	Lindenmuth	Experimental investigations show that thin slicks of oil can be recovered in currents of up to 10fps with a new Surface Velocity Retarder Oil Skimmer (SVROS).This collection device is composed of an array of closely spaced flat plates. The plates serve to gradually dissipate the kinetic energy of the oil/water inflow so that oil can be collected at high relative velocities without the entrainment losses typical of all simple oil booms in currents over about one knot. Tests, in prototype scale, were performed on a thin model of the device. Test variables included velocity, plate spacing and depth, oil type, and slick thickness. The test results are presented with conclusions and recommendations for further development.

(1) 2	1972	Experimental procedures used in the development of oil retention boom designs	Miller, Lindenmuth, Lehr, Abrahams	The experimental procedures used in the development of oil retention boom design criteria are presented in detail. Emphasis is placed on the procedures used to determine the oil containment ability and structural loads on the boom as a function of environmental conditions. The critical scaling parameters for oil containment tests are presented and the test procedures which have been developed are described. It is concluded that it is critical to scale both Froude and Weber number. Tests to determine structural loads can be conducted using standard ship towing tank procedures. However, it is necessary to scale the elastic properties of the boom and its mooring system. There are uncertainties with respect to some parameters which cannot be properly scaled in oil containment tests. Thus, carefully conducted full-scale trial results are required. Available procedures and current plans to obtain full-scale data are presented.
(1) 2	2009	Velocity profiles and interface instability in a two-phase fluid: investigations using ultrasonic velocity profiler	Amini, DeCesare, Schleiss	In the present study the velocity profiles and the instability at the interface of a two phase water-oil fluid were investigated. The main aim of the research project was to investigate the instability mechanisms that can cause the failure of an oil spill barrier. Such mechanisms have been studied before for a vast variety of conditions (Wicks in Fluid dynamics of floating oil containment by mechanical barriers in the presence of water currents. In: Conference on prevention and control of oil spills, Although the velocity field in the region behind the barrier can influence the failure significantly, it had not been measured and analyzed precisely. In the present study the velocity profiles in the vicinity of different barriers were studied. To undertake the experiments, an oil layer was contained over the surface of flowing water by means of a barrier in a laboratory flume. The ultrasonic velocity profiler method was used to measure velocity profiles in each phase and to detect the oil-water interface. The effect of the barrier geometry on velocity profiles was studied. It was determined that the contained oil slick, although similar to a gravity current, cannot be considered as a gravity current. The oil-water interface, derived from ultrasonic echo, was used to find the velocity profile in each fluid. Finally it was shown that the fluctuations at the rearward side of the oil slick head are due to Kelvin-Helmholtz instabilities.

2	2005	Development of a high current streamlined oil boom/skimmer for inland waterways	Folsom, Johnson	The streamlined oil boom/skimmer uses a slightly submerged slotted hydrofoil to skim a thin layer of oil and water into an attached sump where kinetic energy is dissipated, the oil and water are separated and the oil is retained and recovered. Because of the system's simplicity and low drag, it can be deployed as a high speed skimmer supported by a catamaran or as a high current boom with several adjacent sections spanning a high current area. Earlier work, reported in the 1973 and 1975 Joint Conferences on the Prevention and Control of Oil Spills, included preliminary feasibility tests, in which the potential for excellent high current performance was demonstrated, and small-scale bow wave tests. The work reported here includes applying the previous results to full-scale models, refining sump design, developing a stability control/flotation system and integrating these subsystems in a pre-prototype model for testing at OHMSETT.
2	2008	Effect of waves on a flexible containment oil barrier	Amini, Boillat, Schleiss	Oil spills are of major environmental concern in coastal regions. Unfortunately, experience shows that even the best safety efforts can-not prevent occasional occurrence of oil spill accidents at sea. Hence, it is important to improve techniques and equipment that facilitate spill cleanup under such circumstances. Oil spill containment booms are known as an effective equipment to contain slicked oil and to avoid its spread over the water surface. Nowadays most of the commercial oil containment booms consist of flexible skirts, whereas the existing research mainly considers behaviour of rigid barriers. The main aim of an ongoing research is to investigate the efficiency Limits of a flexible barrier in containment of oil spills in deep undulating water. For this purpose, two-dimensional experiments with a flexible oil containment barrier have been carried out in a laboratory flume equipped with a pneumatic wave generator. The results have been analysed and compared with similar cases for a rigid barrier. The hydrodynamic basics describing oil containment behind a rigid barrier have been reviewed. Influence of waves on containment procedure was scarcely investigated even in case of a rigid barrier. In this study failure velocity of containment system was measured in presence of waves with different heights and frequencies. It was shown that increasing wave height augments the instability at oil-

				water interface and provokes oil droplet entrainment into the flowing water. To take into account the effect of barrier's geometry, different drafts and ballast weights were examined. Using deeper barriers do not change the initial failure velocity significantly but it influences the loss rate once the failure starts.
2	2002	Field experiments at the OHMSETT facility for a newly designed boom system	Wong, Barin, Lane	Large quantities of oil are produced, distributed, and consumed throughout the world. Petroleum-based oil is used as a major power source to fuel the factories, various modes of transportation, and in many everyday products. The full-scale test performance of an innovative system was analyzed. The boom system consisted of a ramp boom, which was inclined 15°C with respect to the water surface, followed by three conventional booms with different drafts. The boom system had a better collection efficiency than simple conventional booms. The efficiency of simple booms was very low at oil-water relative velocities > 0.5 m/sec. Hydrocal 300 and Calsol were used as test oils.
2	2002	Field experiments at the Ohmsett facility for a newly designed boom system	Wong, Barin, Lane	In this paper, the full-scale test performance of an innovative boom system is analyzed. The boom system consisted of a ramp boom, which is inclined with respect to the water surface, followed by three conventional booms with different draft lengths. According to the test results, the boom system is observed to have a better collection efficiency than simple conventional booms. The efficiency of simple booms is known to be very low at oil-water relative velocities greater than 1 knot. A high of 86.5% collection efficiency was achieved by the new boom system at a tow speed of 1.5 knots. The new boom system was found to have a critical tow speed of 1.89 knots, beyond which the collection efficiency decreases rapidly. This tow speed of 1.89 knots corresponds to a critical Froude number of 0.36.
2	2005	Flexible, submergence plane oil containment systems	Swift, Dugan, Nourse, Steen, Celikkol, Doane, Hansen	Flexible, floating submergence plane barriers were developed for intercepting and containing oil spills under fast water conditions, that is, at speeds greater than 0.5 m/s (1 knot). When the perpendicular component of relative velocity exceeds 0.5 m/s (1 knot), conventional oil booms are subject to leakage limiting their usefulness in currents and alongside vessels used in "sweeping" operations. In fast water, submergence plane barriers retain oil by allowing the flow to drive incident oil down an

				inclined bow to a gap opening where the oil enters and is trapped in a protected containment volume. After optimizing cross-section shape in flume tests using oil with a wide range of physical properties, two systems were developed - a moored containment configuration and a vessel of opportunity skimming system (VOSS). A 12.2-m (40-foot) wide moored system prototype was constructed and tested at OHMSETT where it consistently retained heavy oil at speeds of 1 m/s (2 knots). Practical and logistical issues were addressed infield deployments carried out in the Piscataqua River, New Hampshire. In contrast, early VOSS experiments at high speeds showed that lift forces on the submergence plane needed to be counteracted by a horizontal hydrofoil mounted transversely below the submergence plane at a negative angle of attack. After development using a 1.7-m (5.6-foot) wide VOSS model in tow tank and field experiments, a 4.3 m (14 foot) wide model was constructed and tested at OHMSETT. The model towed level with no submergence plane rise at the top carriage speed of 3.3 m/s (6.5 knots). Nearly all heavy oil was retained at speeds below 1 m/s (2 knots), while 59% of the oil encountered was retained at a convenient vessel operating speed of 1.4 m/s (2.8 knots).
2	2005	Inclined boom system with hydrofoil for waters with waves	Wong, Miller, Boccabella	Containment booms are used to contain the spread of oil after a spill or inadvertent discharge to reduce the possibility of polluting shorelines. A study was carried out to design and build an innovative oil boom capable of collecting oil in waters with waves. The hydrofoils were effective at high flow rates and waves. At low flow rates, the two boom units relied chiefly on the Styrofoam flotation devices for stability. For experiments without waves, the collection efficiency ranged from a low of 95.9% at the highest velocity to a high of 99.6% at a low velocity. With waves, at least three forward waves were created for the high and intermediate velocities. At the low velocity, at least five forward waves were created. The collection efficiency ranged from a low average of 51.7% at the highest velocity to a high average of 69.3% at the intermediate velocity.
2	2003	Oil spill boom design for waves	Wong, Stewart	The objective of this research was to design and test boom arrangements that will be able to function effectively in the presence of waves and turbulent conditions and be

				modular and free floating. The designs were based on the principle that fluid particles in waves traverse in a circular pattern, so it was imperative to take advantage of that feature. Three models were built and tested in the open channel apparatus introducing the plausible validity of vertical cascading and sinusoidal tapering of an oil boom system. Given several flow velocities, the first two designs averaged efficiencies of 79.2% and 68.2%, respectively. The final model was tested through a series of three conditions: An ideal straight-on condition, a straight-on condition with the first surface was completely out of the water and one condition where the center line of the boom was at an angle to the water current. These three configurations yielded averaged efficiencies of 87%, 80.1%, and 70.9%, respectively.
2	2003	Oil spill containment by a flexible boom system	Wong, Bains	In this paper, a specific boom arrangement is quantitatively analyzed. The boom arrangement was led by a flexible ramp boom, which used the energy of the incoming flow to attain a desirable angle of inclination. It consisted of a number of flaps to adjust itself to non-uniform flow conditions. Vinyl sheets of varying bending stiffness were used to achieve necessary deflections. The ramp boom was setup with three conventional booms downstream. Open channel experiments were carried out for a large number of dimensionless parameters. Volume analysis was performed to determine the amount of the collected oil. The effects of Reynolds number, Froude number, depth ratio, oil relative viscosity, oil relative density, number of flaps and inclination angle on the collection efficiency of the boom system were investigated. The separation distances of the consecutive booms were also investigated. The variation of the scales of the geometric parameters with respect to the draft of the ramp boom and the variation of the above-mentioned dimensionless parameters aided in determining the optimum interval for the total span of the boom system. The critical limiting ratios of total span of the ramp boom system to the draft of the ramp boom were determined as 9.9 and 14.6. The optimum collection efficiency of 100% was obtained at a maximum flow speed of 0.305 m/s corresponding to a Froude number of 0.51. This value would correspond to a prototype flow speed of 1 m/s (about 2 knots) with Froude number scaling.

2	2005	Oil spill recovery methods for inlets, rivers and canals	Wang, Kusijanovic	The objective of this research is to design and test a boom arrangement that will have a collection efficiency which is better than that of simple booms. The design arrangement consisted of a ramp at an angle to the water level and of a set of five simple booms, not all -with the same skirt-lengths. The variable parameters in the boom geometry tested -were the angle of attack of the ramp and the horizontal separation of the ramp from the other booms. Tests were done at two different velocities. There was enough data for the flow velocity of 1.3 ft/s (2.8 knots) to derive correlations between these geometry variables and the oil collection efficiency. From the experiments in the open channel apparatus it was found that this boom arrangement was quite effective, collecting around 98% of the spilled oil when the angle of attack and horizontal separation reached their optimum values. The analysis shows a projected maximum collection efficiency of 99%. The experiments also showed that four simple booms are more than adequate, with the last one having a longer skirt.
2	2015	Preparing the automatic spill recovery by two unmanned boats towing a boom: Development with scale experiments	Giron-Sierra, Gheoghita, Angulo, Jimenez	The menace of floating spills is frequently solved using a team of ships towing a boom. This operation involves specific control and coordination aspects. Some automatic advice, on board the ships, could be helpful for the pilots. Moreover, it could be convenient to have the alternative of using unmanned boats, especially if the spill represents a danger for humans. This paper studies the control and coordination needs for automatically towing a boom, and proposes the use of unmanned boats with autonomous control. The research is supported by simulations and experiments with scaled boats towing a boom.
2	1977	Use of floating deflectors for oil spill control in fast flowing waters	Eryuzlu, Hausser	Experiments were conducted in a straight flume to study the characteristics of hydrofoils used as deflectors. The general location of the several oil refineries around Montreal-East was selected for testing the practical application of the proposed method on a model of the St. Lawrence River. Results show that in the majority of cases without deflectors only about 40% to 50% of the oil would go in the north arm of the river, whereas with the deflectors this can increase to about 90%.

2	1994	Using vortices to trap oil in flowing water	Brown, Goodman, Nicholson	Conventional containment booms fail at relatively low towing speeds or in streams at low water speeds. A three year program to investigate alternative containment concepts utilizing both a laboratory flume and a large outdoor channel has yielded several promising containment ideas. Experiments in the large channel have shown that 'V' booms may be used to generate vortices from which spilled floating oil can be collected. It may be possible to trap viscous dense oils by first bringing them to the water surface with the use of air bubbles and a small amount of a surfactant.

Summary of Highly Ranked Papers: From Other list

Rel	Year	Title	Authors	Summary
1	2000	Instability study of oil slicks contained by oil boom systems	Fang	In this fundamental study of the instability that occurs in oil slicks contained by a single oil boom, the following factors are considered: gravity, interfacial tension, current velocity and depth, boom draft, oil viscosity and density. An advanced VOF (Volume of Fluid) algorithm has been developed to calculate the oil-water flow. The surface tension is modeled by CSF (Continuum Surface Force) method. About 1000 cases with large ranges of parameters have been investigated numerically. Some basic phenomena reported by other researchers are also found in the present numerical simulations. The numerical results give us a better understanding of the factors that play a part when a boom system fails to contain the oil. Among the numerous results obtained, it is observed that the stability of the oil slick movement is very sensitive to the Froude number, while the effect of the interfacial tension is negligible in the drainage failure and critical accumulation failure. The highly viscous oil slicks are subject to large-size oscillations; the low viscous slicks are easily stirred by the current and mixed with the water. The slicks with the oil viscosity of about 100cs are more stable. The depth of the water also affects the oil containment significantly. This is true especially when the current depth is shallow. In the study of the effect of the oil density, it is found that, as the criteria of the instability, the reduced gravity is more appropriate than the Froude number. The numerical model has also been applied to study the performance of an oil boom arrangement, the satisfactory result shows the promise that it can be used in aiding the oil boom design.
1	2013	Numerical modelling of oil spill containment by boom using SPH	Yang, Liu	The ocean environment is protected from oil pollution usually by using floating booms, which involves water-oil two-phase flow and strong fluid-structure interaction. In this paper, a modified multi-phase smoothed particle hydrodynamics (SPH) method is proposed to model oil spill containment by using a moving boom. Four major influencing factors including oil type, moving velocity and skirt angle of the boom, and water wave are investigated. The SPH simulation results demonstrate different typical boom failure modes found in laboratory experiments. It is shown that the ability of a

				boom in containing oil is not only affected by its own characteristics, but also closely related to external environmental factors. It is found that boom failure is more likely to happen for heavy oil, high boom velocity, negative skirt angle, and/or in the presence of water waves.
1	2017	Numerical modelling and experimentation of oil-spill curtain booms: Application to a harbor	Muttin, Campbell, Ouansafi, Benelmostafa	Oil-spill curtain booms are an important response device dedicated to containing and deviating floating pollutants. The hydrodynamic and structural limitations of curtain booms necessitate numerical modelling for efficient usage assessment. A four step model is proposed and applied during an exercise performed in the Galician region of Spain. Experimental results are used to produce a re-analysis of the model and improve contingency planning.
1	2002	Numerical simulation of boom failure	Ning	An oil-boom is a common tool to deal with oil spills on the sea surface. However, oil will escape underneath the boom and the containment will fail if certain fluid-dynamic conditions are not satisfied. This paper studies oil and water's dynamic behavior near an oil-boom by using a commercial computational fluid dynamics software, CFX4.3, in order to provide necessary numerical results for the improvement of boom techniques. The HOMOGENEOUS MODEL [35], which is simplified model of multi-fluids model integrated CFX4.3 software, is used to simulate 2-D two-phase immiscible oil-water transient flow with a free surface. This paper simulates two cases of oil-boom failure in water flow: the drainage failure and the critical accumulation failure. The computational results are consistent with the numerical ones of Cheng S.Y. [19] and An C.F. *et al.* [34] under same conditions. The critical failure velocities obtained in this paper are almost same as the experimental results of Delvigne [6] and Johnston *et al.* [7] for light a
(1) 2	2016	Application of computational transport analysis: Oil spill dynamics	Verma	Transport phenomena of one form or another, e.g. fluid dynamics, heat and mass transfer etc. are the fundamental underlying mechanisms that govern many chemical engineering processes. The rational design of practical applications typically requires the solution of complex coupled equations that cannot be solved analytically. Instead, numerical analysis is usually used for design and optimization. Computational fluid dynamics (CFD) is the method of choice for such analysis. In this thesis we use CFD

				to analyze complex and large scale transport phenomena that govern the dynamics of an off-shore oil spill. Specifically, we study the spill of oil from a drilling platform that is tethered to the sea floor off-shore from a land mass. We use a state-of-the-art multiphysics CFD program, FLOW3D, to study the spread of oil taking into account key phenomena and factors including water-oil two-phase flow, spill rate, properties of different oil grades and fluid-structure interactions as the platform is rocked under the influence of varying wave conditions. We use parametric CFD analysis to determine the impact of these factors on the spill dynamics. The model used for studying these effects is the Drift Flux Model which analyses the relative flow of two intermixed fluid components, one continuous and the other dispersed, based on a difference in densities. This helps in reducing the total number of field and constitutive equations. Two discrete densities for oil are used, 900kg/m^3 (light fuel oil) and 990kg/m^3 (heavy fuel oil). The computational model extends 3937ft (1200m) in x- direction, 3280ft (1000m) in y- direction, 328ft (100m) in depth in z- direction and the distance between the platform and landmass is 1640ft (500m).
(1) 2	2007	Contractile floating barriers for confinement and recuperation of oil slicks	Amini	Marine oil spills can cause serious environmental damages to natural resources and to those whose sustenance depends upon these resources. Unfortunately experience shows that even the best efforts have not prevented occasional occurrences of major accidents on the sea. As long as massive oil spills are probable, special techniques and equipment will remain essential to facilitate spill cleanup in coastal regions. Oil spill containment booms are the most commonly adopted techniques to collect and contain oil on the sea surface, or to protect specific areas against slick spreading. Recently, an anti-pollution boom called the Cavalli system, has been designed with the intention of preventing the spread of spilled oil by trapping it inside a flexible floating reservoir and improving the pumping operation by decreasing the reservoir surface, and consequently increasing the oil layer thickness. Although flexible barriers have become increasingly common as a cleanup facility, there is no more than inadequate elaborate knowledge about their behavior. According to an extensive literature review, most of existing researches, either physical or numerical, have been done for rigid

				barriers. The main motivation for introducing the present research project is to study the efficiency and operational limits of the Cavalli system. However, the objectives are not constrained to this particular case. The present investigation focuses on the behavior of flexible barriers containing spilled oil. Previous researches of containment booms, even for the case of rigid barriers, have been mainly carried out in calm water. Accordingly, the main concentration is devoted to the response of a flexible barrier in presence of sea waves. Both experimental and numerical approaches were pursued to evaluate the efficiency limits and behavior of flexible barriers. Two-dimensional experiments have been carried out in a laboratory flume 6.5 m long, 1.2 m deep, and 12 cm wide. Flexible and rigid barriers containing rapeseed oil were examined, with and without waves. As the first step, the behavior of a flexible barrier in currents without waves was studied and compared with that of a rigid barrier. The key challenge was to contain the oil behind a flexible barrier that can freely deform in the water flow. This could be achieved using a slotted side skirt on the boom where it faces the lateral wall of the flume. The failure mode observed for rapeseed oil was entrainment failure. The initial failure velocity of different experimental conditions was studied and an empirical relationship was suggested in order to assess the maximum permissible oil-water relative velocity as a function of barrier draft and oil characteristics. The geometrical characteristics of the contained slick were examined and empirical equations were proposed to predict the slick length and headwave thickness as a function of contained oil volume. The second and more significant step was to conduct experiments with a flexible floating barrier in presence of five different waves. The analysis focused on the relationship between the failure velocity and the wave parameters with an emphasis on the behavior of flexible barriers. Likewise, empirical equations were proposed for the prediction of the initial failure velocity and geometrical characteristics of the slick. A type of drainage failure, namely, surging drainage was observed in the presence of waves. It was shown that the wave steepness and oil layer thickness are the dominant parameters in such failure. It was noticed that by decreasing the wave period or increasing the wave height, interfacial waves became more aggressive and

				consequently failure initiated at a lower velocity. Flexible barriers were more sensitive to the variations of wave characteristics. Applying appropriate time and length scales, a critical wave period of 6 s and wave height of 0.5 m were proposed for the prototype. Accurate measurements of velocity profiles and flow patterns in the vicinity of barriers with different conditions by means of Ultrasonic Velocimetry Profiling (UVP) and Large-Scale Particle Image Velocimetry (LSPIV) methods provided a reasonable understanding of the hydrodynamics in the vicinity of the barrier. The characteristics of the headwave at the upstream end of the oil slick were deliberately compared with those of a gravity current. It was concluded that despite geometrical similarities, these two phenomena are quite diverse. Furthermore, the oil-water interface was traced by detecting the maximum ultrasonic echo intensity, and velocity profiles in water and oil phases were independently obtained. To enhance the understanding of the mechanisms associated with oil containment failure, numerical simulations of multiphase flow were carried out using FLUENT code, applying the finite volume method (FVM). Comparisons between the obtained flow pattern and velocity field derived from numerical simulations and precise experimental measurements confirmed the capability of the numerical model to simulate the multiphase flow. The turbulence wake downstream of rigid and flexible barriers was simulated with and without the presence of oil phase. The simulations revealed the effect of contained oil on flow pattern and consequently the drag force acting on the barrier. Simulations of a full-scale barrier proposed a drag coefficient, Cd, of 1.90 for rigid barriers. Contrarily a constant value for the drag coefficient cannot be attributed to flexible barriers, since its deformations do not allow it to form similar shapes at different velocities. Last but not least, comparing the drag force on a rigid barrier with that of a flexible barrier towed by the same velocity demonstrated the fact that the forces acting on the skirt could be appreciably reduced by allowing flexibility.
(1) 2	1970	Studies of oil retention boom hydrodynamics	Lindenmuth, Miller, Hsu	Results of an experimental investigation of oil containment hydrodynamics are presented with theoretical analysis to help explain the experimental findings. Two-dimensional model tests were performed using several petroleum products including

				diesel fuel and motor oil. Test variables in addition to oil properties were current, interfacial tension, gravity waves, slick volume, containment boom geometry, and boom depth. Also studied were three-dimensional effects and the efficiency of using absorbent additives and multiple boom configurations as containment aids.
2	1974	A Numerical Model of Droplet Entrainment from a Contained Oil Slick	Zalosh	A theoretical analysis of oil droplet entrainment from a contained oil slick moving relative to water has been performed as a function of relative oil-water velocity. A numerical method incorporating discrete vortices is used to calculate smooth stable headwave profiles at low velocities and unstable profiles at high velocities. An oil droplet formation criterion is formulated and applied to the numerically modeled headwave region. The computed critical velocity corresponding to the onset of significant droplet entrainment is in close agreement with recent laboratory measurements. The computed entrainment rates are in approximate agreement with experiment, but do not exhibit systematic variation with water current. Oil drop trajectories are calculated using realistic starting conditions, but the present work does not extend beyond the first intersection of the drop with the slick. Recommendations are given for extending the work to include: post-formation droplet dynamics, wave effects, turbulence effects, and barrier design changes.

4. Summary of Highly Ranked Papers: Less Pertinent List

Three ranked ‘3’; all others ‘4’ or ‘5’.

6. Papers Denoted as 3/4/5

Papers Denoted as 3/4/5: CFD Modelling

Rel	Year	Title	Authors	Summary
3	1996	An introductory mathematical model and numerical analysis of the evolutionary movement of oil slicks in coastal seas: A case study	Meyer, Cantao, Zanetti, Brebbia	A cooperative effort is being developed presently in Sao Paulo State to prepare both the State Environmental Agency (CETESB) and the National Petroleum Company (Petrobras) for more efficient clean-up strategies and actions. Two state universities (USP and UNICAMP) participate in this work. It is one of the subprojects of a greater effort for the creation of an official manual for organizing protection and cleaning activities, in the case of accidental oil spills. A mathematical model is presented, justified and a numerical scheme for obtaining and exhibiting approximate solutions is presented. Two simulations in the Sao Sebastiao Channel region, in Sao Paulo, Brazil are discussed.
3	2013	CFD simulation of bubble curtains applied to oil spill containment	Skjetne	The hydrodynamics of bubble curtains are investigated using an Eulerian-Lagrangian multiphase computational fluid dynamics (CFD). In particular CFD is used to study the hydrodynamics of bubble curtains for the purpose of oil herding or as oil booms. Simulations successfully captured the general dynamics of the bubble curtain but a more rigorous treatment of the free surface and the bubble size model will be required to capture quantitative trends.
3	1992	Diversion oil booms in current	Swift, Celikkol, LeCompagnon, Goodwin	Diversion boom approaches are developed to contain oil spills close to shore when high-current velocities prevent normal booming operations. In the diversion boom configuration, one end is anchored outside the spill, while the other is secured to shore. The boom is angled to the current to deflect the oil towards a shore pickup point. Boom configuration (planform shape) must be designed for each site-specific current environment to prevent leakage under the boom. A mathematical model relating mooring points, boom parameters, and current is developed, calibrated, and validated. The model is applied, as a representative example, to the design of a boom configuration for the Northeast Petroleum terminal on the Piscataqua River, N.H.

				Current information is obtained, and trial configurations are evaluated employing the model and using a leakage criterion of 0.31 m/s (0.6 knots) for the maximum normal component of current. The recommended design is found to behave as predicted in a demonstration experiment (without oil). Thus, the model and design procedures are observed to be suitable for diversion configuration design in high-speed currents.
3	1975	Fast current oil response system - Stage 1, SVROS development	Lindenmuth, Sundaram, Sinnerwalla	Combined theoretical and experimental studies show the effects of several parameters on the formation of a thickened pool of oil inside the Surface Velocity Retarder oil Skimmer (SVROS), and energy absorbing device designed to recover thin oil slicks in high relative currents. This collection device is composed of an array of closely spaced flat plates that serve to gradually dissipate the kinetic energy of the oil/water inflow so that the oil can be collected without the entrainment losses typical of simple oil booms in currents exceeding ~1 knot. Model tests were performed in prototype scale within thin models of the device in an 80 ft long towing tank and in a recirculating flume. Test variables included velocity (1-10 fps), oil type (from 5 to 1,000 cs), slick thickness (0.04-0.50 in) and model geometry. The final model configuration utilized several interchangeable modules so that pool formation was controlled over the wide range of inflow parameters to optimize the purity and efficiency of oil withdrawal from the SVROS. Curves defining the recovery performance are presented that show essentially complete oil recovery up to 5 fps with thin slicks of light fuel oil such as diesel fuel. Performance degrades with increases in velocity, viscosity and incident wave height.
3	1994	High pressure waterjets for oil containment in calm and wavy waters; a parametric study	Ghaddar, Nawwar	The use of high pressure waterjets (HPWJ) as oil barriers has been proposed and tested. It has been shown that a series of waterjets directed horizontally above the free water surface provide an effective means of containing or deflecting oil slicks. The waterjets generate a high speed air flow capable of moving the surface layer of the liquid. A numerical model is implemented to study the characteristics of the entrained turbulent air flow using the Spectral Element Method (SEM) and an algebraic turbulent model for the Reynolds stresses. A test of the code is done for turbulent Couette Flow to check the accuracy of the calculated shear stresses against published data. A

				parametric study is performed to evaluate the HPWJ system performance at various operating and design parameters which include manifold pressure, nozzle flow rate, nozzle characteristics, jet height and surface wave conditions. The total driving shear force and power required for effective containment are used as performance measures. Shear stress and the total driving shear force at the air-liquid interface are calculated over a reference waterjet distance. Performance is measured under calm and wavy sea conditions. It is found that the containment pressure required to generate a given shear force in wavy surface conditions are 30-50% less than those required in calm water. The driving shear force decreases as the jet height above the liquid surface increased. Shear forces also appear to decrease with the reduction of the entrained air flow. The latter is governed by nozzle type, spread angle and spacing. The results of the parametric study are consistent with the trends observed experimentally, and could be used in optimising the system design and performance as well as in setting appropriate operational conditions.
3	2001	Hydrofoil addition to a fast oil containment system	Dugan, Nourse, Swift, Steen, Celikkol	At the University of New Hampshire, work has been underway to develop a fast moving barrier. Coyne [2] and Swift *et al.* [3,4] showed that an underwater submergence plane towed ahead of an oil collection boom at an inclination of 12 to 15 deg (Fig. 2) allows oil to be collected at higher incident velocities. In operation, the inclined submergence plane bow drives the incident oil downwards to the gap opening where the oil enters and is trapped in the protected containment volume.
3	2001	Modelling the confinement of spilled oil with floating booms	Zhu, Strunin	An effective mechanical method of confining the oil spills in an open ocean is to use barriers such as floating booms. However, the confined oil may leak beneath a boom if either the towing speed of the boom or the amount of oil is too large. In this paper a simple mathematical model based on the potential theory is presented for the two-layer (oil and water) flow near a vertical barrier. A set of non-linear integral equations is formulated and solved numerically. For the indirect approach we adopted to solve the non-linear integral equations, the water velocity at the water-oil upstream contact point becomes a determining parameter of the final results. It is shown that the oil leakage under the barrier is impossible if the contact point is a stagnation one. For other non-

				stagnation cases, we were able to compute flows up to critical Froude numbers beyond which the oil will leak underneath the barrier.
3	1990	Numerical simulation of high pressure waterjet barriers for oil containment; a parametric study	Ghaddar, Nawwar, Sidawi	Computer Techniques in Environmental Studies III. Proceedings of the Third International Conference on Development and Application of Computer Techniques to Environmental Studies.
3	2006	Numerical study of an oil spill containment boom by the finite-element method	Muttin, Nouchi	Oil-spill boom is a technological response to water pollution by floating hydrocarbon. A boom is composed mainly of a floating tube, an immerged skirt, and a longitudinal chain on the skirt bottom. A membrane finite-element is used to represent numerically the different parts of the boom. The dominant external force comes from maritime current velocity. The gravity force comes mainly from the chain. It is balanced by the hydrostatic force applied to the tube bottom line. It is admitted that a sea current higher than 0.35 m/s produces oil leaks under the boom. The numerical model is available to study a full boom contingency planning. A boom section model is defined first, having a minimal number of degrees of freedom. It permits using a homothetic scaling to provide an accurate length model. After, by applying a duplication operator, a real-life length model is obtained (L>750 m). It is completed by the mooring of the barrage on the sea bed. The different assumptions made on the elementary model are given. Operational results on a boom contingency planning are also given. Parameters like skirt angle, skirt curvature, and chain stress, handle the boom response performances. This work was undertaken with the support of the French Environmental Administration.
3	2001	Oil containment by boom in waves and wind. I: Numerical model	Fang, Johnston	The effectiveness of a boom is associated with the hydrodynamics in the vicinity of the oil slick that it is attempting to contain, especially under open-sea conditions. A comprehensive investigation of oil containment is provided under various current, wave, and wind conditions. In this paper, a local two-phase nonlinear hydrodynamic numerical model is developed to simulate oil containment by a fixed boom under open-

				sea conditions. The shape of an oil slick is a function of time, and unstable waves may develop along the oil-water interfacial boundary. This paper describes a simulation of the behavior of the oil slick and deals with important interfacial boundary conditions. A non-hydrostatic pressure is introduced to accommodate the complicated local flow near the oil slick and a successive over-relaxation method is used to solve the pressure equation. A comparison is made of the oil slick shape with and without the hydrostatic pressure assumption. Some simple simulations of free-surface elevations under a number of wave conditions are performed to verify the numerical model. The computed results are in general agreement with those obtained from previous experiments.
3	2001	Oil containment by boom in waves and wind. II: Waves	Fang, Johnston	In the first of these companion papers, a two-phase numerical model was described and tested for some simple cases under wave conditions. This paper applies that numerical model to simulate the interfacial waves and oil free-surface waves under a number of key hydrodynamic conditions. The characteristics of oil-water interfacial waves and free-surface waves are discussed. Effects of currents and waves on the interfacial waves (interfacial elevation, oil-water relative velocity, and interfacial velocity components) are investigated. The variation of the oil thickness under current and wave conditions is also discussed. The computational results indicate that an increase in the incoming wave height and period may (1) cause instability of the oil-water interfacial waves near the front of the oil slick and this may promote entrainment failure; (2) increase the interfacial waves and free-surface waves at the boom; (3) lower the trough of the oil-water interface at the boom and thus promote drainage failure if the oil thickness exceeds the boom draft; and (4) decrease the freeboard of the boom and thus encourage oversplashing failure.
3	1996	Oil containment performance of submergence plane barriers	Swift, Coyne, Celikkol, Doane	Submergence plane oil containment systems are investigated in a laboratory study using large scale physical models in a recirculating flume. Though submergence plane systems have the potential for retaining oil at higher current speeds than conventional oil booms, comparatively little previous research has been done on their operating mechanisms and capabilities. This need is addressed by considering a system consisting of a submergence plane, a containment region and a conventional vertical

				barrier. The system functions by trapping oil in the quiescent containment region protected by the submergence plane. Faster currents are tolerated because, unlike standard booms, the oil is not collected in a position exposed to the incident current. In initial experiments using oil substitutes and oils, an effective generic cross-section configuration was identified. Oil retention tests were then conducted using oils having a wide range of viscosities and densities. Incident flow speed was 0.772 m/s (1.5 knots) which is nearly 3 times the critical leakage velocity for a single vertical barrier under the same flume conditions. Retention results above 80% for all tests and above 90% for several experiments indicated very good to excellent performance. To explore fluid dynamic processes further, velocity distribution measurements were made using a laser Doppler velocimeter.
3	1976	Oil slick instability and the entrainment failure of oil containment booms	Leibovich	The onset of droplet formation from contained oil slicks is interpreted to be due to the breaking of finite amplitude interfacial waves. These waves result from the equilibration of amplifying Kelvin-Helmholtz waves. Experimental evidence is shown to be consistent with this view. From this model, conditions for droplet shedding from the headwave alone and from the entire slick are derived. Also, an earlier result in the stability of thin slicks is shown to be in error.
3	2009	Oil spill boom modelling, numerical approximation and contingency plan optimization	Muttin	Using a non-linear membrane theory we establish a mechanical model for oil spill floating boom. The model is based on the minimization of the internal strain energy minus the external energy of the applied forces. The discretization of the boom uses a four-nodes quadrilateral finite-element. The non-linear variational problem is solved using the Newton-Raphson method. The vertical angle of the boom skirt is computed and is used to evaluate the oil containment efficiency. A boom plan tactical optimization problem is formulated. Several real-life operational constraints are given for the boom plan definition. Numerical examples illustrate the capability of the numerical model.
3	1995	Oil-slick instability near an oil boom: the influence of free-slip and exact	Sundararaghaven, Ertekin	In the event of an oil spill, oil booms are often used to contain the oil before attempting to skim the oil by using oil-skimmers. Under certain conditions, the oil droplets can leave the oil slick and enter the water. A simple balance of hydrodynamic forces on such a droplet results in an instability criterion which determines whether the droplets

		free-surface conditions		will be swept past the boom or not. This criterion depends on the pressure gradient along the boom. In this study, the solution of viscous flow past an oil boom problem by the fractional-step method in a curvilinear coordinate system is used to calculate the pressure gradient and to study the effectiveness of oil-containment by booms. The influence of approximate free-surface conditions, such as rigid-lid no-slip, rigid-lid free-slip, and the exact free-surface condition on the instability criterion is investigated.
3	1994	Potential and viscous flows past an oil boom: The instability problem	Ertekin, Sundararaghaven	An important problem in oil spill containment by booms is the instability of the oil-water interface at the boom. This instability, which represents the conditions under which oil can escape under the boom, is investigated. Both the potential- and viscous-flow models for thin slicks in two-dimensions are developed. Analytical instability formulas are derived using the velocity potentials for attached and detached flows due to uniform current past a flat plate in finite and infinite water depths. To understand the effect of viscosity on the instability criterion, the full Navier-Stokes equations are solved by the fractional-step method in time-domain to determine the pressure gradients along the boom. The numerically obtained viscous instability criterion is then compared with the potential-flow and experimentally determined instability criteria. The results show that the viscous flow model predicts a larger region of stability. It is numerically discovered from the instability criterion that the oil droplets at the boom, between the free surface and down to about 40% of the boom height can never escape, regardless of the current strength. It is also shown that the instability criterion depends weakly on the high Reynolds number. Reanalysis of the previous experimental data confirms these numerical findings.
3	1997	Prediction of Oil Boom Performance in Currents and Waves	Lee, Kang	The threshold velocity of surface currents causing the entrainment failure for oil booms is investigated and an empirical formula for the threshold velocity is proposed. A theoretical prediction of the deformation of the skirt of an oil boom due to surface currents is made, and the results of the prediction are verified by laboratory experiments. The skirt deformation results in reduction of the effective boom draft which in turn degrades the effectiveness of the boom. The motion of oil booms excited by the ocean waves are predicted and verified by experiments. The degradation in the

				boom effectiveness due to the wave motion is discussed. The effectiveness of tandem booms in trapping the leaked oil is investigated and a method of predicting an optimum separation distance between the two booms is described.
3	1980	Probable effectiveness of protection of estuaries by oil booms	Mulligan, Retief	An estuary threatened with pollution from an oil spill at sea can possibly receive some measure of protection by an oil boom. Oil containment capability of an oil boom is lost when structural failure of the boom or its anchorage system occurs or when critical escape velocities are exceeded. A computer numerical model has been developed to assess tensions developed in - and configurations taken up by - oil deflection booms when exposed to water currents. The computer model was calibrated by 1:10 scale physical model tests conducted in a hydraulic laboratory flume and the physical model was calibrated by prototype tests in the Berg River. Calculated tensions will dictate oil boom tensile strength requirements and end anchor design whilst water velocities in conjunction with oil boom configuration will indicate whether critical escape velocities will be exceeded.
3	2000	SlickMap: An interactive computer model of oil containment by a boom	Grilli, Fake, Spaulding	Simplified but accurate and efficient FORTRAN-based computational fluid dynamics (CFD) tools were developed for modelling the behavior of a two-fluid (oil-water) flow system, in a vertical plane through the boom apex, with the possibility of including rigid structures such as booms and a rigid bottom (quasi-hydrostatic model for the oil, and inviscid model for the water, plus the effect of friction and dissipation at the oil-water interface and within the slick). Model results were calibrated using OHMSETT's experiments. The CFD tools were linked to and run by SlickMap's VB interface, which automatically sets-up data and grids for the models, using only a few simple user-supplied parameters. SlickMap can provide both significant insight and useful quantitative results regarding oil slick containment by booms.
3	2000	SPAM -- Submergence Plane Analysis and Modelling for a fast	Fullerton, Roman	Conventional oil booms like those found standard in the oil transportation industry have been an important tool in oil spill recovery. These containment booms are, however, limited by moving water, everyday tidal currents in particular. The failure of an oil boom occurs when the perpendicular component of the current speed exceeds a critical value, which has been determined to be between 0.6 and 1.0 knots, depending on the

		current oil containment barrier		type of oil. A flexible oil barrier and containment device, known as the 'Bay Defender', can successfully collect floating oils in currents nearly three times that speed. The purpose of this yearlong student project was to study the fluid dynamics around submergence planes of varying shapes with the intention of improving containment performance even further.
3	1995	The calculation of the instability criterion for a uniform viscous flow past an oil boom	Ertekin, Sundararaghaven	An important problem in oil spill containment by booms is the instability of the oil-water interface at the boom. This instability, which represents the conditions under which oil can escape under the boom, is investigated. A viscous flow model for thin slicks in two dimensions is developed. To understand the effect of viscosity on the instability criterion, the full Navier-Stokes equations are solved by the fractional- step method in time-domain to determine the pressure gradients along the boom. The numerically obtained viscous instability criterion is then compared with the potential flow and experimentally determined instability criteria. Analytical instability formulas for potential flows are based on the velocity potentials for attached and detached flows due to uniform current past a flat plate in finite and infinite water depths. The results show that the viscous flow model predicts a larger region of stability. It is numerically determined from the instability criterion that the oil droplets at the boom between the free surface and down to about 40 percent of the boom height can never escape, regardless of the current strength. It is also shown that the instability criterion depends weakly on the high Reynolds.
3	2011	The deflection angle impact on the oil containment by boom based on the numerical wave flume	Feng, Wu, Zhang	The 2-D numerical wave flume, based on the Reynolds Averaged Navier-Stokes equations and the standard k - ε turbulence model, was developed to simulate the turbulent flows with the free surface, in which the volume of fluid (VOF) method was used to handle the large deformation of the free surface and the relaxation approach of combined wave generation and absorbing was implemented, utilizing the commercial CFD software-FLUENT. The relationship of the wave parameters, initial failure velocity and the deflection angle was investigated.

3	2015	Theoretical and experimental study of an effect of oil transfer behind booms	Ermakov, Kapustin, Molkov, Sirotkin, Chaeban	According to airborne observations of ocean surface, attempts to contain and recover oil spills using booms may result in partial transmission of oil behind fencing. Results of theoretical and experimental studies of an effect of oil emulsion transfer behind booms are presented. Numerical simulation of the motion of particles of the emulsion in the flow field of near a barrier (booms) is performed. Laboratory and field experiments using special particles, simulating oil emulsion are carried out, and good agreement between numerical results and experiment is obtained. Different regimes of the dynamics of particles were observed, exactly: Barrier particle retention at low speeds of the flow - with Froude numbers less than «critical»; the passage of particles at high speeds corresponding to the Froude number excess of the critical level. An important role of a natural (biogenic) film, accumulating in front of the barrier flowing around by a flow is demonstrated. It is shown that the film results in retention of the emulsion on the water surface and in reduction of the particle transfer behind the barrier. Enhancement of the particle transfer behind the barrier due to surface waves is revealed. Physical analysis of particle dynamics in the flow and conditions of emulsion transfer behind a barrier is given, and qualitative explanation of the results of numerical and physical experiments is presented.
4	2014	A CFD (computational fluid dynamic) simulation for oil leakage from damaged submarine pipeline	Pengzhi,Pan	
4	1975	A natural limit to the containment and removal of oil spills at sea	Leibovich	A simple statistical model is developed to investigate the effect of turbulence in removing oil from the sea surface. The relationship and importance of vertical turbulent transport to oil spill containment and clean-up operations is emphasized. In its final form, the model allows a tentative conclusion to be made concerning the probable

				success of such operations, with wind speed and oil type being the governing parameters.
4	2017	Analysis of an emulsified oil slick	Collins, MacKay, Wong	The performance of mechanical nonporous booms as oil-spill containment devices has been studied previously, and the behavior of contained oil slicks has been observed and analyzed. These investigations are restricted to viscous oils that are Newtonian fluids. Some oils form water-in-oil emulsions, which are Bingham plastic and behave differently than Newtonian fluids. In this work, the stability of contained Bingham plastic oil slicks under the action of water current is investigated. The analysis is based on assuming a simple airfoil shape for the slick and calculating shear stress from boundary layer theory. The effect of dynamic forces on internal stresses is included in the study. The investigation shows Bingham plastic slicks to be more stable than viscous oil slicks.
4	2001	CFD analysis helps develop oil containment booms	Pollution Equipment News 34:3	4-page article
4	2005	Development of a novel ice oil boom for flowing waters	Tsang, Vanderkooy	To contain and recover oil in an ice-infested river, an ice-free area has to be created wherein conventional clean-up gear may be employed. A joint Canada-United States study was begun to develop a barrier which would allow the oil to pass through while barring ice floes from entering the recovery site area. Theoretical and laboratory study showed that the ice floes could be deflected successfully from an oil spill recovery site. The U.S. Coast Guard financed the construction of the prototype and it was successfully tested at the Canadian Coast Guard Base in the Detroit River, Amherstburg, Ontario. The ice boom utilizes the ruddering principle, used by glance booms for the lumber industry. It consists of a sturdy body and a number of short fins or rudders. The angle between the boom and the fins is variable. The upstream end of the boom is tied to the shore. When the fins are gradually closed from the initially open position, the force of the current on the fins brings the boom gradually into the flow. The out-swung boom then prevents the ice floes from entering the area behind it and

				thus creates the desirable ice-free area. Openings are provided in the boom for the oil slick to pass through. After the oil passes through the boom, it may be contained and recovered by conventional methods. Field experiments showed that deployment and manipulation of the boom could be carried out readily. It was also apparent that the fins created a surface current deflecting the oil stimulant directly toward the shore. Quantitative design criteria have been obtained.
4	1974	Dynamic response of surface-moored vertical barrier to wave action by analog and digital simulation	Fowler, Bailey	The 2-dimensional dynamics of an oil containment barrier, which was designed to have very low tensile loads due to current and waves, were simulated with a theoretical model. The model was solved on both analog and digital computers, and a lab test program conducted to verify the model. For nonlinear problems such as this, for which 'exact' solutions do not exist, the analog computer has many advantages, principally rapid parameter studies and convenient plotting output, plus giving the engineer a real time 'feel' for the problem. The problem treated here was especially well-suited to analog simulation. Charts and graphs present maximum force and amplitude data, and experimental verification of the solution was obtained from wave tank studies.
4	1972	Dynamic response of surface-moored vertical barrier to wave action by analog and digital simulation	Fowler, Bailey	The two dimensional dynamics of an oil containment barrier, which was designed to have very low tensile loads due to current and waves, were simulated with a theoretical model. The model was solved on both analog and digital computers, and a lab test program conducted to verify the model.
4	1980	Interactive Simulation of Oil Spill Recovery Operations	Svendsen, Furuholt	Through computer simulation it is possible to analyse many aspects of the recovery operation and find answers to many important questions during the planning phase. SIROP is an EDP-program constructed to analyse the recovery system based on realistic and feasible modelling of the equipment units and how they are affected by oil, environment and other equipment units during the recovery operation. The operator's skill to group the equipment will be reflected in the amount of emulsion recovered as computed by the program. Through parameter variations, bottlenecks in the operation may be detected. The effect of different weather conditions on the

				recovery efficiency can also be studied. When running the program in interactive mode a picture of the recovery system is drawn on a screen showing the position of each equipment unit and amount of emulsion collected in booms and vessels. By means of the picture's information the operator can manipulate the system by adding, moving or removing equipment. SIROP, therefore, can also be used for educational purposes.
4	2009	Numerical analysis of floating boom performance in open waters	Castro, Iglesias, Fraguela, Carballo	Previously proposed numerical models of oil containment booms have a series of shortcomings. The boom is generally considered as a fixed object and in the few cases in which the main boom motions are implemented into the model, the containment is not taken into account. With the aim of overcoming these shortcomings, a more realistic numerical model including the main boom motions and the presence of the contaminant is being developed. This numerical model will be very useful to carry out the optimisation of a new boom design. In this work, the first results obtained from the numerical model are presented.
4	2005	Oil spill containment: Viscous oils	Johnston, Fitzmaurice, Watt	The failure characteristics associated with boom containment of oil slicks consisting mainly of low-viscosity oils have been the focus of previous research. Sufficient experimental and theoretical evidence exists to allow the hydrodynamics of low-viscosity slicks to be predicted. However, a similar hydrodynamic understanding is not avail-able for slicks containing highly viscous oils. This paper addresses this issue and presents the results of an experimental laboratory study in which the containment of highly viscous oils by boom systems was investigated. The results identify a surging type of failure mechanism that normally occurs just before the critical accumulation mode of failure develops. The importance of circulation within the oil slick and its relation to the failure mechanisms is emphasized. The paper also describes a theoretical model being developed to represent the containment of highly viscous oils by booms.
4	2009	Profile of oil spill confined with floating boom	Chebbi	The dynamics of contained oil spills is investigated using both boundary layer and constant drag coefficient models. Oil circulation is included in both models. Results providing oil velocity profile and oil thickness distribution can be used to estimate the minimum draft required to prevent boom drainage failure.

4	2008	Structural analysis of oil-spill containment booms in coastal and estuary waters	Muttin	In this paper, the oil-boom concept is studied using a numerical model based on a non-linear membrane finite-element method. Several parameters are identified as having significant influence on the boom section geometry, on its mechanical stress and on its efficiency. The principal parameter acting on the boom efficiency is the normal sea current velocity. The main observed variable for the boom efficiency is the vertical angle of its skirt. A proposed numerical method is applied to the computation of a boom contingency plan. It is tested in the real environmental conditions of an estuary and a full tide cycle. The Elorn River Contingency Plan in France's Brittany Region was carried out to study oil containment efficiency. It is analysed during tide periods of a reference day. The role of the anchorage system on dead-masses and buoyancy coffers is emphasized. The tensions on the dead-masses, the mooring lines and the buoyancy coffers are considered in the computation. The result of the analysis in the boom stress limit suggests safety coefficients should be included in a boom contingency plan.
4	1980	The containment of an oil slick by a boom placed across a uniform stream	Pietro, Cox	A small region (called the surface tension region) where pressure differences across the oil–water and oil–air interfaces are important is shown to exist between the gravity viscous and monolayer regions in a spreading oil slick (Di Pietro, Huh & Cox 1978). The importance of this new region is that (i) it is necessary in order to connect the gravity–viscous and monolayer regions and (ii) it is a region where slopes of interfaces are large. This idea is used to find the thickness profile of an oil layer contained upstream of a barrier (an oil boom) placed across a channel in which water is flowing at a constant velocity. The assumption is also made that the velocity difference across the oil layer is small compared with the water velocity. The general conditions for the validity of the results are then discussed together with the modifications to the theory which are necessary if the boundary layer in the water below the oil should be turbulent rather than laminar. Good agreement is found to exist between experimental results for unsteady spreading on quiescent water in a channel and the results of the theory applied to this situation assuming quasi-steady spreading.

4	2005	Theoretical and experimental evaluation of oil spill control devices	Marks, Geiss, Hirshman	This paper describes the first phases of a program aimed at providing a means for evaluation of existing oil containment devices (booms, barriers, etc.) and for improving basic design through variation of geometric and physical parameters. A mathematical/computer model is derived that describes the behavior (forces and motions) of a spill control device in given environmental conditions of wind, current, and waves, and specified deployment configuration. The results of evaluating 14 booms in terms of probability of mechanical (structural) and spill-control failure are discussed in general terms as are the results of model-tank tests aimed at obtaining data for comparative evaluation of booms and for validating and improving the analytical model. A more definitive statement of results awaits the completion of at-sea experiments and data analysis, which are presently being carried out.
5	2017	CONICET, Universidad de Buenos Aires, Instituto de Investigaciones en Producción Animal (INPA), Buenos Aires, Argentina	Li, Chen, Zhu	This paper develops a 3D, transient, mathematical model to estimate the oil release rate and simulate the oil dispersion behavior. The Euler-Euler method is used to estimate the subsea oil release rate, while the Eulerian-Lagrangian method is employed to track the migration trajectory of oil droplets. This model accounts for the quantitative effect of backpressure and hole size on oil release rate, and the influence of oil release rate, oil density, current speed, water depth and leakage position on oil migration is also investigated in this paper. Eventually, the results, e.g. transient release rate of oil, the rise time of oil and dispersion distance are determined by above-mentioned model, and the oil release and dispersion behavior under different scenarios is revealed. Essentially, the assessment results could provide a useful guidance for detection of leakage positon and placement of oil containment boom.
5	1970	Containment of oil spills by physical and air barriers (Containment of oil spills by physical and air barriers to	Hoult	

		reduce water pollution)		
5	2011	Experimental and Simulation Studies of the Effect of Vertical Permeability Barriers on Oil Recovery Efficiency During Solvent Injection Processes	Dehghan, Farzaneh, Kharrat, Ghazanfari, Masihi	
5	1975	Hydrodynamic problems in oil spill control and removal	Leibovich	The theoretical performance of oil spill control equipment in calm and rough water is considered. It is concluded that the scale-up of disc-type skimmers is limited by oil layer instabilities: Other skimmer types are also treated. Increases in wave steepness within containment booms are shown to promote the formation of water-in-oil emulsions or enhanced oil dispersion. An operational cut-off is also suggested for oil spill control operations as a function of oil type and environmental conditions. An analysis is also given that explains observed thickening of oil in the crests of waves.
5	1971	Hydrodynamics of oil spillage in the ocean	Ichye	When a bulk of crude oil is dumped on the ocean surface, it spreads mostly in the horizontal direction. In the initial stage, the spreading is caused by the horizontal pressure gradient due to the surface slope. In the later stage, dispersive action of oceanic turbulence becomes more important. For the initial stage, a two-layer model is developed for a circumsymmetric oil pool suddenly dumped on the surface of the motionless ocean. Scaling of the equations of motion for oil of 1.2 x 10 super(9) (10 super(4) barrels) with density 0.9 cm sub(3) super(-3) g and viscosity 0.1 cm super(2)/sec yields the vertical Reynolds number of 10, indicating small effect of viscosity. The equations without the viscous terms are solved as an initial value problem by use of the characteristic method. A numerical result indicates that increase

				of the oil pool area is quite rapid in the initial stage and levels off later, in qualitative agreement with the observation from the Torrey Canyon incident. The effects of wind and current on an oil pool are determined for a two-dimensional flow in a case when a vertical barrier is set up to dam the oil. When only the wind stress acts on the surface, the death of the oil pool at the barrier is given by (3TV rho sub(w)/gL)1 3(rho sub(w) - rho o)-1/3, where T is the wind stress, g is the gravity constant, V is volume of the oil pool, L is width of the barrier, rho w and rho o are densities of water and oil, respectively. When the current is present, the wind stress factor in this relation includes the term relating to the shear stress at an oil-water interface. The Reynolds number of an actual oil pool to be contained is more than 10 super(3), invalidating some experimental results obtained in an hydraulic channel. Internal waves at the oil-water interface play significant roles in detaching oil blobs from an oil pool. This study is sponsored by NSF through a grant GA-26498 and by ONR through a contract N00014-68-A-O308(0002).
5	1974	Hydrodynamics of the containment of oil slicks	Milgram, Van Houten	Many basic hydrodynamic problems become of practical interest when one attempts to clean up an oil spill by physical means. Three of these problems are studied in this paper. The first is the mass transport of oil by water waves and includes a determination of the types of waves that can propagate through a system comprised of an oil layer above deep water. The second problem is the stability of the oil-water interface between a motionless oil layer and flowing water. This is a simplified model of the situation when oil pollution is contained by a containment barrier in a current. The third problem examined is the determination of the equilibrium thickness distribution of an oil pool being contained by a barrier in a current.
5	2015	Mechanism of solid-liquid dual dragging applied in recovering oil spill	Zhang, Li, Zhang, Wang	To rapidly recover the oil spill, the new method of solid-liquid dual dragging was proposed and its mechanism was studied. By using Navier-Stokes equation, the mathematical model which represented dual dragging acting on the intermediate oil layer from bottom water layer and top adhesion belt was established and the numerical simulation of oil layer movement under the condition of both different oil viscosity and adhesion dragging speed was carried out. Simulation results show that the oil spill

				recovery rate is improved significantly, and the effects of oil viscosity on the recovery rate is reduced, therefore various oil spill can be recovered rapidly by solid-liquid dual dragging.
5	2015	Modelling and simulation of synchronous speed control system about electric-hydraulic proportional motor	Yang, Kong, Li, Wang, Guo	Taking the driving control system of oil boom uncoil and rewound for the ship carrying oil spill recovery machine as the research object, aiming at the problem of synchronous control of dual-motor speed synchronization, the electric-hydraulic proportional valve controlled motor speed synchronous scheme of master-slave based on PLC was proposed. The mathematical model of speed synchronous control system was established and the MATLAB/Simulink software was also used to analyze the stability, the output speed and the speed synchronization error. The PID unit had been introduced into this system for improving the stability and reducing the speed synchronization error. The simulation results showed that the stable performance was improved significantly, the motor output speed stability and the synchronization performance had satisfied design effect after the PID unit being introduced into the system. The synchronous control strategy of master-slave based on PLC is feasible when the demand of synchronous precision is not high.
5	2017	Modelling and Control of a Flexible Floating Boom: First Approach	Gapingsi, Korbas, Santos	Floating booms are useful tools in the marine world, especially for marine demarcation where some kind of contamination of sea, ocean or coastal water is present. In this work we have developed a mathematical model for a flexible floating boom which is hooked on two boats (unmanned surface vehicles). It is meant to be used for oil spill containment in marine areas. In order to simplify the model and to make possible its computer simulation, we have adopted a quasi-static approximation where we assume that the inertial forces are small compared with the drag forces applied to the boom. The simulation of this mathematical model has allowed the analysis of the behavior of the floating boom. Based on this knowledge, we have designed a control system which allows us to maintain the flexible floating boom in a specific configuration by controlling its shape. For that purpose, the control approach deals with the speed of the two ends of the floating boom. The results obtained with the implemented control system are

				encouraging, considering the model is a simplified discrete one and the control effort is reasonable.
5	1983	Modelling oil spills	Jenssen, Baker, Carter, Sammarco, Stark	A number of oil spill models have been developed in recent years, and many have shown their usefulness in contingency planning, clean-up operations, and environmental impact assessments. None, however, takes fully account of all oil fate governing processes, categorized as advection, spreading, evaporation, dissolution, emulsification, dispersion, auto-oxidation, biodegradation, and sinking/sedimentation. This paper discusses these processes and suggests some topics for further investigation that will improve oil spill fate predictions.
5	1999	Oil Spill Modelling towards the Close of the 20th Century: Overview of the State of the Art	Reed, Johansen, Brandvik, Daling., Lewis	The state-of-the-art in oil spill modelling is summarized, focusing primarily on the years from 1990 to the present. All models seek to describe the key physical and chemical processes that transport and weather the oil on and in the sea. Current insights into the mechanisms of these processes and the availability of algorithms for describing and predicting process rates are discussed. Advances are noted in the areas of advection, spreading, evaporation, dispersion, emulsification, and interactions with ice and shorelines. Knowledge of the relationship between oil properties, and oil weathering and fate, and the development of models for the evaluation of oil spill response strategies are summarized. Specific models are used as examples where appropriate. Future directions in these and other areas are indicated.
5	2006	Simulation of oil spill behaviour and response operations in PISCES	Delgado, Kumzerova, Martynov	The aim of this paper is to present a novel method of numerical simulation of oil spill behaviour in the conditions of human response. The main point of the method is to extend the Lagrangian approach by introducing interactions between oil particles. This innovation allows some essential disadvantages of the traditional Lagrangian method to be compensated, in particular the impossibility of describing oil interaction with different kinds of natural and artificial barriers like coastlines and booms. The tuning of the interparticle interaction was made via multi-stage parametric optimization with the aid of the alternating-variable descent technique, and includes the verification with known semi-empirical solutions as well as with different logical tests. The model takes into account the main physicochemical processes occurring in the oil slick, which

				include evaporation, dispersion, emulsification and viscosity variation. Simulation is carried out with regard to the following environment factors: coastline, field of currents, weather, sea state, ice conditions and environmentally sensitive areas. In addition, models of response resource application including booming and recovery have been developed. The presented technique is used as model part of the PISCES (Potential Incident Simulation Control and Evaluation System) oil spill simulator produced by TRANSAS and designed for planning spill recovery after accidental marine oil spills.
5	2013	Streamlines simulation of barrier fracture as a novel water shutoff technique	Al-najem, Pirayesh, Soliman, Siddiqui	Excessive water production has been a problem in the oil industry for many years. To handle this problem, many research projects have focused on developing conformance control systems. Conformance fracturing, a combination of hydraulic fracturing and water control, has proven to be an effective conformance control technique. Hydraulic fracturing is now the technology of choice for increasing well productivity. The chemistry of relative permeability modifiers has also undergone extensive change; the most notable result of which has been to prolong the life of water control treatments using relative permeability modifier (RPM) polymers. The purpose of this study was to investigate the application of barrier-fracturing using streamline simulation. Barrier-fracturing is a novel idea that involves modifying the flow profile and diverting the displacing fluid by placing a fracture with essentially zero permeability deep into the reservoir. There are many ways to create a zero permeability fracture, examples of which include injection of cement or a conformance fluid into the fracture. In our study, we created several streamline simulation models to show the fidelity and validity of this innovative idea. The streamline simulation models that are presented in this paper range from a simple homogeneous reservoir to a very heterogeneous reservoir. The effect of different barrier-fracture lengths on the reservoir performance was analyzed. We also built streamline models for conventional mechanical and chemical water shutoff techniques (e.g. re-completion and RPM) to compare them with the novel barrier-fracture water shutoff technique. The resulting saturation distribution maps from the longer barrier-fracture clearly show the power of a barrier-fracture to modify flow profile and divert the displacing fluid in comparison to conventional water

				shutoff techniques. Barrier-fractures helped improve oil recovery by delaying water-breakthrough and eventually improving the volumetric sweep efficiency.
5	1970	The spreading and containment of oil slicks	Hoult, Fay, Milgram, Cross	Recent experimental and theoretical results for the spread of oil slicks in a one-dimensional channel are surveyed. The results imply that there are, in fact, the three regimes of oil spreading on calm water as originally described by Fay. A survey is presented of the main features of how an oil boom holds oil against a steady current.

Papers Denoted as 3/4/5: Scale Modelling

Rel	Year	Title	Authors	Summary
3	1979	Air jet oil collection boom works in three-knot currents		An inflatable air jet boom that diverts oil with 85% efficiency when at a 30 angle to a three-knot current has been developed by Hydronautics, Inc., Laurel, MD, USA. During lab tests at the Environmental Protection Agency's (EPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT), oil loss rate increased only 5-10% in steep 1.2 m waves. Hydronautic's Air Jet Oil Boom depends on a horizontal air jet along the boom at surface level which produces a strong local current. About 10 m long and 0.6 m in diameter, the boom is composed of two inflatable sections and a rigid fiberglass center section. A shore-based compressor and a jet pump connected to the center section provide large volumes of low pressure air. The boom draws about three cm, creates very little drag and stores compactly.
3	2009	Behavior of rigid and flexible oil barriers in the presence of waves	Amini, Schleiss	Although oil barriers have been used for many years to contain slicked oil in open seas, the effect of waves on them has been rarely considered. In the present study, we investigated the response of rigid and flexible oil containment barriers in the presence of currents with and without waves. Two-dimensional experiments with both rigid and flexible oil containment barriers were carried out in a laboratory flume equipped with a pneumatic wave generator. The initiation of containment failure for various conditions were analyzed and compared. In the course of this study, the effect of wave characteristics on containment failure was discussed and some empirical equations were proposed to predict the initiation of failure in different conditions. Once the failure started, the effect of wave steepness on the loss rate was investigated. Finally a failure mode occurring due to the waves' effect, called surging drainage failure, was studied.
3	1979	Booms used for oil slick control	Lau, Moir	Experiments were conducted to determine the conditions for no containment of oil by a boom, the oil-water interfacial friction coefficient and the maximum angle which a boom can be angled to the flow to deflect an oil slick. The criterion that the

				densimetric Froude number has to be smaller than about 0.5 for containment was verified. In addition, a new criterion was discovered which specifies a minimum boom draught. The local value of the interfacial friction coefficient was evaluated along the slick using measured slick profiles, and was found to decrease along the length of a slick. The friction coefficient also increased with increasing oil viscosity. Based on the experimental results, an empirical relationship was derived for the maximum angle at which a barrier could be angled to the flow to completely divert an oil slick. Experiments were conducted to determine the conditions for no containment of oil by a boom, the oil-water interfacial friction coefficient and the maximum angle which a boom can be angled to the flow to deflect an oil slick. The criterion that the densimetric Froude number has to be smaller than about 0. 5 for containment was verified. In addition, a new criterion was discovered which specifies a minimum boom draught. The local value of the interfacial friction coefficient was evaluated along the slick; using measured slick profiles, and was found to decrease along the length of a slick. The friction coefficient also increased with increasing oil viscosity. Based on the experimental results, an empirical relationship was derived for the maximum angle at which a barrier could be angled to the flow to completely divert an oil slick.
3	1972	Containing oil slicks in flows of finite depth	Wilkinson	The hydrodynamics of oil slick containment are examined.it is shown that containment is only possible when a densimetric Froude number based on flow velocity and depth and the oil density is less than a critical value. Experiments confirmed that an oil slick was unable to maintain a stationary front when the Froude number exceeded the critical value.it is also shown that viscous effects ultimately limit the thickness and therefore the length and volume of any real slick. Expressions are derived which enable these limits to be determined.
3	2004	Experimental, numerical and optimisation study of	Muttin, Guyot, Nouchi, Variot	The oil spills consecutive to the shipwrecks of ERIKA and PRESTIGE, showed the efficiency limits of oil spill booms. It is admitted that a stream higher than 1 knot causes oil flight. This study presents a physical modelling upon complementary aspects. The objective is to reinforce the boom efficiency. Firstly, numerical and

		oil spill containment boom		experimental tests in a vertical 2D section are described. The tests are made on a reduced scale model in fresh water, with plant oils. Secondly, a simplified structural model for the boom is presented. The equilibrium of a chain, with articulated bodies, gives the equilibrium equations in 3D. This provides the equilibrium shape of the boom and the possible flight of the boom in terms of stream velocity. Finally, an optimisation procedure of the boom plan is described. It takes into account the barrage handling, the oil containment efficiency, and the barrage storage. This work is done with the support of the French research group RITMER.
3	2010	Floating boom performance under waves and currents	Castro, Iglesias, Carballo, Fraguela	Floating booms constitute a fundamental tool for the protection of marine and coastal ecosystems against accidental oil spills. Their containment performances in exposed areas are often impaired by the action of waves, currents and winds in a manner which is dependent on the boom's response as a floating body, and which is not fully understood at present. In this work the relationship between the design parameters of a floating boom section and its efficiency against the mode of failure by drainage under a variety of wave and current combinations is investigated by means of physical modelling. Seven boom models with different geometries and buoyancy-weight ratios are tested with an experimental setup that allows them to heave and rotate freely. The model displacements under waves (both regular and irregular) and currents, as well as those of the free surface adjacent to the model, are measured with a Computer Vision system developed ad hoc. Two efficiency parameters are defined-the significant and minimum effective boom drafts-and applied to the results of an experimental campaign involving 315 laboratory tests. Thus, the manner in which the design parameters influence the boom's efficiency under different wave and current conditions is established.
3	1996	Laboratory Investigation for Protection of Water Intake and harbors	Lo	Laboratory experiments were carried out to test the effectiveness of air-bubble barriers, floating booms, and a series of barriers in preventing oil slick and jellyfish movement under various current, wind, and wave conditions. Samples of Kuwait light crude, Kuwait heavy crude, and emulsified Kuwait heavy crude oils were selected for the test program. It was found that the double floating boom system

		Against Oil Spills and jellyfish		(with a distance of 16 times the boom's draught) had the best performance in containing oil slick movement. The air-bubble barrier only prevented jellyfish moving within the top 10% of the total depth downstream of the air-bubble barrier. In the air-bubble barriers and floating boom systems, the air-bubble plume lifted the jellyfish to the water's surface and, thus most jellyfish accumulated in front of the floating boom. With the help of a proper collection device (such as a suction pump), the accumulated jellyfish were removed to a desired location. Therefore, the quantity of jellyfish moving into the intake channel was reduced. Based on the test results, three different arrangements for protection of Kuwait's water intakes and harbors from oil slick and jellyfish movement were recommended.
3	1996	Laboratory investigation of single floating booms A and series of booms in the prevention of oil slick and jellyfish movement	Lo	Laboratory experiments were carried out to test the effectiveness of single floating booms, and series of barriers in preventing oil slick and jellyfish movement under various current, wind, and wave conditions. Samples of Kuwait light crude, Kuwait heavy crude, and emulsified Kuwait heavy crude oil were selected for the test program. It was found that the single floating booms were only effective in preventing the oil slick movement at current speeds less than 0.15 m/s for emulsified oil and 0.25 m/s for non-emulsified oil. Double floating booms (with a distance of 16 times the boom's draught between them) prevented both non-emulsified and emulsified oil movement when current speed was less than 0.25 m/s. The double floating boom system had the best performance in containing oil slick movement. In the combined air-bubble barrier and floating boom system, the air-bubble plume lifted the jellyfish to the water's surface, and thus most jellyfish accumulated in front of the floating boom. With the help of a proper collection device (such as a suction pump), the accumulated jellyfish could be removed to a desired location. Therefore, the quantity of jellyfish moving into the intake channel was reduced. Based on the test results, three different arrangements were recommended for the protection Kuwait's water intakes and harbors from oil slick and jellyfish movement.

3	1977	Performance tests of three fast current oil recovery devices	Getman	The basic performance goals for the fast current oil removal system are to recover oil effectively in currents up to ten knots in a two-ft confused sea. Test methods and results are provided for several devices. The Shell ZVR large scale model performed well in fast-current velocities in both calm seas and in a wave train. The Seaward Streaming Fiber Recovery Device performed well in fast currents in calm conditions but performed poorly in waves. The French Cyclonet 050 provided fair performance in medium currents and in calm conditions but gave poor performance when waves were present.
3	2005	Pneumatic barriers for oil containment under-wind wave, and current conditions	Basco	An experimental laboratory study of the pneumatic barrier has recently been completed at Texas A&M University (sponsored by the U. S. Coast Guard). Both the fluid mechanics of air-bubble generated currents and their effectiveness for containing oil under wind, wave, and current loadings were investigated. The bubble-generated current has been found to provide an effective means of containing oil on water. However, under strong currents (2 knots) or breaking wave conditions, large quantities of air are required and the substantial increase in power requirements which results may prove the system uneconomical for some applications. Consequently, use of the pneumatic barrier to prevent oil spreading on water is recommended for protected areas with low (below 1.0 knot) currents.
3	1983	Probable effectiveness of protection of estuaries by oil booms	Mulligan, Retief	An estuary threatened with pollution from an oil spill at sea can possibly receive some measure of protection from an oil boom. The oil containment capability of a boom is lost when structural failure of the boom or its anchorage system occurs or when critical escape velocities are exceeded. Inconsistencies between the different published design theories to determine tension, configuration and consequently escape velocities raised doubts as to their reliability for use in a practical application. To find the most applicable design procedure to assist the Department of Transport Affairs in the preparation of oil spill contingency plans, a number of experiments and determinations were carried out.
3	1980	Probable effectiveness of	Mulligan, Retief	An estuary threatened with pollution from an oil spill at sea can possibly receive some measure of protection by an oil boom. Oil containment capability of an oil

		protection of estuaries by oil booms		boom is lost when structural failure of the boom or its anchorage system occurs or when critical escape velocities are exceeded. A computer numerical model has been developed to assess tensions developed in - and configurations taken up by - oil deflection booms when exposed to water currents. The computer model was calibrated by 1:10 scale physical model tests conducted in a hydraulic laboratory flume and the physical model was calibrated by prototype tests in the Berg River. Calculated tensions will dictate oil boom tensile strength requirements and end anchor design whilst water velocities in conjunction with oil boom configuration will indicate whether critical escape velocities will be exceeded.
3	2005	Recovery of oil spilled under river ice cover	Tsang	Laboratory study showed that oil spilled under river ice cover could be recovered from a slot cut on the ice cover if the slot was properly dimensioned and the river flow and oil properties met certain criteria. The parameters affecting the containment and recovery capability of a slot were identified and their quantitative effects were studied through systematic, experiments. Design curves were derived for proper design of slots normal to the flow. The study revealed that slots at an angle of the flow were more effective in trapping the spilled oil. In addition, they guided the oil to the more desirable points for recovery. Design curves for angled slot diverters were also obtained. In addition to slots, imbedded barriers and slot-barrier combinations were also studied for their effectiveness in containing and diverting spilled oil. The quantitative effects of the affecting parameters were studied through experiments and design curves were obtained for proper design of barriers and slot-barrier combinations. The laboratory study was used to guide a successful exercise in March 1978 on the North Saskatchewan River in Alberta. In the field exercise more than 99 percent of the oil spilled up stream was recovered by the slot. The field results and the laboratory predictions are compared.
3	1979	Recovery of oil spilled under river ice cover	Tsang, Bascom	Laboratory study showed that oil spilled under river ice cover could be recovered from a slot cut on the ice cover if the slot was properly dimensioned and the river flow and oil properties met certain criteria. The parameters affecting the containment and recovery capability of a slot were identified and their quantitative effects were

				studied through systematic experiments. Design curves were derived for proper design of slots normal to the flow. The study revealed that slots at an angle to the flow were more effective in trapping the spilled oil. In addition, they guided the oil to the more desirable points for recovery. Design curves for angled slot diverters were also obtained. In addition to slots, imbedded barriers and slot-barrier combinations were also studied for their effectiveness in containing and diverting spilled oil. The quantitative effects of the affecting parameters were studied through experiments and design curves were obtained for proper design of barriers and slot-barrier combinations. The laboratory study was used to guide a successful field exercise in March 1978 on the North Saskatchewan River in Alberta. In the field exercise, more than 99 percent of the oil spilled upstream was recovered by the slot. The field results and the laboratory predictions are compared.
3	1996	Seakeeping performance of containment boom section in random waves and currents	Kim *et al.*	The seakeeping characteristics of various boom geometries in irregular waves and currents are investigated. The response of a floating boom section on the open sea is a function of a number of parameters, such as boom geometry, distribution of mass, buoyancy/weight ratio, and wave and current characteristics. To understand the relationship between these design parameters more clearly, a series of regular and irregular wave tests were conducted with six different 1:4 scale models for three current velocities and six different wave conditions. To simplify the problem, only rigid boom section consisting of a buoyancy cylinder and vertical skirt were used. In parallel with this experimental program, a numerical model for the response of two-dimensional floating boom section in small-amplitude waves is also developed. The numerical results are compared with our large-scale experimental results. The boom effectiveness on the open sea is evaluated based on the concept of "effective draft" and "effective freeboard" assuming that drainage and oversplashing failures are the prime mechanisms of containment failure. Using the present results, a guideline for the optimum design/selection of future booms is developed.

3	1992	The containment of heavy oil in flowing water	Brown, Goodman, Nicholson	Viscous litumen from the oil sand deposits of Northeastern Alberta is diluted with a gas condensate before transport by pipeline to distant markets. Because of its unique properties, the diluent/bitumen mix (Dilbit), may require novel containment and recovery techniques should an accidental spill occur. Preliminary experiments have been conducted in a large flowing water channel to determine if several conventional containment devices could be utilized to trap weathered and emulsified Dilbit and bitumen. These studies indicate that conventional barriers need improvement to be effective at higher water velocities and suggest that new concepts in containment should be considered.
3	1979	The use of deflectors for deployment of oil booms in rivers	Greene, Brodsky, Charles, Mackay, Bascom	A study was conducted to design, develop, and test deflectors for use in aligning oil containment booms at an angle to the current direction in flowing waters. A series of experimental field trials were undertaken in which booms, fitted with deflectors, were either towed in a lake or deployed in flowing water. During the program, several design improvements were incorporated and a final suggested design was established. A simple hydrodynamic theory has been devised which enables the boom deflection angle to be predicted from the number, dimensions, and configuration of the deflectors and the dimensions of the boom. Agreement between the simplified theory and the experimental results is satisfactory. A graphical procedure has been devised by which an on-scene commander can calculate the requirements for deflecting a given boom. Two promising applications for deflectors are discussed. A permanently deployed system could be used across a water-way subject to periodic oil discharges. A boom with deflectors closed could be moored alongshore in sensitive areas, allowing rapid deployment into the river current upon release of the deflectors.
3	1977	Use of floating deflectors for oil spill control in fast flowing water	Eryuzlu, Hausser	Although oil booms of various types now are available, it is well established that they are ineffective when the spill occurs in fast flowing waters. A system was developed to control an oil spill under such circumstances. The principle employed is to deflect the oil from where the spill takes place into a portion of the river where the currents are slower and the oil could be collected by conventional means. This is achieved

				by a system of floating deflectors comprising a series of hydrofoils mounted on a horizontal frame anchored to the shore. The interaction of the hydrodynamic forces on the hydrofoils creates an equilibrium state at which the system floats at an angle with the main current. At this equilibrium state the deflectors induce a controlled spiral circulation which deflects the surface currents and spilled oil in a selected direction. Experiments were conducted in a straight flume to study the characteristics of hydrofoils used as deflectors. The general location of the several oil refineries around Montreal-East was selected for testing the practical application of the proposed method on a model of the St. Lawrence River. Results show that in the majority of cases without deflectors only about 40% to 50% of the oil would go in the north arm of the river, whereas with the deflectors this can increase to about 90%. Presently, preparations are being made for a prototype testing program to be conducted near Montreal-East on the St. Lawrence River.
3	2004	Using currents induced by a submerged pneumatic boom to separate ice floes from surface oil slicks	Wigton, DeBord, Cooper	Results were presented for preliminary scoping experiments designed to assess the feasibility of diverting oil from between dynamic ice floes to a collection unit using surface currents induced by a submerged pneumatic boom. Current profiles were characterized for the experimental system. Bubble boom induced currents generated in the presence of a background current decay at a much faster rate than would be predicted based on previous studies. Experiments were conducted in large plume using model ice floes constructed of ballasted foam and an oil surrogate to assess the efficiency of ice-oil separation. The oil surrogate could be separated from dynamic model brash ice and diverted to a collection device to some degree. Recoveries ranged from 28 to 75% for the system tested. Simple linear superposition could not estimate the observed velocity profile for the range of background and induced currents investigated due to plume deflection and apparent losses in current generation efficiency.
4	2005	Full scale implementation of state-of-the-art	Brekne, Eide, Skeie	The Nonvegian Clean Seas Association for Operating Companies (NOFO) has recently completed a comprehensive Research & Development (R&D) program. The main objective of this program was to provide a basis for decisions regarding

		mechanical OIL spill response technology on the norwegian continental shelf		selection of equipment in the next generation of NOFO's oil spill response. The R&D program was initiated in 2000 and the results from the preliminary phase of the program were presented at the 2003 IOSC in Vancouver. In the summer of 2003, NOFO successfully carried out an Oil-on-water exercise. This exercise encompassed a full scale testing of new equipment developed in the second phase of the program. A series of experiments were performed where oil was released to the sea and subsequently recovered. In total, 170 cubic metres of oil emulsion was released, and approximately 80 % recovered. Based on the experiences from the Oil-on-water exercise, NOFO implemented Phase 3 of the R&D program. This phase comprised of redesign and modifications to fvro types of booms, and of a high capacity skimmer. Final testing of the Phase 3 results was completed in the first quarter of 2004, and concluded that the design criteria were met. Concurrently, NOFO has embarked on a three-year replacement plan, in which existing booms and skimmers are replaced by the new equipment types. Phase 2 included a feasibility study on enhanced detection of oil spills under conditions of low light and reduced visibility. Based on results from this study, a project has been initiated to develop and implement a ship based radar system for detection of oil spills. This project is considered the first step towards the goal of achieving an oil spill response that is independent of light and visibility. This paper outlines the conclusions of the R&D program and the 2003 Oil-on-water exercise, as well as the results from the final performance tests of the new equipment. Further, the new oil spill response is comprehensive, in terms of total capability and geographical coverage.
4	2007	Heavy oil booming	Cooper, Velicogna, Brown	Heavy oil is usually viscous with a high specific gravity (near 1.000 g/cm^3) and can either sink, float, or remain neutrally buoyant and stay suspended in the water column when spilled. A number of factors can affect this behaviour and impact recovery efforts including water temperature, weathering, and emulsification over time. The containment of heavy oil presents a number of problems to spill responders because the oil may float near the surface without sufficient buoyancy to be properly contained by conventional booms. Specialized equipment is needed

				to help contain heavy oil. One option is the use of draft extensions made of netting material that would allow water to pass, but restrict the flow of heavy oil so that it can be collected using conventional or adapted equipment. A number of experimental runs have been performed to compare the effectiveness of a boom modification. Specifically, the impact of different netting skirts on the containment abilities of the booming system under specific flow conditions has been assessed. This paper provides initial testing results to evaluate their containment abilities and their impact on restricting the flow of oil.
4	1993	Laboratory testing of a flexible boom for ice management	Loeset, Timco	Combatting oil spills in the Arctic is a major challenge. Drilling or producing oil or gas in the marginal ice zone (MIZ) may allow booms to be deployed upstream of an offshore structure to clear the water of ice, thereby enabling conventional oil spill countermeasures to be used. Such a boom would be kept in place by two ice-going service vessels or by moored buoys. SINTEF NHL and NRC have performed a number of small-scale tests with a flexible boom in the NRC ice basin in Ottawa. The purpose of the tests was to measure the effectiveness of using a flexible boom for collecting ice, and to determine the loads associated with collecting the ice. In the tests, various boom configurations were towed against a broken ice field consisting of ice pieces typically 50-100 mm across and 30 mm thick. The ice concentration was usually 10/10, but it was reduced to 8/10 and 5/10 for two tests. The boom was towed at speeds of 20 and 50 mm-s super(-1). Both the width of the boom and the slackness of the boom were varied over reasonable ranges. Two six-component dynamometers were used to support the boom. Thus, the force components on each end of the boom were measured. Further, two video cameras were used to record the effectiveness of each boom configuration. In this paper, the full results of this test program are presented and the application of the test results to the full-scale situation are discussed. The tests show that, under certain conditions, the use of boom is feasible for ice management in oil-contaminated water.

4	1995	Quantitative analysis of shore-line protection by boom arrangements	Wong, Guerrero	The objective of this paper is to quantitatively analyze the arrangement of booms to improve their effectiveness in protecting natural resources. The boom arrangements tested were parallel booms placed at angles of 60 degree, 90 degree and 120 degree to the shore-line. It was found that the angle between the shoreline and the parallel booms was effective in the range of 45 degree and 75 degree for all velocities. The arrangement that was found to be particularly effective was principally a set of three parallel booms placed at an angle of 60 degree to the shore-line with cylinders placed along the center-line. The open channel experiment was carried out for four different flow velocities, ranging from 0.2 to 0.7 knot. For each speed the position of the parallel booms and the size of the cylinders were changed. Cylinder sizes varied from 4.5 to 7.5 cm. A volume analysis was performed to determine the volume of oil contained. The variation of the length scales for the position of the parallel booms and the size of the cylinders were used to determine the optimum position for the parallel booms and the optimum cylinder diameter for each velocity. A relationship of effectiveness vs U sub(2)/gR was found which displayed a maximum. This relationship was tested experimentally with random parameters, and verified. With a particular velocity U, the graph may be used to find the optimum radius R for the cylinders to be used. The maximum in the relationship can be explained as follows: for cylinders with smaller diameters the effectiveness increases with increase in diameter because of the increased contribution of the centrifugal forces. A maximum is reached because of the physical relationship between the cylinder diameter and the channel width.
4	2005	Research and development of oil spill control devices for use in cold climates in Japan	Suzuki, Miki	In 1981, the Institute of Ocean Environmental Technology (100ET) began work on the five-year Arctic Marine Oil Spill Control Devices Research and Development program in Japan. The following tests were conducted at the 100ET's test facility. The physical properties and evaporation of a crude oil were examined under a variety of temperature conditions. Two selected adhesion type oil skimmers, a mop and a disc type, were evaluated for their recovery efficiency and oil recovery rate using an oil which had the same viscosity as crude oil at low temperatures. The mop

				type oil skimmer was newly developed in this program. Performance tests were conducted with two portable oil booms which were popular in Japan. Booms were towed in the catenary configuration with oil and simulated ice pieces. Booms were tested for the critical tow speed at which oil or ice began to escape the boom. Experiments using midwater trawl nets were conducted for recovering oils sunk below the water surface. Various types of trawl net were designed and tested in the circulating water channel with emulsified bunker C fuel oil. This paper summarizes the results of the tests and shows the applicability of each device for use in cold waters.
4	1995	Study on the technology of protection from oil spill pollution in coastal areas	Li, Hou	Oil spill recovery systems and methods have been successfully developed in the Institute of Ocean Technology in the recent years. Once an oil spill occurs, various systems and methods should be used combinedly for the successful protection from oil spill pollution. In this paper, three combined oil recovering systems are described, and the applications of the oil-absorbing materials and oil dispersers in the coastal areas are assessed on the basis of experiments.
4	1999	Summary of development and field testing of the Transrec oil recovery system	Nordvik	This paper summarizes the development, field testing and performance evaluation of the Transrec oil recovery system including the Framo NOFO Transrec 350 skimmer and multi-functional oil spill prevention and response equipment and presents performance data, not published before, from full-scale experimental oil spills in the North Sea from 1981 to 1990. The rare data provides useful information for evaluation of mechanical clean-up capabilities and efficiency, in particular, for responders who are using this equipment in many countries around the world. The development of the Transrec oil recovery system represents one of the most comprehensive efforts funded to date by the oil industry in Norway to improve marine and open ocean oil spill response capabilities. The need for improvements was based upon early practical user experience with different oil recovery systems, and test results from experimental oil spills in the North Sea. The result of the development efforts increased: (1) skimmer efficiency from approximately 15-75% (it reached 100% under favorable environmental conditions); (2) oil emulsion

				recovery rate from approximately 20-300 m^3/h; (3) recovery system efficiency from approximately 15-85% in 1.5 m significant wave height; (4) oil emulsion thickness from approximately 15-35 cm; (5) weather-window for mechanical recovery operations from 1.5 to 3.0 m significant wave height; (6) capability for transfer of recovered oil residue to shuttle tankers in up to 4 m significant wave height and 45 knot winds; (7) capability for operations at night. The new Transrec oil recovery system with the special J-configuration virtually eliminated skimming operation downtime, and damage to booms and equipment failures that had been caused by oil spill response vessel (OSRV) problems with maintaining skimming position in the previous three-vessel oil recovery system with the boom towed in U-configuration. The time required to outfit OSRVs dropped from approximately 30-<1 h, reducing time from notification to operation on site by more than 24 h. Improvement in oil recovery resulted in the acceptance of a new oil spill preparedness and response plan. The new plan reduced the need for oil recovery systems from 21 to 14, towing vessels in preparedness from 42 to 18, and personnel on stand-by from 135 to 70, which subsequently reduced the total contingency and operational costs by almost 50%. These cost reductions resulted from lower contingency fees for personnel, fewer towing vessels on stand-by, less expensive open ocean training and exercises, less equipment and reduced storage space to lease, and simplified equipment maintenance.
4	2005	The use of deflectors for deployment of oil booms in rivers	Greene, Brodsky, Charles, Mackay	A study was conducted to design, develop, and test deflectors for use in aligning oil containment booms at an angle to the current direction in flowing waters. A series of experimental field trials were undertaken in which booms, filled with deflectors, were either towed in a lake or deployed in flowing water. During the pro-gram, several design improvements were incorporated and a final suggested design was established. A simple hydrodynamic theory has been devised which enables the boom deflection angle to be predicted from the number, dimensions, and configuration of the defectors and the dimensions of the boom. Agreement between the simplified theory and the experimental results is satisfactory. A graphical

				procedure has been deviled by which an on-scene commander can calculate the requirements for deflecting a given boom. Two promising applications for deflectors are discussed. A permanently deployed system could be used across a waterway subject to periodic oil discharges. A boom with deflectors closed could be moored alongshore in sensitive areas, allowing rapid deployment into the river current upon release of the deflectors.
4	2014	Towing a boom with two USVs for oil spill recovery: Scaled experimental development	Giron-Sierra, Gheoghita, Angulo, Jimenez	
5	1994	A study on the effects of oil fires on fire booms employed during the in-situ burning of oil	Lazes	For over 10 years scientists have studied the effects of in-situ burning of oil on air and water quality and potential related health issues. The recent Newfoundland Offshore Burn experiment, conducted by Environment Canada, was the culmination of several years of work. The results of this experiment found that 'emissions from the in-situ oil fire were lower than expected and all compounds and parameters measured were below health concerns at 150 m from the fire' (The Newfoundland Offshore Burn Experiment-NOBE, Preliminary Results of Emissions Measurement). Polyaromatic Hydrocarbons (PAHs) were found to be lower in the soot generated from the fire than in the starting oil prior to the fire. The conclusion reached was that the environmental benefits resulting from the burning of oil spills far outweigh the potential air pollution caused from the smoke. These findings now open the door on the use of in-situ burning of oil as a major tool to be used to mitigate environmental damage from oil spills. As a result of these and other test findings, Region 6 of the Regional Response Team (made up of the U.S. Coast Guard, The Minerals Management Service, The Department of Environmental Quality, The U.S. Environmental Protection Agency, and other state and federal agencies) had pre-approved the use of in-situ burning of oil spills for offshore Louisiana and Texas. Other parts of the country and other countries are evaluating the use of in-situ

				burning to combat oil spills. Now that the scientific community has weighed the environmental costs and benefits of in-situ burning it is time to address the operational and procedural issues.
5	2004	About construction of simulation tank for oil recovery in marine situations	Yoshie, Fujita, Saito	Since "NAKHODKA" oil spill incident in 1997, several new equipment or systems for oil recovery have been researched and developed in Japan. New oil skimming vessels were launched and expected to work well. It is hard to judge how effectively each equipment or product performs at the site of coasts without experience. Canada and U.S. test the equipment in a large tank of Ohmsett with towing bridge, Norway does in big circulating tank and on the sea. They can improve their outcomes with many data from the experiments in such real situations. However, we did not have such a test tank in Japan, and we could not have any opportunities to test in real situations. The government appropriated funds for constructing new tank at PARI for research and development of oil spill response in supplementary budget for 2002. The tank's specifications were planned to test equipment for oil recovery as if we test them at the site of coasts. This paper collects requirements that the tank should satisfy and themes that we should do with this tank. Objective of the tank is to advance researches and developments about recovery of emulsified heavy oil that causes hard damages in marine environments. We should simulate waves, velocities of vessels (or currents), water temperatures, viscosities of the oil, and winds at the site of coasts, and test several skimmers, oil booms, oil recovery systems in order to judge their performances and behaviors under being influenced by several factors. Therefore, the tank dimensions are that the width for 6m, length for 20m, and water depth for 2.5m. Salty water is filled in and controlled its temperature by chiller and heater, and leftovers of the oil are cleaned through oil filter. We can generate waves for the max 0.5m, current for the max 1m/s. Physics and chemistry analyzing room and a cylindrical tank (depth for 10m) are placed as supplementary facilities and the plant is appreciated synthetic.
5	1972	Air barriers as oil-spill containment devices	Jones	Based on experimental investigations it is concluded that air barriers will not completely retain oil in the presence of currents normal to the barrier as low as 0.75

				ft/sec. The main body of the oil slick is retained, but oil drops are torn from the bottom of the slick by the turbulent surface current produced by the air barrier. These drops are entrained in the current and swept through the bubble plume below the water surface. Air barriers will retain essentially 100 percent of the oil when placed across the mouth of an enclosed body of still water if the oil density-water velocity combination produces a head-wave type of flow.
5	1974	An In-situ Investigation of Oil Barrier Shape and Drag Coefficients	Larrabee, Brown	In-situ experimentation on a moored 100 foot section of commercially procured oil barrier was carried out. The objectives of this study were three-fold: To study oil barrier shape and tensions as influenced by current and wave action, to analyze data on the barrier shape with existing analyses and to compare results of tension and drag coefficient data with previous investigations. Actual barrier shape, measured by transit, was compared with a theoretical catenary drawn through the barrier end points. Shape, load, current, and wave data were used to calculate various drag coefficients for the boom. Two techniques were used to calculate drag coefficients for the barrier and results of each were compared. The effects of wave action on barrier loading were determined by the analysis of two previous investigators and the results compared. Values of drag coefficient were reduced to a basic drag coefficient, independent of barrier shape configuration as well as wave effects. Results of the investigation showed that the catenary curve is a good approximation to barrier shape.
5	2012	An oleophilic/hydrophobic nanoporous composite/membrane for oil spill cleanup	Avila, Santos, De Olivera, Lacerda, Munhoz	This paper reports the development of super-hydrophobic nanocomposite systems which are also oleophilic. As hydrophobicity is based on low energy surface and surface roughness, the electrospinning technique was selected as the manufacturing technique. N, N' dimethylformamide (DMF) was employed as the polystyrene (PS) solvent. The "pastry-like" nanocomposite system is based on exfoliated graphite surrounded by PS super-hydrophobic membranes. The pastry-like nanocomposites were tested regarding its adsorption and absorption rates. These properties were tested against motor oil, new and used (which has physical properties - viscosity and specific gravity - similar to crude oil), and vacuum pump

				oil (which does not form oil/water emulsion). The oil adsorption rate is dependent on oil surface tension, while the absorption rate is mainly dependent on membrane/exfoliated graphite surface area. Experimental data show oil absorption rates ranged between 2.5 g/g to 32 g/g, while the adsorption rate per minute ranged from 0.32 g/g.min-1 to 0.80 g/g.min-1. Furthermore, the "pastry-like" nanocomposites were tested as containment barriers and sorbent materials with good results.
5	1974	Applications of an offset floating breakwater configuration	Dailey, Moore, Sethness	Laboratory tests performed at the University of Texas at Austin have shown that a floating offset breakwater configuration can achieve wave transmission coefficients less than 0.2 in both regular and wind waves. The offset configuration consists of vertical reflecting surfaces separated by a distance which is one-half the wave length of incident design waves. Experiments indicate that the offset break-water provides effective wave attenuation for angles of incidence up to 45 degrees. Therefore, many applications to wave protection in confused seas are possible. Portability of the floating breakwater permits field adjustment to give the best results. Temporary protection can be provided to construction sites where offshore facilities may be fabricated or installed. Also, the offset configuration can be built into booms for oil slick collection and confinement in heavy seas. Good motion characteristics of the offset configuration encourage many applications to floating structures. A model circular structure for possible use as an offshore supertanker terminal has been tested in the laboratory.an offset configuration is suggested for pipeline lay barges to reduce their down time in rough weather, particularly beam seas.
5	2004	Behavior of a Contractile Floating Reservoir for the Confinement and Recovery of Oil Slicks	Sayah, Boillat, Scleiss	A new system for the confinement and recovery of oil slicks or other floating materials is tested in a physical model to evaluate its feasibility and effectiveness. It consists of encircling a polluted area by a specially designed boom using light-weight material, in such a way as to trap entirely the oil slick inside a circular reservoir, making its dispersion less widespread. The system allows the oil slick to be slowly towed to safer zones, where it can be pumped and recycled after separating the reservoir into several compartments in order to increase the

				efficiency of pumping and treatment. The experimental investigation was carried out in a small-scale model and demonstrated the effectiveness of the system in practical situations. In terms of oil loss, the limits for the critical waves and towing velocities were determined. Carefully selected polymer granulate layers were used to reproduce the characteristics of oil slicks.
5	1975	Behavior of oil spilled under floating ice	Keevil, Ramseier	Cold room experiments designed to simulate a hot oil spill demonstrated the basic behavior of crude oil under ice. Hot crude oils separated into particles 0.1 to 2.0 centimeters in diameter and rose to the ice-water interface. Under planar freshwater ice the particles spread in concentric rings at a radial rate of about 1.0 centimeter per sec. In still water the particles coalesced and formed an oil lens about 1.0 centimeter thick which tended to become trapped in concavities on the ice bottom. Comparing cold room data with accidental oil spill data verified that crude oil separates into particles when released in cold waters. Pour point is important for predicting the initial behavior of spilled oils. As observed at Chedabucto Bay, tanker oil surfaces as a discrete rope-like piece. Hot oil melting through ice was contained by a natural ice boom. The ice cover can be a working platform simplifying cleanup operations.
5	1974	Containment of oil spills	Herbich	Two methods of oil containment at sea are reviewed, the pneumatic barrier and the mechanical barrier. General requirements, lab test, and applications of the pneumatic barrier are discussed. Although the power requirements to contain oil under severe environmental wave conditions are high, the pneumatic system should be considered as an effective oil containment device for applications near the coast, in estuaries, and around oil platforms. A promising mechanical barrier is described with can operate under both wave and current conditions and is designed to separate the oil retention skirt from the rigid, highly-loaded tension cable. The barrier has a capacity to contain over 100,000 barrels of oil under ideal conditions. A mechanical barrier which conforms to ocean surface profile provides the best concept for oil containment.

5	1974	Containment of oil spills	Herbich	A pneumatic barrier concept has proven to be a most effective oil containment device under open sea environmental conditions. Its effectiveness was demonstrated in the laboratory at various water depths up to 7. 5 feet. The air, power, etc., requirements have been based on experimental studies. Since the air discharge and power requirements tend to decrease with an increase in model size, (or ″the scale effect″ is likely to exist) it can be expected that the air and power requirement may be further reduced for the prototype installation.
5	1998	Control and recovery of spilled oil by using ice boom	Takahashi, Ohshima, Kawai, Watanabe, Saeki	Development of oil and natural gas deposits off Sakhalin's northern coast in the Sea of Okhotsk are currently under way. An accident involving a spill of crude oil or other effluents during the current development of the oil and natural gas deposits off the eastern coast of northern Sakhalin could be expected to affect the environment and economy of the Hokkaido's Okhotsk and Pacific coast. This paper describes a recovery method for spilled oil under the ice floes established through systematic experiment.
5	2011	Development and testing of new mobile skimmers for oil recovery in ice-covered waters	Singsaas, Solsberg, Leirvik, Sorheim, Daae	Mechanical recovery in ice-covered waters presents additional challenges compared with open waters. It becomes difficult to use booms to collect the oil when the ice cover exceeds 10-30 %. In higher ice covers, the ice itself can act as a boom to confine the oil, but ice pieces can impede movement of oil to the skimmer. A skimmer therefore needs to be able to deflect the ice in order to gain access to the oil (referred to as ice processing). Several methods of separating oil and ice have previously been evaluated. These methods include lifting or submerging the ice or its lateral deflection in the water. It is also necessary for the skimmer to be protected and/or heated to avoid freezing in low temperatures. During a Joint Industry Program (JIP) from 2006 through 2010 (Sørstrøm *et al.*, 2010), SINTEF, together with manufacturers of oil spill response equipment, developed two new skimmer concepts for the recovery of oil in Arctic and ice-covered waters. The overall objective of this effort was to improve and develop technologies for oil recovery in ice and to document the capabilities and limitations of such technologies. The building of skimmer prototypes and initial testing were conducted at the

				manufacturers' premises. Further testing was carried out in the SINTEF ice basin and final testing and verification were performed during an experimental field trial in the Norwegian Barents Sea in May 2009. This paper discusses the findings arising from the development and testing of the two skimmers. It is concluded that both developments have contributed to improved mechanical recovery capability in broken ice. The two brush drum skimmers seem to have better ice processing capability than many other skimmer technologies. They were developed to a prototype level during the JIP and recommendations were made for further improvement of the final and commercial products.
5	2014	Development of a burning bench dedicated to in-situ burning study: Assessment of oil nature and weathering effect	Jezequel, Simon, Pirot	Since the Deepwater Horizon spill (2010), the controlled In-Situ Burning (ISB) of oil has been demonstrated to be a "primary" response option and not only an "alternative" solution to treat offshore oil spills (Allen. 2011). However, like the other techniques usually deployed (mechanical recovery, dispersion), the efficiency of the response option depends on various parameters (the pollutant itself and environmental conditions). Considering ISB, the efficiency is related to the oil nature, slick thickness, weathering degree, water content. In order to assess the influence of these parameters on the ignitability and burning efficiency, an experimental device was developed at Cedre. The Burning Bench comprises a burning cell which was designed to avoid any boilover phenomenon and to ensure water temperature homogenization during the burning. Glass barriers, a specific hood and plume exhaust system complete the device to ensure safety conditions. Burning tests are conducted on a maximum of 300 mL of oil sample. During the combustion, water and flame temperature are recorded at different heights by using 4 temperature probes. A gravimetric impactor is mounted in the hood to continuously collect the particles produced during the burning and afterwards, to quantify the PM 2.5. PM 10 and PAH content in the soot. At the end of a burning test, residues are collected and quantified after solvent extraction. Different analyses are then performed on the residues: density, viscosity, simulated distillation, chemical family separation (saturates, aromatics. resins, asphaltens). PAH and alkane distribution and content,

				... Potential PAH transfer from the oil to the water column is assessed by PAH extraction and quantification. During the burning bench development, many tests were performed on different products (light refined products, fresh or weathered crude oil. heavy fuel oil, ...). The preliminary results highlighted a very good reproducibility of the tests. For the refined product, more than 70% of the product burnt. For most of the fresh crude oils tested, the burning efficiency was measured between 50 and 60%. While testing heavy fuel or weathered products, the burning efficiency never exceeded 40%.
5	1979	Development of a novel ice boom for flowing waters	Tsang, Vanderkooy, Bascom	To contain and recover oil in an ice-infested river, an ice-free area has to be created wherein conventional clean-up gear may be employed. A joint Canada-United States study was begun to develop a barrier which would allow the oil to pass through while barring ice floes from entering the recovery site area. Theoretical and laboratory study showed that the ice floes could be deflected successfully from an oil spill recovery site. The U.S. Coast Guard financed the construction of the prototype and it was successfully tested at the Canadian Coast Guard Base in the Detroit River, Amherstburg, Ontario. The ice boom utilizes the ruddering principle, used by glance booms for the lumber industry. It consists of a sturdy body and a number of short fins or rudders. Openings are provided in the boom for the oil slick to pass through. After the oil passes through the boom, it may be contained and recovered by conventional methods. Field experiments showed that deployment and manipulation of the boom could be carried out readily. It was also apparent that the fins created a surface current deflecting the oil simulant directly toward the shore. Quantitative design criteria have been obtained.
5	1979	Development of a novel ice oil boom for flowing waters	Gee, Vanderkooy	The ice boom utilizes the ruddering principle, used by glance booms for the lumber industry. It consists of a sturdy body and a number of short fins or rudders. The angle between the boom and the fins is variable. The upstream end of the boom is tied to the shore. When the fins are gradually closed from the initially open position, the force of the current on the fins brings the boom gradually into the flow. The out-swung boom then prevents the ice floes from entering the area behind it and thus

				creates the desirable ice-free area. Openings are provided in the boom for the oil slick to pass through. After the oil passes through the boom, it may be contained and recovered by conventional methods. Field experiments show that deployment and manipulation of the boom could be carried out readily.
5	2017	Development of the Geo-Fiber Filter (GFF)™ - A geotechnically-engineered sediment control drain inlet protector (made from biodegradable African tropical fiber plants)	Adegoke, Olowokere	Under the Clean Water Act (CWA) of 1972, it is prohibitive of anyone to pollute "Waters of the U.S". At any construction site, any disturbed or excavated area of the earth constitutes an area of potential erosion if proper erosion/sediment control best management practices (BMPs) are not adopted. Erosion Sediment (E&S) control BMPs at construction sites include seeding, mulching, vegetation buffer strips, tree preservations and installations of some structural controls such as stabilized construction entrance, sediment basins, silt fences, velocity dissipators, drainage swales, earth dikes/berms, storm water inlet protections such as Hay Bales, Straw Bales and Silt Fence. Of all the afore-mentioned BMP's, storm water inlet protection is the secondary, ultimate and last line of defense in forestalling pollution - i.e if other BMP's fail this must not fail; although Sediment Basins may be used for the same purpose on some other construction sites where applicable. The use of agricultural materials/waste (such as grass, cotton, wool, fabrics etc) to stabilize roads in soils of questionable quality has been found to be as old as Egyptian civilization. Modern applications of such materials are now known as Geo-Textiles (GT). In this study, the applicability of using natural fibers derived from African tropical fiber plants (Urena, Kenaf Sisal) as filter elements to remove sediments from polluted storm water, was investigated. A Geo-Fiber Filter (GFF)™ Storm Drain Inlet Protector was innovated employing natural plant fibers, geologic (quartz gravel) and agricultural waste materials (palm kernel shells-PKS) as components. Laboratory test evaluation showed the efficacy of the GFF in removing sand-sized and clay-sized particles from polluted storm water. Comparative evaluation of filtration elements made from urena, kenaf and sisal fiber plants were made in a Percolation Test Table and the first two were found to be equally efficacious in removing sediments and they all met the minimum discharge capacities of 0.5cfs (cubic feet per second) or

				14.2l/s or 3.75gpm stipulated by USEPA. Sisal fiber was found to be incapable of sufficient tensile strength/frictional cohesion as it could not hold back the PKS resulting in excessive bulging. It was therefore discarded from further investigations. In fact, a flow rate of 40l/min (10gpm) was freely passed through the urena/kenaf filter element without backflow thus satisfying adequate flow requirements of a good inlet protector. Water and oil absorbent capacities were also investigated and was found to be highest for kenaf, urena and sisal in that order respectively. Kenaf was found to be capable of absorbing more than 300% of its own weight. It is therefore a good candidate for use in Oil spill Clean-up and bio-remediation works. Capability of filter element in removing dissolved hydrocarbon/organic contaminants will be enhanced if the PKS is of the activated carbon (AC) type due to the higher adsorbing surface areas in the AC. The GFF filter element was also found to be applicable to conditioning and conserving water in modern conservative aquaculture management system specifically as Bio-Filters in Re-circulatory Aqua culture Systems (RAS). Original product conceptualization was evolved at Paul Quinn College Dallas TX in 2006, some fiber permeability tests were later carried out at Texas Southern University while the final Filtration Tests in a Percolation Test Table were concluded at the Geotechnical laboratory of Landmark University, Omu-Aran, Kwara State Nigeria.
5	2010	Employing chemical herders to improve marine oil spill response operations	Buist, Potter, Belore, Guarino, Meyer, Mullin	As a result of the experimental success thickening slicks for in-situ burning in drift ice using the herding agent USN, a research program was carried out on using herders for other marine oil spill operations. In particular experiments were carried out to see if herders could be used to: • Improve the recovery rate and efficiency of skimmers operating in drift ice without the use of containment booms; • Clear thin oil from large areas of oiled marsh and/or concentrate it for removal; and, • Thicken oil slicks on open water prior to chemical dispersant application to improve the operational efficiency of dispersant application to spills from offshore platforms. Experiments to study the use of herders to improve skimmer operations in drift ice were carried out at the SL Ross lab and at Ohmsett using both weir and oleophilic

				skimmers. The addition of herder improved the performance of the weir skimmer by factors of 3 to 10. No significant improvement was measured in the performance of the disc skimmer. A series of small-scale experiments was also undertaken at the SL Ross lab to determine the feasibility of using herders to clear oil slicks from salt marshes. The experiments utilized similar local fresh water marsh plants as surrogates for salt marsh species. In none of the static tests did the herder clear the oil completely from the marsh plants. In some tests the herder caused the oil slicks to contract in size sufficiently to significantly reduce the oiled area of the marsh; however, even in these cases, there remained a ring of oil at the waterline around the originally oiled stalks of the marsh plants. A short series of tests to simulate oil entering a salt marsh on a rising tide indicated that herders might prevent this. Tests were conducted at Ohmsett to compare dispersant application on herded slicks at rates representative of aerial spraying vs. boat spraying. The use of herders on an oil slick did not detract from the effectiveness of chemical dispersant application. Using herders to contract slicks on open water can improve the operational efficiency of dispersants applied by vessels. Herding a slick to be sprayed with dispersants from aircraft could reduce operational efficiency (by wasting large amounts of the dispersant).
5	1999	Estimation of towing forces on oil spill containment booms	Potter, McCourt, Smith	Effective use of skimmers or in-situ burning for an oil spill generally requires that the spill first be contained using booms. A series of towing tests were conducted at the Ohmsett test facility to estimate the towing forces on a number of booms using a range of gap ratios, wave conditions, and tow speeds. The data from these experiments was used to develop a simple relationship to predict the tow force and required tensile strength for the various boom and tow parameters. A comparison was performed between the tow forces as measured in the Ohmsett test tank against those measured in recent in-ocean testing. The tension experienced by a boom was not constant, particularly when towed through waves. As the boom followed the crests and troughs of the waves the tension fluctuates, peaking when

				the apex of the boom catches the front of a wave. The boom must be designed to be able to withstand these maximum tensions.
5	1999	Evaluating a Protocol for Testing a Fire-Resistant Oil-Spill Containment Boom	Bitting	Most response plans for in-situ burning of oil at sea call for the use of a fire-resistant boom to contain the oil during a burn. Presently, there is no standard method for the user of a fire-resistant boom to evaluate the anticipated performance of different booms. The ASTM F-20 committee has developed a draft standard, "Standard Guide for in-situ Burning of Oil Spills on Water: Fire-Resistant Containment Boom"; however, the draft provides only general guidelines and does not specify the details of the test procedure. Utilizing the guidelines in the draft standard, a series of experiments were conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves.
5	1998	Evaluating a protocol for testing fire-resistant oil-spill containment boom	Walton, Twilley, Hiltabrand, Mullin	The ASTM F-20 committee has developed a draft Standard Guide for In-Situ Burning of Oil Spills on Water: Fire Resistant Containment Boom; however, the draft provides only general guidelines and does not specify the details of the test procedure. Utilizing the guidelines in the draft standard, a series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves. The boom test evaluations were conducted in a wave tank designed specifically for evaluating fire-resistant boom. The tank was located at the Fire and Safety Test Detachment facility on Little Sand Island in Mobile Bay, AL. The burn characteristics were substantially influenced by the wind speed and direction. When the wind speed was low, the smoke and flames rose nearly vertically providing a relatively uniform thermal exposure to the entire boom circle. If the wind direction changed during the burns, differing sections of the boom received the most intense thermal exposure. Burning outside the boom was observed early in the burns even though no oil was observed leaking from the boom during the initial fueling. The effect of the circular boom configuration and effect of the water-cooled stanchions used to constrain the boom was not uniform for all the booms. Most of the booms were not affected by the short turn radius although the sections of the relatively rigid stainless steel boom were touching on the inside of the circle. The six

				stanchions used inside the boom circle to constrain the boom did not interfere with boom movements. However in some cases, the contact of the boom with the stanchions caused wear, which would not be expected at sea.
5	2005	Evaluation and limits of protective boom plans for high tidal range and strong current areas	Fauvre	The French organization of onshore oil spill response is defined by specific intervention plans (Polmar plans), established for every coastal department. One of the main elements of these plans consists of detailed plans for deploying booms to protect sensitive areas. The Ministry of the Sea, with assistance from CEDRE, carries out exercises every year in different coastal locations to test the feasibility and efficiency of the boom deployment plans and also to train local personnel in handling antipollution equipment. Lessons learned from these exercises enable the improvement of deployment plans and help define new research areas. Within this framework, CEDRE has undertaken a feasibility study for the installation of booms in high tidal range and strong current areas. This experimental study involved a 15-day period, during the autumn of 1993 of on-site observations on the behavior of booms installed in one of the most difficult sites on the Atlantic shoreline. The main parameters observed were resistance, containment efficiency, and mechanical behavior of booms during the tide cycle, particularly when booms are stranded at low tide. In spite of successful boom installation, the experiment encountered difficulties due to meteorological and instrumentation problems. Nevertheless, important lessons have been learned. Static boom protection seems to be difficult for such sites, which leads us to question the validity of numerous Polmar plans. We should test alternative response techniques such as dynamic recovery systems set up at the openings to sensitive areas, which will necessitate good coordination between at-sea and on-shore response authorities. Mooring systems design and installation are jobs for specialists and should be prepared in advance. Various local means, such as fishing vessels or oyster farm barges, can be used for deploying protective booms.

5	1976	Evaluation of a pneumatic barrier for oil containment	Grace	The investigation concerns the development and evaluation of a pneumatic barrier for restraining the natural flow of surface oils in the buffalo River. The initial phase of the study involved lab experiments to evaluate the surface currents produced by buoyant air-water plumes which were formed by the injection of air through single and multiple orifices submerged below the water surface. Based upon the data obtained, a full scale, prototype air barrier system was designed. This barrier system was built and installed and a full scale test program was initiated to evaluate the performance. Additional lab tests were conducted in a water channel facility to investigate the performance of the barrier system at higher currents and for different oil types. It was determined that a pneumatic barrier could be an effective device for stopping the flow of surface oils for currents moving at <1 ft per second. The actual limiting speed for a particular oil was a function of its viscosity and specific gravity. In no instance was any oil that was tested restrained in a current of more than 1.5 fps.
5	2011	Experimental research on solid float type oil containment boom	Zhang, Wang, Yao	Oil containment booms are mainly used for emergency actions to prevent oil spill and diffusion on open sea, around harbors, docks and naval architectures. This paper presented one experimental research on available depth of solid float type oil containment boom under current and its oil containment performance under waves and currents.
5	2004	Experimental study on separating oil trapped under pack ice fields	Otsuka, Hirofumi, Ishikawa, Saeki	When an oil spill occurs under pack ice fields in the ocean, oil would spread beneath the ice cover and then would be trapped into recesses under the pack ice. In this paper, the method for separating oil that is trapped into recesses of pack ice is investigated as an elemental technique for oil recovery. In this method, it is proposed to remove oil from recesses by introducing air bubbles and flush out through relative velocity between ice floes and seawater. A series of laboratory experiments were carried out to investigate the behavior of oil and air bubbles.
5	1980	Feasibility of water spray barriers as	Comfort, Menon, Purves	The successful use of a water spray barrier as a heat shield in conjunction with a conventional boom for in-situ burning of oil slicks is described. Further laboratory test programs to evaluate the oil containment capabilities of a ″fixed″ water spray

		fireproof oil slick containment devices		barrier are elaborated. Results of testing the device in currents, winds and waves along with its performance in cold environments, are presented. It is concluded that the fixed spray barrier tested is capable of performing satisfactorily in environments specified for conventional booms.
5	2016	Fully automatic boom towing by unmanned ships: Experimental study	Giron-Sierra, Gheoghita, Jimenez	A commonly used technique for oil spill response is to use two or more ships towing a boom. Our research proposes fully automated operations based on unmanned ships and a computer-based planning system. The system will carry on a complete autonomous operation, requiring only the position of the oil-spill and to push a start button. The paper describes the steps of the research already accomplished, which involves computer modelling and experimental studies. The experiments started with scaled ships and now are based on real scale zodiacs. Boom towing is a peculiar task, which require specific control strategies.
5	1997	In-situ burning: An alternative approach to oil spill clean-up in Arctic waters	Guenette	In-situ burning is a spill countermeasure which involves burning the oil in place, usually at or near the spill site, under controlled conditions. During the 1980's in-situ burning emerged as a promising technology for dealing with oil spills in arctic waters, where ice cover can prevent deployment of conventional response equipment (skimmers and booms). In Norway, this method has been considered to be the most likely response option in high ice cover areas, for example in the Barents Sea. In light of this fact, an experimental Programme, spanning over four years, was initiated in 1990 to study in-situ burning. This research was carried out by SINTEF as part of a wider Programme `Oil spill response in Northern and Arctic waters' (ONA) sponsored by the Norwegian Clean Seas co-operative (NOFO). This paper describes the general principals of in-situ burning and presents some of the research carried out in Norway in this field.
5	2014	Nano-based systems for oil spills control and cleanup	Avila, Munhoz, *et al.*	This paper reports the development of super-hydrophobic nanocomposite systems which are also oleophilic. As hydrophobicity is based on low energy surface and surface roughness, the electrospinning technique was selected as the manufacturing technique. N,. N' dimethylformamide (DMF) was employed as the polystyrene (PS) solvent. The "Tea-bag" (T-B) nanocomposite system is based on

				exfoliated graphite surrounded by PS super-hydrophobic membranes. The T-B systems were tested regarding its adsorption and absorption rates. To test these properties, it was employed three different water/oil emulsions, i.e., new and used motor oil, which have physical properties (viscosity and specific gravity) similar to heavy crude oil extracted in Brazil, and vacuum pump oil (which does not form oil/water emulsion). It was observed that oil adsorption rate is dependent on oil surface tension, while the absorption rate is mainly dependent on membrane/exfoliated graphite surface area. Experimental data show that oil absorption rates ranged between 2.5. g/g and 40. g/g, while the adsorption rate oscillated from 0.32. g/g/min to 0.80. g/g/min. Furthermore, T-B systems were tested as containment barriers and sorbent materials with good results including its recyclability.
5	1977	Oil pollution	Cormack	Various methods and techniques used to combat oil spills are reviewed. The UK's response capability for oil spills is now based on dispersant spraying equipment developed at Warren Springs Laboratory (WSL). Details of the equipment used (spraying techniques, dispersant concentration and type of agitation boards, application from the air possibility) are described. A separate paragraph deals with the environmental impact of dispersed oil; experiments with Ekofisk and Kuwait oil were carried out to assess the environmental impact on different classes of organisms. Developments in the field of spilled oil recovery are discussed. New devices are continuously being tested at WSL. An optimal boom design (spraying from ships) has now been established; the next step will be to design optimal skimmer features. Finally the recovery aspect must be seen in the light of suitable vessel type available; here too great strides are being made at WSL. (13 references)
5	1969	Oil slick containment on collecting devices	Hoult	Main engineering features of physical and pneumatic booms operating as oil containment devices in the open sea are discussed. The oil containing capacity of a pneumatic boom is limited by the power available to compress the air. It is suggested, through the results of preliminary experiments, that the containment capacity of physical booms (barriers) is limited by the effective depth of the boom.

				A brief review of the main types of collection systems in use (roller and towed or pushed boom) is given.
5	2005	Oil spill cleanup with dispersants: A boomed oil spill experiment	Buckley, Green, Humphrey	Three experimental oil spills of 200, 400, and 200 litres (1) were conducted in October, 1978, in a semi-protected coastal area on Canada's west coast. The surface slicks were restrained with a Bennett inshore oil boom. The spilled oil was chemically dispersed using Corexit 9527, applied as a 10-percent solution in sea water and sprayed from a boat. The dispersed oil was monitored fluorometrically for some hours. Surface and dispersed oil were sampled for chemical analysis. The highest recorded concentration of dispersed oil was 1 part per million (ppm). After a short time (30 minutes), concentrations around 0.05 ppm were normal, decreasing to background within 5 hours. The concentrations were low compared with those expected for complete dispersion which, as visual observation confirmed was not achieved. The dispersed oil did not mix deeper into the water column with the passage of time, in contrast to predicted behaviour and in spite of the lack of a significant vertical density gradient in the sea water. This was attributed to the buoyancy of the dispersed oil droplets and the limited vertical turbulence in the coastal locale of the experiment. The integrated quantity of oil in the water column decreased more rapidly than either the mean oil concentration of the cloud or the maximum concentration indicating that some of the dispersed oil was rising back to the surface. The surfacing of dispersed oil was confirmed visually during the experiment. The mixing action of the spray boat and breaker boards apparently created large oil droplets that did not form a stable dispersion. Horizontal diffusion of the dispersed oil was initially more rapid than expected, but the rate of spreading did not increase with time as predicted. The results imply that the scale of diffusion was larger than the scale of turbulence which again can be attributed to the locale of the experiment.
5	2008	Recent testing, training and research conducted at ohmsett	ullin, Devitis, Guarino, Meyer, Delgado	Ohmsett, The National Oil Spill Response Test Facility, plays a critical role in developing, testing and evaluating effective response technologies as well as preparing responders with the most realistic training available. Ohmsett is a national

		- the national oil spill response test facility		asset where government agencies (state and federal), private industry, academia and foreign countries can conduct full-scale oil spill research and development programs. It is also the premier training site for spill response personnel from oil spill response organizations, private industry, and government agencies such as the U.S. Coast Guard, U.S. Navy, and the Environmental Protection Agency. During the past two years test programs have included oil weathering experiments in broken ice, dispersant effectiveness experiments conducted on heavy Outer Continental Shelf and Alaskan crude oils, dispersant research conducted in calm seas and in low sea states and on realistic emulsions, evaluation of oil herding surfactants to thicken spilled oil in broken ice, remote sensing flyovers, containment boom and skimmer testing, development projects, and numerous training sessions. Extensive renovations and repairs were also performed. This paper will provide a summary of the most recent Ohmsett test programs.
5	2005	Research and development in the institute of ocean environmental technology	Yazaki	This paper presents a summary of research and development projects at the Institute of Ocean Environmental Technology. First, projects in the field of oil boom and skimmer development are described. Oil containment performance for each of four new oil booms, and the oil recovery rate for each of seven new oil recovery devices and a new oil recovery ship are explained. Next, as typical examples of research projects concerning ocean and marine environmental problems, summaries of the following themes are presented: (a) oil spreading on the water surface, (b) the mechanism of oil leakage from a flat plate barrier, (c) oil slick behavior around a moving catamaran skimmer, (d) a law of similarity for the performance of all recovery equipment, (e) evaporation of gasoline under various conditions, (13 the relationship of spilled ail and dissolved oxygen in sea water, (g) the effectiveness of chemical dispersants for spilled gasoline, (h) the generation of transient waves in a circulating water channel, and (i) experiments with a wave energy absorber.
5	1999	Second Phase Evaluation of a	Walz	Most response plans for in-situ burning of oil at sea call for the use of a fire-resistant boom to contain the oil during a burn. Presently, there is no standard method for the

		Protocol for Testing a Fire Resistant Oil Spill Containment Boom		user of fire-resistant boom to evaluate the anticipated performance of different booms. The American Standard for Testing Materials (ASTM) F-20 Committee has developed a draft standard, `Standard Guide for in-situ Burning of Oil Spills on Water: Fire-Resistant Containment Boom'; however, the draft provides only general guidelines and does not specify the details of the test procedure. Utilizing the guidelines in the draft standard, a second series of experiments was conducted to evaluate a protocol for testing the ability of fire-resistant booms to withstand both fire and waves.
5	1970	The spreading and containment of oil slicks	Hoult, Fay, Milgram, Cross	Recent experimental and theoretical results for the spread of oil slicks in a one-dimensional channel are surveyed. The results imply that there are, in fact, the three regimes of oil spreading on calm water as originally described by Fay. A survey is presented of the main features of how an oil boom holds oil against a steady current.
5	1975	United States Coast Guard arctic oil-pollution program	Getman	The United States Coast Guard, responsible for maritime pollution control, has stepped up its arctic pollution surveillance and response research and development. Field experiments on the behavior of oil, I under summer conditions in 1970 and another under winter conditions in 1972, have been run. These indicated that oil spreads at a much slower rate under arctic conditions, and that it pooled on and under the ice. Oil is quickly covered by snow, but the resulting mulch is easily handled by mechanical means. Burning was always a readily available and effective alternate means of removal. Off-the-shelf equipment was evaluated in 1973, resulting in a number of conclusions concerning barriers and moorings, oil recovery systems, and personnel. Based on this field evaluation, there will be additional oil/ice tests of recovery devices.
5	2005	United States Coast Guard arctic oil-pollution program	Getman	With the burgeoning forecasts of oil production and transportation in the cold weather regions-especially Alaska-expectations of spills in the fragile and hostile arctic environment must increase. The Coast Guard, responsible for maritime pollution control, has stepped up its arctic pollution surveillance and response research and development. Field experiments on the behavior of oil-one under summer conditions in 1970, and another under winter conditions in 1972-have been

				run. These indicated that oil spreads at a much slower rate under arctic conditions, and that it pooled on and under the ice. Oil is quickly covered by snow, but the resulting mulch is easily handled by mechanical means. Burning was always a readily available and effective alternate means of removal. Off-the-shelf equipment was evaluated in 1973, resulting in a number of conclusions concerning barriers and moorings, oil recovery systems, and personnel. Based on this field evaluation, there will be additional oil/ice tests of recovery devices.
5	1999	Wave generation system	Turnelle, Lamb, Regnier	The development and design of oil spill management and cleanup technologies at UNH utilizes a 4-foot-wide, 3-foot- high, 40-foot-long flume tank. The tank generates flow rates of up to 0.9 m/s and has a transparent side for experiment observation. To investigate failure modes of oil containment booms in a more realistic environment it was determined that a wave-generating device was a necessary addition. The challenge was to develop a device capable of generating uniform, sinusoidal waves with one-to three-inch amplitudes over a range of frequencies. This student project report describes the design tested.

Papers Denoted as 3/4/5: Other

Rel	Year	Title	Authors	Summary
3	2000	Analysis of oil containment failure and spreading	Sundararaghavan	Oil containment and spreading are the two aspects of oil slicks investigated in this study. In certain conditions, the oil is known to escape near the boom causing containment-failures. This near-boom containment failure is considered by defining a neutral-stability criterion. The uniform flow past the boom problem is studied using potential and laminar viscous flow theories. The flow patterns are presented and the neutral stability curves are determined. The results demonstrate the effects of viscosity on oil containment and also show that the containment is more likely to fail in shallow waters. The influence of waves on the containment failure is investigated by solving wave diffraction due to boom using the linear wave theory and defining a new stability criterion to analyze containment failure in the presence of waves. The containment failure may occur only during a part of the wave cycle and the results show that the failure is more likely due to shorter waves and in shallow waters. The spreading of oil on water is influenced by external forces such as tides, winds and waves. A three-dimensional coastal circulation model, incorporating a new numerical procedure, is developed to determine the tide- and wind-driven surface currents. The results show that the currents are parallel to coasts with a strong tidal dependency To determine the wave-induced surface drift, a wave transformation model is developed to obtain the distribution of wave heights and directions which are, in turn, used to calculate the Eulerian surface drift. Even though the wave-induced surface drift is small compared with that of the coastal currents, its contribution to the oil transport towards the coast is significant. Using the surface currents due to winds and tides and the wave-induced surface drift as driving forces, oil transport is formulated using a thin-layer approximation. A finite-element model is developed to determine oil thickness distributions and is applied to a hypothetical oil spill. The results indicate that the slick moves in a reversing fashion due to reversing tidal currents and splits into two parts with one in the southern area and another in the western.

3	1974	Development of a novel high velocity oil slick skimmer. Final report	Lindenmuth	Experimental investigations show that thin slicks of oil can be recovered in currents of up to 10 fps with a new Surface Velocity Retarder Oil Skimmer (SVROS). This collection device is composed of an array of closely spaced flat plates. The plates serve to gradually dissipate the kinetic energy of the oil/water inflow so that oil can be collected at high relative velocities without the entrainment losses typical of all simple oil booms in currents over about one knot. Tests, in prototype scale, were performed on a thin model of the device. Tests variables included velocity, plate spacing and depth, oil type, and slick thickness. The test results are presented with conclusions and recommendations for further development.
3	1975	Development of a Streaming Fiber Oil Spill Control Concept	Beach, March	Seaward, Inc., has developed a simple and effective new concept for control of oil spills in currents up to 10 knots. The concept utilizes long, continuous fibers that stream out into the current to slow down and thicken spilled oil. Extensive tests have demonstrated that in a containment device, a thick, stable pool of oil can be created from which conventional techniques can be used to recover the oil. Losses beneath the system are negligible compared with the catastrophic losses a conventional containment barrier or oil skimmer would experience under the same conditions. An extensive test program was conducted during the program, including model testing in a 7 fps flume and testing of a prototype-scale fiber array in a commercial skimmer at speeds up to 6 knots. A preliminary prototype design for a 6-knot, self-propelled river skimmer was developed.
3	1974	Effects of currents and waves on an oil slick retained by a barrier. Final report	Hale, Norton, Rodenberger	The report presents the results of experimental studies conducted on the behavior of a floating oil slick subjected to various external mechanical influences and to the action of currents and waves. Specifically, studies were made of the behavior of a thick slick, retained by a barrier, subjected to currents and waves, and subjected to the influence of various slick shield devices. Studies were also made of the effects on a moving thin slick of energy absorbing barriers and various other slick control devices. The laboratory experiments closely duplicated prototype conditions except for wave size. The results of this investigation clarify many previous misconceptions of thick slick behavior and introduce several new concepts of slick behavior including a

				mathematical model describing the entrainment loss phenomena. Oil diversion schemes, rapid removal schemes and energy absorption barriers were evaluated in terms of their effect on thin slick behavior at high current velocities.
3	1974	Evaluation of the Strength and Seakeeping Ability of Pollution Control Barriers	Milgram, O'Dea	The purpose of the work described by the report is to provide a basis for the evaluation of arbitrary oil pollution control barriers without the need for full scale testing. It is described that for well-designed barriers the principal cause of oil leakage is droplet entrainment which has little, if anything, to do with the barrier, but rather depends on how the barrier is used. Since the leakage from droplet entrainment cannot be quantitatively predicted at this time and is only slightly dependent on barrier design, a barrier is best evaluated on its strength and seakeeping ability. A barrier is adequate for the task intended if it is strong enough and follows the seas well enough for it to provide a surface-piercing curtain with adequate draft and freeboard. The report gives means for making these evaluations. These are substantiated with full scale, model and analytical results.
3	1974	Fast Current Oil Control Study	Graebel, Phelps	Model studies of oil containment barriers and herding devices were conducted in an open channel of six foot width and three and one-half foot depth. Currents up to four feet per second were used with three different oils. Incipient failure of the barriers occurred for values of the densimetric Froude number of about unity. Trajectories of the oil drops at incipient failure are given. Oil herding devices were tested at various angles to the current. This performance in regard to loss rates was superior to that of the barriers, and improved as the angle between current and herder was decreased. Multiple barriers and barriers with nets were also tested. A vortex oil recovery device was conceived and tested, which showed only very small loss rates at all speeds tested. Its rate of recovery of a slick increased with current speed.
3	1975	Fast Current Oil Response System	Mueller	A relative velocity can be imparted to a floating oil slick by moving an air jet across the surface of the water. If two long booms are arranged in a 'V' shape and moved across an oil slick, the oil will be blown into a concentrated strip which can then be collected with a suitable collector. The collector application in this study used a flow-through trough and a second air boom to skim the oil off the surface and into an oil concentrator.

				The complete unit was tested by the Univ. of Michigan at speeds up to 7 ft/sec. The 'Vee' air booms did an excellent job of 'herding' the oil with efficiencies ranging from 100% at 1 ft/sec to 80% at 7 ft/sec. The development of the collector did not reach a point where good efficiencies could be obtained above 4 ft/sec.
3	1975	Fast Current Oil Response System - Stage I, SVROS Development	Lindenmuth, Sinnerwalla, Sundaram	Combined theoretical and experimental studies show the effects of several parameters on the formation of a thickened pool of oil inside the Surface Velocity Retarder Oil Skimmer (SVROS), an energy absorbing device designed to recover thin oil slicks in high relative currents. This collection device is composed of an array of closely spaced flat plates that serve to gradually dissipate the kinetic energy of the oil/water inflow so that the oil can be collected without the entrainment losses typical of simple oil booms in currents exceeding about one knot. Model tests were performed in prototype scale with thin models of the device in an 80 foot long towing tank and in a recirculating flume. Test variables included velocity (1-10 fps), oil type (from 5 to 1000 cs), slick thickness (0.04-0.50 in.) and model geometry. The final model configuration utilized several interchangeable modules so that pool formation was controlled over the wide range of inflow parameters to optimize the purity and efficiency of oil withdrawal from the SVROS. Curves defining the recovery performance are presented that show essentially complete oil recovery up to 5 fps with thin slicks of light fuel oil such as Diesel fuel. Performance degrades with increases in velocity, viscosity and incident wave height.
3	1994	Improving the Performance of Oil Spill Containment Booms in Waves. Part 1; Literature Review. Part 2; Physical Model Study: Procedure and Results	Van Dyck	This study to improve boom performance is intended to complement the ongoing oil spill research at the Ohmsett facility and within the Marine Spill Response Corporation. After an extensive review of the literature, new model testing instruments and procedures have been developed to provide a direct measure of containment boom heave response to wave excitation at several points along a catenary-towed boom. Measurements have been made in reproducible regular, irregular and breaking waves for various generic model boom configurations over a range of wave characteristics and boom buoyancy/weight ratios at typical towing speeds. Total towing forces have also been measured and are scaled up to full size predicted drags. Based on analyses

				of the results, highly flexible booms with buoyancy/weight ratio of at least 10 and sufficient freeboard are recommended for open sea operation with a catenary tow at about 0.5 knot.
3	1982	Oil slick behaviour in waves	Kamata	An experimental investigation was performed to determine the drift velocities of oil slicks and the pile up of oil layers against barriers in the presence of water waves. Other investigations of the drift response were made by substituting thin plastic sheets in place of the oil slicks. Parameters were developed which govern these movements. Discrepancies in the literature between drift of oil lenses and the "Stokes' drift" were solved. It was discovered that the boundary layer between the drifting oil slick and wave motion has turbulent character and is not laminar as was derived from theory and assumed to be the case.
3	2000	SPAM -- Submergence Plane Analysis and Modelling for a fast current oil containment barrier	Fullerton, Roman	Conventional oil booms like those found standard in the oil transportation industry have been an important tool in oil spill recovery. These containment booms are, however, limited by moving water, everyday tidal currents in particular. The failure of an oil boom occurs when the perpendicular component of the current speed exceeds a critical value, which has been determined to be between 0.6 and 1.0 knots, depending on the type of oil. A flexible oil barrier and containment device, known as the 'Bay Defender', can successfully collect floating oils in currents nearly three times that speed. The purpose of this yearlong student project was to study the fluid dynamics around submergence planes of varying shapes with the intention of improving containment performance even further.
3	1977	The design, analysis and field test of a dynamic floating breakwater	Agerton	
3	1974	The Effects of Currents and Waves on an Oil	Hale, Norton, Rodenberger, Texas	The report presents the results of experimental studies conducted on the behavior of a floating oil slick subjected to various external mechanical influences and to the action of currents and waves. Specifically, studies were made of the behavior of a thick slick, retained by a barrier, subjected to currents and waves, and subjected to the influence

		Slick Retained by a Barrier		of various slick shield devices. Studies were also made of the effects on a moving thin slick of energy absorbing barriers and various other slick control devices. The laboratory experiments closely duplicated prototype conditions except for wave size. The results of this investigation clarify many previous misconceptions of thick slick behavior and introduce several new concepts of slick behavior including a mathematical model describing the entrainment loss phenomena. Oil diversion schemes, rapid removal schemes and energy absorption barriers were evaluated in terms of their effect on thin slick behavior at high current velocities.
4	1973	An investigation of the effects of currents on an oil slick retained by a physical barrier	Agrawal	
4	1971	Concept development of a hydraulic skimmer system for recovery of floating oil	Blacklaw, Crea, Simonson, Walkup	Efforts are being directed to develop effective countermeasures against floating oil slicks. Mechanical recovery methods, which do not cause additional environmental insult, are most attractive. Such a concept, a hydraulic skimmer, was investigated. Floating headers, providing a linear water spray pattern on the water surface, are attached to an open sea workboat. Sea water is pumped through spray nozzles mounted on the headers to move an oil slick toward the boat. Side mounted chambers are positioned to collect the concentrated floating oil. Recovered fluid is pumped to an onboard separation system from which the oil is transferred to floating tanks or barges and the water is recycled to the spray system. Experimental work was directed toward component development and evaluation of a large system model in a simulated environment. Model experiment results showed, for light oils, 80 to 100 percent effectiveness and oil recovery rates of 6600 to 8700 gph. Results with Bunker fuel were not as good, being on the order of 1300 to 1800 gph and 12 to 30 percent effective in recovering oil from the water surface.

4	1970	Concept development of a prototype lightweight oil containment system for use on the high seas. Final report, 5 December 1969-5 June 1970	Hoult, Cross, Milgram, Pollak, Reynolds	As part of a federal program to develop control measures for oil spills, a two stage procurement plan was initiated in 1969 for an oil containment system for use on the high seas. The report describes the development of a system based upon the utilization of a physical barrier to confine spilled oil in as small an area as possible to permit effective removal procedures. Some of the methods which were used to develop the concept are described such as small-scale modelling in the laboratory, mathematical analyses, computer simulation techniques, logistical analyses, and scale model field tests. Included in the presentation is a summarized proposed plan for the detailed design of the system.
4	1970	Containment of oil spills by physical and air barriers	Hoult	A review of the state of the understanding of barriers to contain oil is presented. Using recent results, the main design parameters for a physical barrier in a steady current are presented. Included are discussions of draw down, forces, moments, and the configuration a boom takes on when deployed in a current. In each topic, comparison is made with experimental results and available theory. It is shown that a properly designed boom may hold large amounts of oil against a steady current. A brief discussion of the implications of these new results for air barriers is presented also.
4	2018	Development of the Electromagnetic Boom and MOP System (EMOP)	Warner etal.	Several large-scale oil spills typically occur in the USA and other places around the world. Such events threaten the Great Lakes as well. The cleanup process is not necessarily efficient or environmentally safe. In addition, the remediation and recovery process is time consuming, expensive and can lead to harmful environmental effects. An innovative electromagnetic approach by Natural Science, LLC uses materials that are reusable, recoverable, and environmentally safe. When micron-sized magnetite (Fe_3O_4) particles are dispersed in oil on water, the particles form a unique and preferential bond with the oil due to a combination of forces, e.g. Van der Waals. Magnetic fields can then be used to manipulate, trap and remove the oil in an environmentally safe manner with high efficiency. In the case of oil spills on water, the water becomes the primary transport medium for manipulating the oil. Videos demonstrating the process will be shown. Both the particles and the oil are recaptured

				and separated for reuse. This process is being applied to electromagnetic systems that can replace and/or increase the efficiency of the passive boom and skimmer systems used today.
4	1973	Fabric boom concept for containment and collection of floating oil	Bonz	The feasibility of applying the concept of oil-water separation by means of woven hydrophilic fabric to a floating oil containment boom was investigated through a series of model tests. A preliminary model boom configuration was developed and towed at speeds to 0.686 metres/sec (2.25 ft/sec) in both calm water and waves. Oil retention performance of this model was clearly superior to that of a conventional flat plate boom of comparable draft in the environment investigated. A larger model of similar configuration demonstrated no oil leakage when towed at 0.77 metres/sec (1.5 kt) in calm water. While further detailed analysis, engineering, and testing are required to fully examine this concept, it appears that a properly designed flexible boom which uses a hydrophilic skirt material offers significant potential both as a containment device for floating oil in high current situations and as a high-speed collecting device.
4	1973	Multicomponent Evaluation Test of Harbor Oil Spill Recovery System	Graham	Development work performed by other governmental agencies does not evaluate and recommend equipment for operation use in oil spills. An urgent current need exists within the Navy for a systematic evaluation of available oil spill recovery components individually and in combination as an oil recovery system for Naval Harbors. This report and a companion narrated 16 mm film summarize results of the initial project under a continuing NAVFAC program to fill this Navy need. The main emphasis of this program currently underway at NCEL is a comparative evaluation of oil spill containment booms, skimmers, and related equipment resulting in the recommendation of a harbor oil spill recovery system for Navy use.
4	2001	Oil spill response performance review of booms	Schulze	
4	2006	Optimization of outrigger spacing of a trimaran hull	Nair	The purpose of this study is to evaluate the total resistance of a trimaran by optimizing the outrigger spacing, along both longitudinal and transverse directions, using the potential flow solver from a numerical model called SHIPFLOW, a commercial

		using Computational Fluid Dynamics (CFD)		Computational Fluid Dynamics (CFD) package. A body plan of the tri-hull was considered from an existing report and was converted into a 3-D model using the RHINO software. The outriggers were modified along the length for our study. Using the offset file obtained from the RHINO software, rung were then made for different outrigger positions along both longitudinal and transverse directions with respect to the main hull. The wave making drag was obtained from the SHIPFLOW analyses. The frictional drag was calculated using the ITTC 1957 line. The total drag was then calculated adding the wave making drag and frictional drag. The total resistance obtained from the SHIPFLOW analysis was then compared with the results obtained from the MICHELET, a software based on Michelle's Thin Ship theory.
4	1975	Research, Design, and Development of the U.S. Coast Guard High Seas Oil Containment System	Tierney	The objective of this program was to develop a lightweight air-deliverable oil barrier system, capable of containing significant quantities of oil at sea states to 5 foot waves and 1 knot currents, and in winds up to 20 knots, and of sustaining with minimal damage 10 foot waves, 2 knot currents, and 40 knot winds. An inflatable-supported curtain barrier, self-floating air-deliverable barrier-storage/deployment container, and barrier moorings were developed from initial concept stages to full-scale usable equipment. Model and field tests were conducted and modifications were made as required. An at-sea test of the interfaced subsystems demonstrated the validity of the final design and the viability of the air-delivery method.
4	1976	Spreading, retention and clean-up of oil spills. Final report	Wilson	This study reviews and assesses the technology of oil spill spreading, retention and cleanup and proposes research needs in these areas. Sources of oil spills are analyzed and the difficulty of gathering meaningful statistics is discussed. Barrier technology is reviewed and problem areas analyzed. Natural and forced biodegradation and natural and chemical dispersion of oil spills are considered. Research recommendations are categorized under the following two headings (1) Preventive techniques and (2) Containment, Cleanup and Dispersion.
5	2016	A Theoretical and Experimental Analysis of the	Moutassem	In recent history, the manufacturing of products and waste generation has significantly increased, causing an increase in the amount of waste residing in landfills. To promote sustainability, the recycling industry has embarked on two major goals: the reuse of

		Density Separation of Non-magnetic Materials with the Use of Imposed Magnetic Fields		expensive post-consumer materials and the reduction of the amount of waste in landfills. In recent years, the recycling of various materials such as aluminum, newspapers, and steel was proven to be very efficient and economically viable. However, recycling of plastics was a much more challenging task, mainly due to the inability to accurately and efficiently sort the different types of plastic out from other waste. The goal of this research was to introduce a new technique for sorting non-magnetic materials (including shredded plastics) by the use of ferrofluid and an imposed magnetic field. By submerging shredded post-consumer materials into a pool of ferrofluid and imposing a magnetic field gradient, the density of the fluid can be adjusted, and can cover a broad range of densities by changing the magnetic field strength. Using this phenomenon, a sink-float separation technique can be developed as future research. Experimental testing was conducted for validation by developing a ferrofluid separation model. Additionally, experimental testing was carried out to ensure the accuracy of the theoretical findings. With an accurate theoretical model, the tough to sort, low-density plastics were then analyzed for separation.
5	1974	An In-situ Investigation of Oil Barrier Shape and Drag Coefficients	Larrabee, Brown	In-situ experimentation on a moored 100 foot section of commercially procured oil barrier was carried out. The objectives of this study were three-fold: To study oil barrier shape and tensions as influenced by current and wave action, to analyze data on the barrier shape with existing analyses and to compare results of tension and drag coefficient data with previous investigations. Actual barrier shape, measured by transit, was compared with a theoretical catenary drawn through the barrier end points. Shape, load, current, and wave data were used to calculate various drag coefficients for the boom. Two techniques were used to calculate drag coefficients for the barrier and results of each were compared. The effects of wave action on barrier loading were determined by the analysis of two previous investigators and the results compared. Values of drag coefficient were reduced to a basic drag coefficient, independent of barrier shape configuration as well as wave effects. Results of the investigation showed that the catenary curve is a good approximation to barrier shape.

5	1971	Annual Report on Marine Resources and Engineering Development, Message from the President. Congressional Document		
5	1972	Development of a high seas oil recovery system	March, Beach, Bishop, Blockwick, Sahgal	A model test development study was conducted of a floating weir oil recovery system for rapid recovery of oil spilled on the high seas. The oil recovery system consists of two floating weirs connected by a flexible basin material. The operation of the system is based on the fact that oil thickens in front of a physical barrier moving relative to the water surface. Volume 1 contains a summary of model test results and prototype performance projections.
5	1973	Development of a High Seas Oil Recovery System. Phase II. Appendix III. Systems Tests. Volume IV	Beach *et al.*	The Phase-II report covers design, construction, and test of a prototype 2,000 gpm oil recovery system for the high seas. The prototype system consists of a weir/basin assembly, transfer and control system, and auxiliary equipment which includes a handling system, packaging system, and a flotsam fence. The transfer system has four hydraulic-motor-driven gear pumps, a 300 ft hydraulic umbilical, an oil-water interface sensor array, and a remote-control system. The report describes subsystems tests, component assembly, air transport capability, and a complete oil-recovery test in a pool at Battelle Northwest, Richland, Wa. Pool tests utilized light and heavy fuel oils in calm water and 2 ft waves, with tow speeds to 2.76 knots.
5	1976	Evaluation of a Passive Microwave Technique for the Measurement of Oil Film Thickness	Holinger, Kenney	The performance testing and evaluation of various oil slick containment and cleanup devices, such as booms and skimmers, requires an accurate determination of the distribution and thickness of the oil being contained or recovered from the water surface. The results of a series of airborne measurements of marine oil spills, sponsored by the U.S. Coast Guard, have demonstrated the remote determination of oil slick thickness using a multi-frequency passive microwave technique. The objective

		in a Test Tank Environment		of the present investigation is to develop and apply this technique to the measurement of oil film thicknesses in a test tank environment for the quantization of performance data in oil cleanup and containment device evaluation tests.
5	1971	Filter Belt Oil Recovery System	Moses, Blackstone	The results of a systems development program (Phase I) for preliminary design of a high seas oil recovery system are presented. Requirements were to project a system capable of recovering 2000 gpm of oil with a low water content. Oil would be recovered from the water surface by two continuous filter belts mounted in the center of a catamaran hull. The filter material retains oil but allows water to pass through freely. An additional oil/water separation system is not required. The system would include a 2000 gpm oil transfer system for offloading recovered oil. It may be used in conjunction with oil containment booms, floating oil storage bags, barges, or small tankers. The system would be designed to operate in waves up to 5 ft. average height. The system would be required to be transported by land vehicles or C-130 cargo aircraft. This report describes basic filter material performance testing, model basin testing, filter belt development, subsystem requirements definition, and preliminary design.
5	1978	French oil spill. cleanup proves tough	Kosman	Inclement weather, rough seas, and strong currents prevented widespread use of skimmer and boom devices for cleaning up to 220,000 metric tons of crude oil discharged by the wreck of the Amoco Cadiz, but were effective in dispersing some of the oil. The only skimming system used was an experimental 15 m long, metal-box jib, devised by the U.K. Department of Industry's Warren Springs Laboratory. The effective use of dispersants was hampered by the size of the spill and by a French ruling that prohibits their use onshore or in waters less than 50 m deep. Absorbents used included 20 metric tons of rubber crumb, treated to absorb three times its weight in oil; Norsopol, a polynorbornene-based powder developed by Charbonnages de France Chimie; and approx. 4 metric tons of a talc/water mixture developed by the Institut Francais du Petrole, which costs $40-$60/metric ton and adsorbs only its own weight in oil; the oil is then oxidized by naturally occurring bacteria.

5	1976	Harbor Oil Spill Removal/Recovery Systems. Phase 2	NAVFAC Engg Command	The Navy has committed itself to the development of adequate capabilities to remove oil attributable to accidental spills from harbor waters. The overall program has evolved into three phases. The objective of Phase I, completed in FY-73, was to identify the best commercially available 'off-the-shelf' equipment for cleaning up spills in both confined and open harbor areas. The objectives of Phase II were to develop standard performance test procedures applicable to the EPA (Environmental Protection Agency) OHMSETT (Oil and Hazardous Materials Simulated Environmental Test Tank) facility, to improve equipment and procedures, and to evaluate utility equipment in a harbor. The objective of improving equipment and procedures included the following subtasks: development of a support system for containment booms; laboratory testing of a model skimmer and boom; full scale testing at OHMSETT; conducting a human factors study of oil spill cleanup equipment; development of oil spill cleanup scenarios, an oil spill cleanup data report form, and alternative methods of using oil spill containment boom; and a study of boom materials. This report summarizes Phase II. The objectives of Phase III, currently underway, are to conduct cost and system effectiveness studies of oil spill cleanup procedures, and to evaluate new equipment at OHMSETT.
5	1976	Harbor oil spill removal/recovery systems. Phase 2. Executive summary	NAVFAC Engg Command	TRN: 61980332: The objectives of Phase II were to develop standard performance test procedures applicable to the EPA (Environmental Protection Agency) OHMSETT (Oil and Hazardous Materials Simulated Environmental Test Tank) facility, to improve equipment and procedures, and to evaluate utility equipment in a harbor. The objective of improving equipment and procedures included: development of a support system for containment booms; laboratory testing of a model skimmer and boom; full scale testing at OHMSETT; conducting a human factors study of oil spill cleanup equipment; development of oil spill cleanup scenarios, an oil spill cleanup data report form, and alternative methods of using oil spill containment boom; and a study of boom materials.
5	1993	Laboratory testing of a flexible boom for ice management	Loeset, Timco	Combating oil spills in the Arctic is a major challenge. Drilling or producing oil or gas in the marginal ice zone (MIZ) may allow booms to be deployed upstream of an offshore structure to clear the water of ice, thereby enabling conventional oil spill countermeasures to be used. Such a boom would be kept in place by two ice-going

				service vessels or by moored buoys. SINTEF NHL and NRC have performed a number of small-scale tests with a flexible boom in the NRC ice basin in Ottawa. The purpose of the tests was to measure the effectiveness of using a flexible boom for collecting ice, and to determine the loads associated with collecting the ice. In the tests, various boom configurations were towed against a broken ice field consisting of ice pieces typically 50--100 mm across and 30 mm thick. The ice concentration was usually 10/10, but it was reduced to 8/10 and 5/10 for two tests. The boom was towed at speeds of 20 and 50 mm/s. Both the width of the boom and the slackness of the boom were varied over reasonable ranges. Two six-component dynamometers were used to support the boom. Thus, the force components on each end of the boom were measured. Further, two video cameras were used to record the effectiveness of each boom configuration. In this paper, the full results of this test program are presented and the application of the test results to the full-scale situation are discussed. The tests show that, under certain conditions, the use of boom is feasible for ice management in oil-contaminated water.
5	1986	Laboratory testing of an oil-skimming bow in broken ice	Abdelnour	This report summarizes the results of laboratory experiments carried out on a model (small prototype) of an oil-skimming bow (OSB). The OSB is a device designed to recover oil from waters obstructed by broken ice. The system could be fitted to most ice-reinforced ships or ice-breakers servicing the offshore industry in a particular area, enabling them to assist in the recovery of oil after a major oil spill. A series of 69 tests was carried out to evaluate the efficiency of the OSB model at Arctic Canada's environmental ice tank in Kanata, Ontario. The tank is 30 m long, 5 m wide, and 1.5 m deep. The temperature of the room can be set between 0 and -20C.
5	1971	Lightweight oil containment system, low tension barrier system. Part I	Houser	The report presents the results of studies and tests of a low tension light weight oil containment system. The system is capable of deployment from an aircraft and deploys rapidly with a minimum of support equipment. The barrier design described uses an external tension shock absorbing bridle line to insure the barrier a high degree of high sea surface confirmability.

5	1971	Mathematical model of the Texas A&M low-tension oil containment barrier	Fowler	
5	2016	MEDSLIK oil spill model recent developments	Lardner, Zodiatis	MEDSLIK oil spill model recent developments Robin Lardner and George Zodiatis Oceanography Center, University of Cyprus, 1678 Nicosia, Cyprus MEDSLIK is a well-established 3D oil spill model that predicts the transport, fate and weathering of oil spills and is used by several response agencies and institutions around the Mediterranean, the Black seas and worldwide. MEDSLIK has been used operationally for real oil spill accidents and for preparedness in contingency planning within the framework of pilot projects with REMPEC-Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea and EMSA-European Maritime Safety Agency. MEDSLIK has been implemented in many EU funded projects regarding oil spill predictions using the operational ocean forecasts, as for example the ECOOP, NEREIDs, RAOP-Med, EMODNET MedSea Check Point. Within the frame of MEDESS4MS project, MEDSLIK is at the heart of the MEDESS4MS multi model oil spill prediction system. The MEDSLIK oil spill model contains among other, the following features: a built-in database with 240 different oil types characteristics, assimilation of oil slick observations from in-situ or aerial, to correct the predictions, virtual deployment of oil booms and/or oil skimmers/dispersants, continuous or instantaneous oil spills from moving or drifting ships whose slicks merge can be modelled together, multiple oil spill predictions from different locations, backward simulations for tracking the source of oil spill pollution, integration with AIS data upon the availability of AIS data, sub-surface oil spills at any given water depth, coupling with SAR satellite data. The MEDSLIK can be used for operational intervention for any user-selected region in the world if the appropriate coastline, bathymetry and meteo-ocean forecast files are provided. MEDSLIK oil spill model has been extensively validated in the Mediterranean Sea, both in real oil spill incidents (i.e., during the

				Lebanese oil pollution crisis in summer 2006, the biggest oil pollution event in the Eastern Mediterranean so far) and through inter-comparison using drifters. The quality of the MEDSLIK oil spill model predictions depends on the quality of the meteo-ocean forecasting data that will be used. The guidelines set by the MEDESS4MS project to harmonize the meteo-ocean, oil spill and trajectory models input/output formats are implemented in MEDSLIK to suit the operational oil spill predictions. The output results of the trajectory predictions may available in the MEDESS4MS output standards (XML)and in ASCII, while the images in BMP or PNG, TIF,GIF, JPG (image), in KML (Google Earth).
5	2010	Modelling the Formation and Vertical Mixing of Oil Droplets and Oil-Mineral Aggregates (OMAs) Under Breaking Wave Conditions	Shen	Cleanup of oil spills, especially at the shoreline, is confronted with challenging problems of both technology and cost-effectiveness. Over the past decades, a new hypothesis has emerged, that the formation of Oil-Mineral Aggregates (OMAs) consisting of oil droplets and mineral fines, enhances the dispersion of oil in aquatic environments. Despite its documented role in cleaning oil spills along shorelines through reported experimental studies, the literature on the mathematical modelling of the formation and dispersion of OMAs has been limited. In the present study, the physical processes were investigated including oil slick breaking up under breaking wave, the formation of OMAs, and oil/OMAs vertical mixing. A modelling approach was developed for simulating the formation and vertical mixing of oil droplets and OMAs, namely Oil Droplet and OMAs Simulation (OMA-SIM). This method integrated modelling tools for addressing the oil vertical mixing model and density based OMAs formation model to examine the dispersion of oil droplets and OMAs. The OMA-SIM was validated using data obtained from mesoscale wave tank experiments. The concentration and size of oil droplets and OMAs generated under breaking wave condition were simulated and compared with experimental data. The main factors that affect oil droplets and OMAs formation and vertical mixing have been studied and concerned in the developed model. These factors include oil density and viscosity, oil/water interfacial tension, wave energy dispersion rate, dispersants, and environment temperature. The results of the case studies suggest that the OMA-SIM

				developed in this study provide effective methods for simulating and predicting the vertical dispersion of spilled oil. A computation system was then developed that couples the OMA-SIM with a user-friendly interface system, and the system was applied to real case studies based on field data. OMA-SIM results indicated that the energy dissipation rate of breaking waves is the predominant factor which affects the concentration and particle size of oil droplets and OMAs. The higher the breaking wave energy, the more oil was dispersed with time after the experimental oil spill. Oil viscosity has a significant influence on dispersed oil concentration. The mass of dispersed oil decreased with increasing oil viscosity. Increasing temperature to decrease oil viscosity and then to enhance the formation of OMAs resulted in a greater concentration of oil. The dispersants reduce oil/water interfacial tension and result in a decreased size of oil droplets and OMAs. The application of mineral fines facilitates the formation of OMAs.
5	2016	New techniques on oil spill modelling applied in the Eastern Mediterranean sea	Zodiatis, Kokinou, Alves, Lardner	Small or large oil spills resulting from accidents on oil and gas platforms or due to the maritime traffic comprise a major environmental threat for all marine and coastal systems, and they are responsible for huge economic losses concerning the human infrastructures and the tourism. This work aims at presenting the integration of oil-spill model, bathymetric, meteorological, oceanographic, geomorphological and geological data to assess the impact of oil spills in maritime regions such as bays, as well as in the open sea, carried out in the Eastern Mediterranean Sea within the frame of NEREIDs, MEDESS-4MS and RAOP-Med EU projects. The MEDSLIK oil spill predictions are successfully combined with bathymetric analyses, the shoreline susceptibility and hazard mapping to predict the oil slick trajectories and the extend of the coastal areas affected. Based on MEDSLIK results, oil spill spreading and dispersion scenarios are produced both for non-mitigated and mitigated oil spills. MEDSLIK model considers three response combating methods of floating oil spills: a) mechanical recovery using skimmers or similar mechanisms; b) destruction by fire, c) use of dispersants or other bio-chemical means and deployment of booms. Shoreline susceptibility map can be compiled for the study areas based on the Environmental

				Susceptibility Index. The ESI classification considers a range of values between 1 and 9, with level 1 (ESI 1) representing areas of low susceptibility, impermeable to oil spilt during accidents, such as linear shorelines with rocky cliffs. In contrast, ESI 9 shores are highly vulnerable, and often coincide with natural reserves and special protected areas. Additionally, hazard maps of the maritime and coastal areas, possibly exposed to the danger on an oil spill, evaluate and categorize the hazard in levels from low to very high. This is important because a) Prior to an oil spill accident, hazard and shoreline susceptibility maps are made available to design preparedness and prevention plans in an effective way, b) After an oil spill accident, oil spill predictions can be combined with hazard maps to provide information on the oil spill dispersion and their impacts. This way, prevention plans can be directly modified at any time after the accident.
5	1973	Oil recovery system using sorbent material	Gurntz, Meloy	The feasibility of recovering oil in slicks 1 mm and thicker by the use of recycled sorbents has been shown in laboratory and wave tank tests. Sorbents made of recticulated foam are broadcast on the sea, herded by a boom, picked up by a porous belt and the oil squeezed out of the sorbents by a wringer. The sorbents are then rebroadcast on the sea for further oil recovery. General equations were developed for basic sorption properties, sorbent broadcasting, sorbent herding, sorbent pickup, recovery of oil from the sorbent and for the total system. Based on the laboratory modelling and general equations, the total system concept was developed. It was concluded that one inch cube sorbent particles distributed in a shrouded rectilinear screw fed system was optimal. A 4/1 compression ratio of the slick by a boom herding the sorbent and oil to the channel would work under virtually any wave condition.
5	2017	Oil spill response capabilities and technologies for ice-covered Arctic marine waters: A review of recent	Beegle-Krause *et al.*	

		developments and established practices		
5	1975	Random models of spilled oil movement	Fallah-Araghi	
5	1977	Similarity solutions for the spreading of oil slicks	Foda	
5	1989	Spill Containment and Cleanup Technology. CRS Report	Congressional Research Service	
5	2011	Surface Films: Do they Influence the Effectiveness of Oil Spill Chemical Dispersants as Studied in a Wave Tank Facility?	King	Lab basins and wave tanks have unnatural boundaries (walls) that provide an ideal environment for surface film formation on seawater. Surface films form from natural surfactants in oil and dispersant overspray when applied to seawater. The adsorption process of selected crude oils, Arabian Light (ALC) and Alaskan North Slope (ANS) on static seawater in a lab basin was demonstrated to follow diffusion-controlled short time limit adsorption kinetics. The process of crude oil spreading on the surface of the basin seawater was affected in the presence of surface films as shown using kinetic models. ANS dispersed in the dynamic wave tank seawater with and without a surface film (dispersant overspray) was evaluated using kinetic models. It was found that oil dispersed in wave tank seawater, in the presence of dispersant overspray, influences oil dispersant effectiveness and produced confounding outcomes that are an unnatural model of dispersed oil fate and effects.
5	1976	Tests of the Arctic Boat configuration of the Lockheed Clean Sweep oil	Schultz	This project consisted of full size tests of the Arctic Boat configuration of the Lockheed Model R2003 Clean Sweep oil spill recovery device operating in a simulated Arctic environment incorporating freezing temperatures and ice infested waters. Tests were conducted in a broken fresh water ice field of moderate ice piece size with crude oil.

		recovery system in a broken ice field. Final report		The tests were directed towards the evaluation of the oil recovery performance of the Arctic Boat configuration in comparison to the performance obtained from the unmodified device in tests conducted for the U.S. Coast Guard. The test results indicated that the oil recovery performance as measured by oil recovery rate and throughput efficiency is improved in the case of the Arctic Boat configuration with little effect on oil recovery efficiency in comparison to the unmodified unit, assuming that a suitable method is developed for the recovery of oil contained within the throughput barrier region. The Arctic Boat configuration tested showed a great tendency towards drum jamming, and a far greater tendency towards ice rafting than was the case for the unmodified device. The oil recovery performance tests also indicated that the performance of the unit is highly dependent upon operating conditions.

Papers Denoted as 3/4/5: Less Pertinent

Year	Title	Authors	Summary
2010	7 cleanup solutions for the disastrous Gulf of Mexico oil spill		
1988	1987 Newfoundland oil spill experiment - an overview	Tennyson, Whittaker	A joint Canadian-US exercise involving the intentional spilling of 18,000 gallons of specially treated crude oil was conducted off Newfoundland in September 1987 to evaluate the containment and recovery capabilities of three state-of-the-art booms and skimmers. As part of the exercise, data were collected on a specially instrumented oil spill boom in an attempt to verify a proposed performance test procedure for open-ocean oil spill booms. A viscoelastic chemical additive was used after the equipment evaluation was completed to enhance recovery operations. Additional observations were made on the persistence of spilled oil slicks in advanced sea states. The containment and recovery effort was one of the most successful on record and was conducted in winds and sea states commonly thought to be beyond existing capabilities.
1994	A study on the effects of oil fires on fire boom employed during the in-situ burning of oil	Lazes	For over 10 years scientists have studied the effects of in-situ burning of oil on air and water quality and potential related health issues. The recent Newfoundland Offshore Burn experiment, conducted by Environmental Canada, was the culmination of several years of work. The results of this experiment found that "emissions from the in-situ oil fire were lower than expected and all compounds and parameters measured were below heath concerns at 150 metres from the fire". P.A.H.'s were found to be lower in the soot generated from the fire than in the starting oil prior to the fire. The conclusion reached was that the environmental benefits resulting from the burning of oil spills far outweigh the potential air pollution caused from the smoke. These findings now open the door on the use of in-situ burning of oil as a major tool to be used to mitigate environmental damage from oil spills. As a result of these and other test findings, Region 6 of the Regional Response Team (made up of the U.S. Coast Guard, The Minerals Management Service, The Department of Environmental Quality, The Environmental Protection Agency, and other state and federal agencies) has pre-approved the use of in-situ burning of oil spills for offshore Louisiana and Texas. Other

			parts of the country and other countries are evaluating the use of in-situ burning to combat oil spills.
2015	A topological approach to using cables to separate and manipulate sets of objects	Bhattacharya *et al.*	In this paper we study the problem of manipulating and transporting multiple objects on the plane using a cable attached at each end to a mobile robot. This problem is motivated by the use of boats with booms in skimming operations for cleaning oil spills or removing debris on the surface of the water. The goal in this paper is to automate the task of separating the objects of interest from a collection of objects by manipulating them with cables that are actuated only at the ends, and then transporting them to specified destinations. Because the cable is flexible, the shape of the cable must be explicitly modeled in the problem. Further, the robots must cooperatively plan motions to achieve the required cable shape and gross position/orientation to separate the objects of interest and then transport them as specified. The theoretical foundation for the problem is derived from topological invariants, homology and homotopy. We first derive the necessary topological conditions for achieving the desired separation of objects. We then propose a distributed search-based planning technique for finding optimal robot trajectories for separation and transportation. We demonstrate the applicability of this method using a dynamic simulation platform with explicit models of the cable dynamics, the contact between the cable and one or more objects, and the surface drag on the cable and on the objects. We also demonstrate the working of the proposed algorithm on an experimental platform consisting of a system of two cooperating autonomous surface vessels and stationary/anchored objects.
2008	Alkaline Surfactant Polymer enhanced oil recovery process	Liu	This thesis improves the understanding of the Alkaline Surfactant Polymer (ASP) enhanced oil recovery process in order to optimize the ASP operational strategy. The conventional oil recovery methods leave large amounts of oil in the reservoir. ASP process is considered as a promising method for enhanced oil recovery. This dissertation reveals the ASP characteristics by using phase behavior, interfacial tension, surfactant consumption and numerical simulation techniques. The flooding experiments that I performed show that my ASP strategies successfully recover the oil trapped after waterflooding. The optimal salinity varies when either synthetic surfactant concentration or Water Oil Ratio (WOR) changes in ASP system. In this thesis, these results could be collapsed to a single curve for each synthetic surfactant/crude oil combination in which the optimal salinity depends only on the molar ratio of natural soap to synthetic surfactant, or soap fraction of total soap plus surfactant. The ASP

			system studied here has a much wider low IFT region (< 0.01 mN/m) than the system without alkali. In much of the Winsor I region where an oil-in-water microemulsion coexists with excess oil, a second surfactant-containing phase was seen to exist in colloidal form. This colloidal dispersion plays an important role in reaching the ultra-low tension. A new protocol, which significantly reduces the time that is required to reach equilibrium, is developed to assure that enough of the dispersed material is initially present to achieve low tensions but not so much as to obscure the oil drop during IFT measurements. Surfactant retention is one of the most significant barriers to the commercial application of ASP. It was found that Na sub(2)CO sub(3) but not NaOH or Na sub(2)SO sub(4), can substantially reduce adsorption of anionic surfactants on carbonate formations, especially at low salinities. A one-dimensional numerical simulator was developed to model the ASP process. By calculating transport of water, oil, surfactant, soap, salt, alkali and polymer, the simulations show that a gradient in soap-to-surfactant ratio develops with conditions shifting from over-optimum ahead of the displacement front to under-optimum behind the displacement front. This gradient makes the process robust and permits injection at conditions well below optimal salinity of the synthetic surfactant, thereby reducing adsorption and improving compatibility with polymer. More than 95% of waterflood residual oil was recovered in ASP sand pack experiments at ambient temperature with a slug containing a partially hydrolyzed polyacrylamide polymer and only 0.2 wt% of a particular anionic surfactant blend. The simulator predicts recovery curves in agreement with those found in the flooding experiments.
2005	An experimental high pressure water jet barrier	Meikle, Whittaker, Laperriere	A novel barrier to contain or deflect floating oil has been developed using an array of high-pressure waterjets. Preliminary experiments have demonstrated that oil can be controlled effectively with this technique even in the presence of waves. Trials of an experimental prototype have established that it is stable, has good mobility, and is able to maintain position as a deflector or as a collector in currents approaching 2 knots.
2005	Antipol 97-Totem 97 a large-scale exercise in the Mediterranean sea	Colonne, Rousseau	To implement the national POLMAR Plan, the French maritime and terrestrial authorities organise yearly large oil spill exercises called "Antipol." Antipol 97 was of a greater scale than any other operation conducted in the past ten years in the Mediterranean sea. During the two days of the exercise, major spill response capabilities were deployed on the sea with ten ships, including French Navy ships, together with the 280,000 tons tanker ISEULT, owned by TOTAL. In the air, were five

			planes, including one of OSRL's C 130's flown in from Southampton and an Italian reconnaissance plane, as well as five helicopters. Various response actions were conducted at sea and on the shoreline: evacuation of injured crew from the tanker, tanker towing, lightering operation, deployment of boom and recovery equipment, shoreline cleanup using POST cooperative resources and strike team. In parallel a large crisis management exercise called "Totem 97," supported by TOTAL, and prepared and conducted by CEDRE (Centre for Documentation, Research, and Experimentation in the field of accidental water pollution), mobilised crisis management teams in Toulon, Paris, Marseilles, Nantes, and Brest. This major operation had a triple objective: To test the efficiency of the new POLMAR Plan, the TOTAL Group, and FRANCE SHIPMANAGEMENT emergency plans; To update and improve the procedures laid down in those plans; To demonstrate the collective crisis management performance of the three key players: the public authorities, the ship operator and the oil company. For added realism Totem 97 included a unit run by CEDRE, that simulated reactions from the media, lobby groups, and the general public.
2013	Applying emulsion breakers to extend the window-of-opportunity for ignition and burning of oil in fire booms	Cooper, Buist, Mabile	During the response to the Macondo incident in the Gulf of Mexico, in-situ burning (ISB) in fire booms was used extensively and successfully to eliminate a considerable amount of oil. Due to the nature of the incident, a continuous supply of relatively fresh, unemulsified oil was available for burning. Once the source of fresh oil was controlled, the ISB operations were quickly curtailed by the ongoing emulsification of the remaining oil. The objective of this scoping study was to determine, through tank testing, whether proven, broad-spectrum emulsion breaking chemicals could be applied to emulsified oil contained in a fire boom to reduce its water content sufficiently to allow ignition and efficient burning. Future work is necessary to refine and define the parameters necessary for applying to a response scenario. Small-scale and wave tank experiments were undertaken at the SL Ross lab. In the first series of experiments, small standardized tests were undertaken to identify three crude oils in storage at the SL Ross lab that formed stable, high water content emulsions for the experiments. In the second series, small amounts of a contained emulsion were placed in an enclosed flexible, rectangular floating containment system (100 cm long, × 20 cm wide) constructed of 30-cm height boom material on the surface of the new wind/wave tank. Demulsifier was placed drop wise onto the surface of the slick which was then subjected to wave action. Small grab samples of the slick were taken over a period of

			one hour, and then analyzed to monitor water content. Final testing involved bench scale ignition tests using emulsion samples collected from selected wave tank tests. The test matrix included varying demulsifier dosage, wave energy, slick thickness, oil type, and initial water content of the emulsion. Some positive results in the water content and ignition tests indicated that the demulsifier was starting to have a beneficial impact in breaking the emulsion but the right mixing energy may not have been imparted to the emulsions during the wave tank tests. This was reinforced by the observations of the emulsions breaking readily when they were siphoned off the water surface during cleanup between test runs. Additional testing to evaluate if higher wave energy would be sufficient to increase the positive impact of the demulsifier is recommended.
2011	Behavior of oil spills in ice and implications for arctic spill response	Dickins	The paper reviews the history of research into the behavior spills in ice covered waters and documents our current state of knowledge, drawing on the findings from a number of milestone field experiments conducted over the past 40 years. In particular the paper focuses on the unique aspects of spill behavior in different ice regimes that can both hinder and benefit spill response, depending on the timing and type of release. With increasing interest in exploiting Arctic oil resources, the knowledge base summarized in this paper can be used to identify priority topics for future research and development. There is an extensive background of research into all aspects of Arctic spill response and our level of understanding is extremely good in many areas, such as understanding how close pack ice contains the oil from spreading, how oil trapped in the ice through the winter is maintained in a fresh state, and how trapped oil is exposed on the ice surface in the spring. Key observations from large-scale field experiments are that the natural containment, reduced wave action and slower weathering in the presence of significant ice cover, can greatly extend the windows of opportunity and effectiveness for response operations such as burning and dispersant application. These benefits are not experienced with traditional response options relying on boom and skimmer systems where ice interference severely reduces the recovery effectiveness. Future advances in our ability to respond to spills in ice will require a new approach to permitting experimental spills. The record shows that it is entirely possible to plan and execute experiments safely with no harm to the environment. Continued regulatory intransigence could jeopardize industry's ability to develop

			credible and effective contingency plans to permit future Arctic exploration and development activities.
1993	Bioremediation for oil spills -- an update	Hoff, Lash, Raaymakers	Three main types of bioremediation technologies are currently being developed or applied in oil-spill cleanup: addition of fertiliser to oiled shorelines, addition of microbial products to oiled shorelines, and open water application of either fertiliser or microorganisms to open-water oil slicks. In each case, the effectiveness of the treatment depends on complex interactions between organisms, nutrients, and environmental factors such as temperature, salinity and oxygen supply. Decisions will continue to be made necessarily on a case-to-case basis. Open-water treatment in particular is at best an experimental technique, and cannot be recommended in practice for the moment.
1979	Criteria for the selection of oil spill containment and recovery equipment for use at sea	Cormack	The elements of the Warren Spring Laboratory research and development program on oil spill recovery at sea are set out, the range of skimmers and booms tested at sea is described and principles and criteria for selection presented against that background. It is then shown how these principles and criteria have been used to design and develop the Springsweep oil recovery system, details of which are presented as an example of the implementation of the principles and criteria. It is concluded that this approach can be used to give guidance in the selection of new projects for research and development support and to select equipment already available, for trials at sea.
2000	CytoSol - Cleaning Oiled Shorelines with a Vegetable Oil Biosolvent	Von Wedel	A cleanup process has been developed to aid in the removal of crude or fuel oil from shorelines using CytoSol "biosolvent" formulation based on vegetable oil methyl esters in combination with bioremediation enhancers. The CytoSol biosolvent dissolves and floats the oil, the oil/biosolvent mixture is rinsed off with ambient temperature water for collection as a consolidated layer with skimmers. The collected oil mixture can be recycled as a burner fuel. Nutrient enhancers in the formulation then stimulate the natural biodegradation of the remaining residual hydrocarbons. This new approach minimizes physical and chemical impacts to marine organisms, cleans oiled surfaces effectively, and allows the oiled ecosystem to recover with less mortality than conventional methods involving hot water, detergents or other chemical cleaners. CytoSol is ideally suited for port facilities and waterfronts dealing with occasional small oil spills and has undergone extensive laboratory testing for the US EPA. In 1997, the CytoSol biosolvent was licensed in the state of California as a shoreline cleaner and set up for commercial distribution. CytoSol biosolvent can extract heavy petroleum

			(crude, fuel oils) off shoreline habitats, mussel-encrusted breakwaters or pilings, and estuary vegetation. The viscosity of the product tends to limit the penetration of the CytoSol/oil mixture into sand and gravel beaches, allowing more of the dissolved oil to be removed from the shoreline by washing. The product has a low specific gravity (0.87), tends to consolidate oil, and is practically immiscible with water, so it facilitates the recovery of spilled oil with conventional skimming and absorbent boom technologies. Since it is non-volatile and non-flammable, there is little danger of explosion or fire when spraying it inside confined spaces.
2013	Dynamic simulation of autonomous boats for cooperative skimming and cleanup	Kim, Bhattacharya, Kumar	We consider the use of autonomous boats for oil skimming and clean up of surface debris by operating two boats with a boom cooperatively. A boom, or a cable as considered in this paper, attached to two robots at each end can be used to efficiently manipulate multiple objects on the surface of the water. In our previous work, Bhattacharya, *et al.* (ICRA 2011), we showed the feasibility of this concept with an experimental testbed using two autonomous boats and a towed cable. This work showed that an accurate dynamic simulation of the system is indispensable in analysis and development of efficient control schemes. For the purpose of manipulating objects in such a way, not only do we need to model the drag forces, but we also need to model the interaction between the cable and the objects. In this paper we model the boom or the cable as a chain with a discrete number of rigid links connected by passive revolute joints and model the interaction of the cable with the water (drag) as well as the contacts with objects on the surfaces. We derive the equations governing the cable and object dynamics and model the contact interactions as linear complementarity constraints. The boats are driven by simple controllers that only require knowledge of positions and velocities at the both ends of the cable. Several examples are used to illustrate the performance of the numerical simulation.
2016	Effective workflow to clean-up oil spill using ferromagnetic nano-particles	Kakade *et al.*	Permanent environmental damage cannot be compensated in terms of money. Unfortunately, oil spills contaminate water, restraining marine species of their habitat and food supply. Despite the numerous methods available today to clean up the water body by separation of oil and water, none have restored water to its previous quality or saved marine animals from its deleterious effects to the full extent. The biggest hurdle to this cause is the sunken oil; the oil which may have either sunken mixed with sand and mud or by dispersion due to weathering. Mechanical containment with recovery and use of dispersants will always be the most widely used response option

			for surface clean up due to its capability to directly remove oil from environment till today. Another spill response tool is In-situ burning which is under study from several decades. Efforts are being made to enhance In-situ burning such as Aerial Ignition System (AIS) and Chemical Herders. Although it is expected that this oil will float right up due to the density difference and cleaning will hence be easy, this is not always the case. The authors suggest the most effective workflow to clean up surface oil in marine oil spills as well as a way to tackle the sunken oil droplets. Choosing of an effective clean up method should always start with determining the amount of oil, density of oil, type of oil (crude or refined), salinity of water and the weather conditions. The authors thus propose an arrangement for real time tracking and mapping of an oil spill and then using most effective modern cleanup methods like booms, in-situ burning, dispersants and skimmers followed by the use of polymer coated ferromagnetic nano particles to clean up sunken oil droplets. Magnetic nanoparticles are non-toxic nano sized sponges that sink deep inside the water body, absorb 10 times their weight of oil and float back up on the surface. Experiments with two samples of oil were conducted to check the effectiveness of ferrous nanoparticles in attracting oil out of water in various concentrations of nanoparticles to find the optimum level.
1986	Experimental and theoretical basin studies of dispersant effectiveness in cold water	Brown, To, Goodman	During November, 1984 and April, 1985, tests of dispersant effectiveness were carried out at Esso's wave basin facility in Calgary, Alberta, Canada. Regular, non-breaking waves were used, and oil concentrations in the water column were continuously monitored by the fluorescence emission technique. Analysis procedures designed to examine the measured oil concentrations were established. Cross correlation lag time calculations were used to identify the time it tool oil to migrate from one measurement port to another in the water column under the effect of waves and dispersants. A kinematic model which solves the diffusion-advection equation numerically was used to calculate the efflux of oil from the containment boom. The calculations enabled a comparison to be made between the effectiveness of Corexit 9527 and CRX-8. It was found that in the modelled examples, oil travelled down the water column faster and more dispersed oil stayed in the water column when CRX-8 was used.
1973	Ferromagnetic Sorbents for Oil Spill Recovery and Control	Turbeville	Buoyant, ferromagnetic, sorbent particles with an affinity for oil will transform a maritime oil spill into a magnetizable surface film whereby it is possible, with suitable magnetic equipment, to control and recover any oil so treated. Laboratory experiments were conducted to develop ferromagnetic sorbents and study their properties when

			combined with various test oils. These experiments provide information on the magnetic advantage of such a recovery concept. This advantage is expressed as gain and is shown to increase as the viscosity of the oils under test decreases. A drain rate equation was also obtained from the experiments and is incorporated with results obtained from experimental tests with a model oil recovery unit. Together, they provide a general expression for recovery rates which can be used as a scaling equation for larger units. Prototype floating magnetic grid units were constructed and tested for possible use as "magnetic nets" or "magnetic barriers". The advantages gained by the addition of magnetic principles to sorbent systems of oil spill recovery could possibly outweigh the disadvantages of sorbents now in general use.
2005	First German Oil Spill Handbook for Hamburg Harbor	Spengler	Motivated by two greater oil spills in 1981 and 1982 with total cleaning costs of about $11 million, the Free and Hanseatic City of Hamburg developed in 1983 a complete oil spill contingency plan with a detailed environmental sensitivity map. This book concerns the Elbe River inside the boundaries of Hamburg and, of course, the harbor region, which covers about 87 km. The contingency plan is called Olunfall-Handbuch (Oil Spill Handbook). It starts with general remarks about the physical and chemical characteristics of oil. Especially, there are lists of imparted and exported crude oil and oil products in the Hamburg Harbor complete with list of important parameters for combating the effects of these oils and products. This is followed by chapters dealing with the behavior and characteristics of oil after a spill, and the classification and identification of oil. Some analytic methods for in-situ measurements are listed. Safety measures during combating actions are followed by a general discussion of corn-baring methods such as various booms, skimmers, pumps, chemicals, and interim depots. Simulations and experiments were carried out to get better knowledge of the hydraulic conditions and to enable predictions, especially in the streamed harbor basins, The contingency plan details the notification and mobilization of the command team of the government environ-mental agency, the mainly scientific support teams, and the private action team. Environmental sensitivity maps have been developed to help the command team identify priority areas for maximum effort for combating actions. The system includes 18 general profiles, which describe the location of beaches and quays in Hamburg a sensitivity scale from 2 to 10 with respect to the cleanup possibilities in oil spills. The maps also show if combating has to be done only from the waterside, where there are ramps and cranes for loading ships with

			equipment, and prepared places for OSC containers. Most important are the areas of ecological significance marked by symbols of the types of birds, plants, fish and benthos with symbols for the time of year they will be there. Finally, 162 points are designated for which special recommendations are given for combating actions, including remarks about needed facilities, staff, and times to arrive.
1999	In-situ bioremediation strategies for oiled shoreline environments	Lee, Mora	Despite advances in preventative measures, recent events have demonstrated that accidental oil spills at sea will still occur. While physical (e.g. booms and skimmers) and chemical (e.g. chemical dispersants) methods have been developed to recover and/or disperse oil spilled at sea, they are not 100% effective and are frequently limited by operational constraints attributed to sea state and/or nature of the contaminant. As a result, oil spills frequently impact shoreline environments. In-situ bioremediation, the addition of substances or modification of habitat at contaminated sites to accelerate natural biodegradation processes, is now recognised as an alternative spill response technology for the remediation of these sites. Recommended for use following the physical removal of bulk oil, this treatment strategy has an operational advantage in that it breaks down and/or removes the residual contaminants in place. Laboratory experiments and field trials have demonstrated the feasibility and success of bioremediation strategies such as nutrient enrichment to enhance bacterial degradation of oil on cobble, sand beach and salt marsh environments. With improved knowledge of the factors that limit natural oil degradation rates, the feasibility of other strategies such as phytoremediation, enhanced oil-mineral fines interaction, and the addition of oxygen or alternative electron acceptors are now being evaluated. Laboratory and field test protocols are being refined for the selection of effective bioremediation agents and methods of application. It is recommended that future operational guidelines include real time product efficacy tests and environmental effects monitoring programs. Termination of treatment should be implemented when: 1) it is no longer effective; 2) the oil has degraded to acceptable biologically benign concentrations; or 3) toxicity due to the treatment is increasing.
1992	In-situ burning via towed boom of oil spilled at sea	Carrier, Fendell, Mitchell	Operational guidance for the efficient use of combustion in the cleanup of a surface oil film, formed as a result of a spill at sea, is sought by approximate analysis. In remediation by burning, the spilled oil itself provides the energy for its cleanup. Attention is focused on situations holding relatively far from the source of the spill and/or relatively long after the spill: the oil is taken to have so dispersed that the

			thickness of the film is on the order of a few millimeters. Under such conditions, the oil film is unlikely to burn without the use of multiple towed booms, each boom spreading its already-ignited, localized fire to continuously collected, previously unignited portions of the oil film. A simple, quasi-steady, two-dimensional analysis suggests efficient values for the tow speed and the tow-line length as functions of such parameters as the oil density, oil-film thickness, oil burn/evaporation rate, etc. The analysis leads to specific suggestions for apparently unreported laboratory experiments that may be informative prior to at-sea operation.
2005	Large wave tank dispersant effectiveness testing in cold water	Belore	Research experiments were completed to determine the viability of using chemical dispersants on two crude oils in very cold water conditions. Tests were completed at Ohmsett (the National Oil Spill Response Test Facility in Leonardo, New Jersey) in late February and early March of 2002. Ohmsett is a large outdoor, above-ground concrete tank (203 m long by 20 m wide by 3.4 m deep) filled with 9.84 million gallons of salt water. The tank has a wave-generating paddle, a wave-dissipating beach, and mobile bridges that transport equipment over its surface. A refrigeration unit was installed to ensure that the water was kept at near freezing temperatures during the entire test program. A total of twelve large-scale tests were completed. Corexit 9500 and Corexit 9527 were applied to fresh and weathered Hibernia and Alaska North Slope crude oils, on cold water (-0.5 to 2.4°C), at dispersant-to-oil ratios (DORs) ranging from 1:14 to 1:81. The average wave amplitude for the tests ranged between 16.5 and 22.5 cm and the average wave period was between 1.7 and 1.9 seconds. The effectiveness of the dispersant in each test was documented through extensive video records and by measurement of the residual oil remaining within the containment boom at the end of each test. The results clearly show that both dispersants were effective in dispersing the two crude oils tested in cold-water conditions.
2005	Measurement of surfactant-induced interfacial interactions at reservoir conditions	Xu, Ayirala, Rao	The effect of surface-active chemicals on oil-water interfacial tension (IFT) and wettability in crude oil-brine-rock systems at reservoir conditions is important in enhanced oil recovery processes. However, most of the experimental studies on IFT and contact angles have been conducted at ambient conditions and using stocktank crude oils. In this study, live and stocktank crude oils have been used at reservoir conditions to make IFT and dynamic contact angle measurements using the Drop Shape Analysis (DSA) and Dual-Drop-Dual-Crystal (DDDC) techniques, respectively. Yates reservoir rock and fluids and two types of surfactants (nonionic and anionic) in

			varying concentrations have been used at reservoir conditions of 82° F and 700 psi. The dynamic oil-water IFT was found to be a strong function of oil composition, temperature and showed a slight dependence on pressure. An attempt has been made to explain the dynamic behavior of IFT using a four-stage mechanistic model involving induction, diffusion, kinetic barrier and equilibrium stages. The significant difference observed between the advancing contact angles of live oil (55°) and stocktank oil (154°) clearly indicates the need to use live oils at reservoir conditions to determine in-situ reservoir wettability. Anionic surfactant altered the weakly water-wet behavior of live oil to strongly oil-wet (165°). It was also able to alter the strong oil-wet behavior of stocktank oil to less oil-wet (<135°). The nonionic surfactant was able to alter water-wet live oil system to intermediate-wet (82°), while it did not affect the strongly oil-wet behavior of stocktank oil system. The oil-wet behavior observed with the live oil due to the surfactants used indicates the possibility of these surfactants to develop continuous oil-wet paths for potential mixed wettability development. Thus, this study is of practical significance where the surfactant-induced wettability alterations to either intermediate-wet or mixed-wet can result in improved oil recovery through lowering of both capillary and adhesion forces.
2017	Modelling and assessment of accidental oil release from damaged subsea pipelines	Li, Chen, Zhu	This paper develops a 3D, transient, mathematical model to estimate the oil release rate and simulate the oil dispersion behavior. The Euler-Euler method is used to estimate the subsea oil release rate, while the Eulerian-Lagrangian method is employed to track the migration trajectory of oil droplets. This model accounts for the quantitative effect of backpressure and hole size on oil release rate, and the influence of oil release rate, oil density, current speed, water depth and leakage position on oil migration is also investigated in this paper. Eventually, the results, e.g. transient release rate of oil, the rise time of oil and dispersion distance are determined by above-mentioned model, and the oil release and dispersion behavior under different scenarios is revealed. Essentially, the assessment results could provide a useful guidance for detection of leakage positon and placement of oil containment boom.
2017	Modelling the naval transport associated hydrocarbon pollution risks in the Danube Delta biosphere reservation	Nicolae *et al.*	Although large accidental pollution incidents are now rare, accidental or operational pollution is still rampant across the world, and has a severe impact on the environment, especially in sensitive areas, like natural reservations. The unique simulation environment for oil spill modelling, composed of various maritime and technological simulators represents a valuable aid for battling oil spills, assessing proper

			containment solutions and assessing the associated pollution risks. The core element, Potential Incident Simulation, Control and Evaluation System (PISCES 2), is a response simulator intended for preparing and conducting command centre exercises and area drills. PISCES 2 provides an interactive information environment based on the sophisticated mathematical model of an oil spill interacting with surroundings and combat facilities, computing spill trajectory and weathering in both real-time and fast-time modes, interactions with models of booms, skimmers, chemical dispersant systems, absorbent resources, complex coastlines, and user-defined zones containing at-risk assets. The available resources will be used for evaluating the overall risks, associated to the hydrocarbon pollution, by considering a case study, which follows real situations and threats in the Danube Delta area.
2014	Navigation of autonomous vehicles for oil spill cleaning in dynamic and uncertain environments	Jin, Ray	In the context of oil spill cleaning by autonomous vehicles in dynamic and uncertain environments, this paper presents a multi-resolution algorithm that seamlessly integrates the concepts of local navigation and global navigation based on the sensory information; the objective here is to enable adaptive decision making and online replanning of vehicle paths. The proposed algorithm provides a complete coverage of the search area for clean-up of the oil spills and does not suffer from the problem of having local minima, which is commonly encountered in potential-field-based methods. The efficacy of the algorithm is tested on a high-fidelity player/stage simulator for oil spill cleaning in a harbour, where the underlying oil weathering process is modelled as 2D random-walk particle tracking.
2008	Oil spill boom modelling by the finite-element method	Muttin	During an oil-spill crisis, emergency action plans define priority locations on coastal zones to be protected by floating booms. Estuaries, fisheries, oyster production, and water supply are some of the most concerned examples. An oilspill boom is a long floating structure, the boom length can be as long as 1 km. A boom is used to deviate or to stop a floating pollution. The strategy to be adopted (deviative or stopping) depends on the current velocity. The sea current velocity and direction are variable in a coastal zone and it can depend on fluvial or tide flow. The variability of the environmental conditions increases the complexity of the mechanical problem. Another difficulty of a boom contingency plan comes from the definition of the adapted boundary conditions. Sea depth and coastal morphology must be compatible with the boom mooring devices: anchor, pile, and fixed point. This paper presents two numerical models named FORBAR and SIMBAR. FORBAR uses a 1D cable equation

			which permits to handle the boom curve on the sea surface. SIMBAR uses a 3D membrane finite-element which permits to characterize the submarine boom skirt angle. These numerical models are able to give as much mechanical information as required to optimize the system. A comparison between the two numerical models, 1D model (FORBAR) and 3D model (SIMBAR), is shown in the case of the Elorn river (Brittany, France) contingency plan.
2017	Optimizing oil spill cleanup efforts: A tactical approach and evaluation framework	Grubesic, Wei, Nelson	Although anthropogenic oil spills vary in size, duration and severity, their broad impacts on complex social, economic and ecological systems can be significant. Questions pertaining to the operational challenges associated with the tactical allocation of human resources, cleanup equipment and supplies to areas impacted by a large spill are particularly salient when developing mitigation strategies for extreme oiling events. The purpose of this paper is to illustrate the application of advanced oil spill modelling techniques in combination with a developed mathematical model to spatially optimize the allocation of response crews and equipment for cleaning up an offshore oil spill. The results suggest that the detailed simulations and optimization model are a good first step in allowing both communities and emergency responders to proactively plan for extreme oiling events and develop response strategies that minimize the impacts of spills.
1998	Particulate and carbon dioxide emissions from diesel fires: the Mobile 1997 experiments	Fingas *et al.*	A series of 12 mesoscale burns were conducted in 1997 to assess fire-resistant booms and to study various aspects of in-situ burning of diesel oil. Combustion gases, including CO2, did not reach exposure level maximums. The particulates were emitted at low levels by the smaller burns and the maximum extent of hazardous levels was ~ 50 m in terms of PM-10 (particulates of size less than 10 µm). Both electronic instruments and standard filter-collection devices were used at six stations for TSP (Total Suspended Particulate) for PM-10 and PM-2.5. The amount of the TSP corresponded to the amount of both PM-10 and the PM-2.5. The amount of the smaller particulates was generally larger than expected, indicating that particles are broken down by the instrumentation. This was especially true of the DataRAM. The electronic measuring instruments, the RAM and DataRAM, yielded relatively good results for total particulate, if corrected by using background readings taken before and after the burns. They were less reliable than standard instruments for measuring PM-10 and PM-2.5. CO2 was measured at 13 stations, and at 7 of these stations was measured at 4 different elevations to establish the three-dimensional distribution. The highest

			concentrations of CO2 were found most frequently at the lowest levels or at the 2-m level depending on ambient conditions. The distribution of CO2 was fitted to a three-dimensional model.
2016	Performance of a modified polyurethane foam on oil-water separation	Xu *et al.*	Oil spills frequently occur and cause water pollution. Techniques for oil removal or separation from water bodies have attracted much worldwide attention. The conventional methods used to solve these problems include combustion, oil containment booms and oil skimmer vessels. However, they are limited by environmental incompatibility, low absorption capacity, poor recyclability, and so on. A new modified material with improved performance compared with traditional methods was developed. With the effect of silanes coupling agent, polyurethane foam was modified with the raw material of expanded graphite, zinc oxide and lauric alcohol solution. It was characterized by scanning electron microscopy (SEM) and contact angle measurement. In the experiment of separating oil-water solution, the factors including adsorption performance for oil/water and recycling properties were investigated. The best conditions for oil-water separation in the experiment were also obtained. The result showed that the modified polyurethane sponge exhibited hydrophobicity and was super lipophilic. The best separation ability was achieved when expanded graphite and zinc oxide had the same volume. For the mass concentration of 20 g/L, saturated adsorption capacity was up to 17.7 g/g, and the selective adsorption coefficient of oil was 10.41. Oil-water separation efficiency could reach 78.41% within 15 min in the selective adsorption process. After each recycling, the amount of adsorption decreased by less than 7.3%. Therefore, the modified polyurethane foam had a good recycling performance. The modified polyurethane foam had a good selectivity about oil-water system. It could be recycled with a simple squeeze. With the characteristics of convenience, efficient circulation and no secondary pollution, the modified polyurethane foam has broad application prospects.
1971	Recovery of floating oil by rotating disk type skimmer		Laboratory tests indicated the feasibility of recovering 50,000 gal. of oil per hour using a series of powdered metal discs approximately 7 ft. in diameter and 12 ft. long. Testing included various oils ranging from light diesel oil to Bunker C grade oil. Oil spread as thinly as 1.5 mm in thickness was amenable to collection, but recovery efficiency greatly improved with increased thickness. Herding of the oil with booms, as well as current, whether natural or caused by towing the disc unit through the oil, were shown to increase the oil thickness. Oil starvation, in the form of insufficient oil contacting the

			disc was shown to be a significant problem, but recovered oil still contained only around 2% moisture, eliminating the need for a separator. Wave action was shown to actually enhance pick-up.
2015	Regulatory policies for using oil dispersants in the Barents Sea	Belkina, Sarkova, Jensen	[...] timely response to oil spills and use of traditional mechanical recovery (booms and skimmers) in the Barents Sea could be significantly impeded (Lyons & Castaneda 2005; Guevarra 2011). Because spilled oil can dramatically change its properties during the weathering processes, dispersant use has a distinct "window of opportunity" when it is most effective (Trudel *et al.* 2003). Substantial testing and research, including field experiments in the Barents Sea (Chandrasekar *et al.* 2003; Sørstrøm *et al.* 2010), have demonstrated that dispersants can be effective in cold waters (Owens & Belore 2004; Mullin *et al.* 2008; Belore *et al.* 2009). [...]icy conditions slow down weathering processes, lengthening the window of opportunity for applying dispersants (Bjerkemo 2011; Velez *et al.* 2011).
1996	Seakeeping performance of containment boom section in random waves and currents	Kim *et al.*	The seakeeping characteristics of various boom geometries in irregular waves and currents are investigated. The response of a floating boom section on the open sea is a function of a number of parameters, such as boom geometry, distribution of mass, buoyancy/weight ratio, and wave and current characteristics. To understand the relationship between these design parameters more clearly, a series of regular and irregular wave tests were conducted with six different 1:4 scale models for three current velocities and six different wave conditions. To simplify the problem, only rigid boom section consisting of a buoyancy cylinder and vertical skirt were used. In parallel with this experimental program, a numerical model for the response of two-dimensional floating boom section in small-amplitude waves is also developed. The numerical results are compared with our large-scale experimental results. The boom effectiveness on the open sea is evaluated based on the concept of "effective draft" and "effective freeboard" assuming that drainage and oversplashing failures are the prime mechanisms of containment failure. Using the present results, a guideline for the optimum design/selection of future booms is developed.
2002	Study on a spilled oil recovery system	Ueda *et al.*	In the case of oil spill incidents at sea like NAKHODKA incident, if the spilled oil drifts to the shore and sticks to rock and sand, it is very hard to remove. Then we researched on an effective technique to recover oil in waves. As it is necessary to remove the oil in offshore waves, a new technology to recover spilled oil efficiently in the open sea was developed. A barge type oil recovery vessel model was investigated, which is

			generally operated as a multipurpose work vessel for an offshore construction, sea surface cleaning and so on. Spilled oil is taken into the moon-pool located at the center of the ship through the intake and waterway at the stern, where the gathered oil is to be lifted from the water surface by the mechanical equipment. The key issue for the effective recovery of spilled oil is how to subdue the water-surface movement in the moon-pool. With certain appendages attached to the ship, the goal of calming the operational water surface is to reduce the water surface movement in the center of moon-pool by less than 30 % of the incident wave height. The simplification of such appendages in order to attain the good efficiency of oil recovery operation is also important. This target has been attained. The inflow of oil was turned out to be difficult due to the reflection wave from the sidewall of the intake area when the intake confronts with the incident wave in the tank experiment with floating oil. This tendency becomes outstanding in the long wave range. The inflow of oil was improved by changing the direction of intake against the wave not to generate the reflection wave, the removal of bottom plate of intake area and the installation of the watermill to accelerate the surface flow. However, it is considered to be necessary to improve the structure narrowed down to the waterway from intake. Since the stagnation is produced in the front of intake as for taking in of the floating oil in still water, the reconstruction preparing the duct penetrated from moon-pool to bow was performed. As the oil recovery equipment was manufactured in order to investigate its performance independently, the breadth of net conveyer was approximately half in scale of that of moon-pool of oil recovery vessel. For this reason, oil in waves turned back of both sides of net conveyer leading to the fall of recovery efficiency. Concerning the recovery of spilled high viscosity oil, as it is difficult to pump the oil, the performance of a test device with a net conveyer was examined experimentally. In the case of low viscous oils, it is important to thicken the oil layer at the oil recovery point in order to be pumped efficiently. Then the state of the oil layer at an advancing barrier was also investigated. A method is studied that creates a calm region inside a recovery vessel (skimmer), and induces the floating oil into the vessel and thicken the oil layer, then removes the accumulated oil. A baffle and a narrowed and widened water channel inside the vessel create a calm pool and accumulate oil. As a result, the spilled oil is induced well into the recovery region when the vessel is heading into the waves and when the wavelength is shorter than that of the vessel. The 150 degree baffle gives a smooth

			surface and good water flow in the recovery area. Highly viscous oil is withdrawn well by the net conveyer. The collecting mixture with low viscous oils can be made to contain less water by controlling the position of the suction funnel.
2014	Technological development in oil recovery in ice conditions	Wilkman *et al.*	Oil spills and oil recovery has become an issues as exploration and transportation is moving to more harsh offshore environment. In the early days of offshore development in the 1970ies and 1980ies most of the activity took place in open water where the existing systems; oil booms etc. where considered quite adequate. However, the recent incidents like Macondo in the Gulf of Mexico have shown that the traditional recovery methods are not sufficient, not even in open water conditions. What comes to conditions where the recovery has to be done among ice conditions and even more so in cold environment where it could be dark at very remote location? For the purpose to prevent incidents from happening and to be prepared to take proper actions in recovering spilled oil among ice we need a new approach to ensure safe operation without any harm to the environment. The accident of Antonio Gramsci in winter 1979 with an oil spill of 5.000 tons which mostly came to shore in the Western coasts of Finland created the impetus for changing the helpless status of the nation's winter response. The active development work, Finland thus started already in the early 1980ies by performing laboratory experiments as well as full-scale tests. Today we have a clear national target for 30.000 tons year-round response capability and are entering in the home waters to modem, tailored ice capable oil recovery vessels with dedicated tasks and integrated systems ready for oil recovery challenges in various conditions; open water and ice, warm and cold environment, good infrastructure and with no infrastructure at all. This paper describes the new possibilities in ship design relevant to oil recovery together with earlier studies in testing the possibility of oil collection from ice.
2005	The "Prestige" oil spill: an emergency response plan for the Cantabrian coast	Castanedo *et al.*	In this paper the pre-operational oceanographic system developed to assist the response actions to the Prestige oil spill in Cantabria is presented. The goal system developed was to forecast the wave climate, tidal and wind currents and oil spill trajectories to provide the decision makers with technical assessment in the response to the Prestige oil spill. The two main components of the system were the data collection and processing and the integration with numerical models in order to provide forecasts. Regarding the data used, the information on overflights received daily became essential in order to achieve a correct initial position of the oil slicks.

			Meteorological and oceanographic data were also received daily by means of an emergency protocol established between Puertos del Estado (Spain), the Naval Research Laboratory (USA) and the University of Cantabria. These data were used to run the trajectory model, the wave propagation model and the shallow depth-integrated flow model. The information generated by the numerical simulations was presented to the decision makers every day in the form of maps of easy and quick interpretation as a tool helping in the response planning. In addition, in order to develop a defensive or protection strategy for sensitive areas like estuaries and rias, a hydrodynamic study was carried out by the University of Cantabria in all the estuaries of the region. The result of this study consisted of a boom deployment plan for each of them.
2005	The 1987 Newfoundland oil spill experiment	Tennyson, Whittaker	A joint Canadian-United States exercise involving the intentional spilling of approximately 18,000 gallons of specially treated crude oil was conducted off Newfoundland in September 1987 to evaluate the containment and recovery capabilities of three state-of-the-art booms and skimmers. As part of the exercise, data were collected on a specially instrumented oil spill boom in an attempt to verify a proposed performance test procedure for open-ocean oil spill booms. A visco-elastic chemical additive was used, after the equipment evaluation was completed, to enhance recovery operations. Additional observations were made on the persistence of spilled oil slicks in advanced sea states. The containment and recovery effort was successful, despite winds and sea states commonly thought to be beyond existing capabilities.
1990	The Alyeska tactical oil spill model	Anderson *et al.*	In a research effort to improve response planning for oil spills, Applied Science Associates, Inc. (ASA) is creating an innovative oil spill model system for the Prince William Sound (PWS) region for Alyeska Pipeline Service Company (Alyeska). The model system includes modules to simulate the surface and subsurface movement of oil, the tactics, operational constraints, and effectiveness of spill response (dispersant, mechanical cleanup, and burning), and the environmental impact of the spill on the biota of the Sound. The model system is implemented in a personal computer workstation environment with a graphical interface including mouse-driven menus, color overlay mapping, and animations of model predictions. A commercial data base system is employed to organize and present information on spill response resources, shoreline types, and biological resources. Water surface, water column, and shoreline

			biota are included in the biological data base, as are critical habitats for these organisms.
2012	The Effect of Geometrical Properties of Reservoir Shale Barriers on the Performance of Steam-assisted Gravity Drainage (SAGD)	Fatemi	Many bitumen reservoirs contain shale layers of varying thickness, lateral extent, and frequency. These shale layers, depending on their size, vertical and horizontal locations, and continuity throughout the reservoir, may act as a flow barrier and severely reduce vertical permeability of the pay zone and slow down the steam-assisted gravity drainage steam chamber development. Therefore, to improve productivity in these reservoirs, understanding of the effects of reservoir heterogeneities has become necessary. This work presents numerical investigation of the effects of shale barriers on steam-assisted gravity drainage performance when applied to produce mobile heavy oil. The most concern of the work is upon how different geometrical properties of these shale barriers, such as vertical and horizontal position, density, discontinuity, and dispersion through the reservoir, affect the steam-assisted gravity drainage performance and steam chamber development in above wells region. Simulation results showed that the performance of steam-assisted gravity drainage is lower in the case of presence of continued shale layers, their longer extension, and their higher density (number of shale layers per unit volume). As the vertical distance between the continued shale layer and injector decreases, the recovery factor will be less. Distribution scheme of the layers also affected the recovery performance and production rates, since higher was the produced oil in the case of scattered layers as compared with the case of stacked shale layers on top of each other. It was found that the effect of the aforementioned parameters on the ultimate oil recovery factor and production rates was less in the case of presence of discontinuities in the shale barriers.
1999	The Gladstone Field Experiment: Weathering and Degradation of Hydrocarbons in Oiled Mangrove and Salt Marsh Sediments with and Without the Application of an	Burns, Codi, Duke	This field study was a combined chemical and biological investigation of the relative rates of weathering and biodegradation of oil spilled in sediments and testing the influence of a bioremediation protocol. The aim of the chemistry work was to determine whether the bioremediation protocol affected the rate of penetration, dissipation or long-term retention of a medium range crude oil (Gippsland) and a Bunker C oil stranded in tropical mangrove and salt marsh environments. Controlled oil spills were performed in the Port Authority area of Gladstone, Queensland (Australia). Sediment cores from three replicate plots of each treatment for mangroves and four replicate plots for the salt marsh (oil only and oil plus bioremediation) were analysed for total

	Experimental Bioremediation Protocol		hydrocarbons and for individual alkane markers using gas chromatography with flame ionization detection (GC-FID). Sediments were collected at day 2, then 1, 2, 5/6 and 12/13 months post-spill for mangroves and day 2, then 1, 3 and 9 months post-spill for salt marshes. Over this time, oil in the oil-treated plots decreased exponentially. There was no statistical difference in initial oil concentrations, penetration of oil to depth, or in the rates of oil dissipation between untreated oil and bioremediated oil in the mangrove plots. The salt marsh treated with the waxy Gippsland oil showed a faster rate of biodegradation of the oil in the bioremediated plots. In this case only, degradation rate significantly impacted the mass balance of remaining oil. The Bunker C oil contained only minor amounts of highly degradable n-alkanes and bioremediation did not significantly impact its rate of degradation in the salt marsh sediments. The predominant removal processes in both habitats were evaporation and dissolution, with a lag-phase of 1 to 2 months before the start of microbial degradation. The chemistry data provided the context for interpretation of the biological and microbiological observations that are given in companion papers.
2006	The Prestige Oil Spill in Cantabria (Bay of Biscay). Part I: Operational Forecasting System for Quick Response, Risk Assessment, and Protection of Natural Resources	Castanedo *et al.*	In this paper, we present the operational forecasting system developed to assist in the response to the 2002 Prestige oil spill in Cantabria. The objective of the system developed was to forecast the wave climate, tidal and wind currents, and oil spill trajectories to provide a technical assessment to decision makers for a response to the oil spill. The two main components of the system were data collection and processing and integration with numerical models for forecasting. The information from overflights received daily became essential in achieving a correct initial position of the oil slicks. Meteorological and oceanographic data were also received daily by means of an emergency protocol established between Puertos del Estado (Spain), the Naval Research Laboratory (USA), and the University of Cantabria (Spain). These data were used to run the trajectory model, the wave propagation model, and the shallow depth-integrated flow model. The information generated by the numerical simulations was presented to the decision makers every day in the form of maps that were easy and quick to interpretation as a tool to help in the response planning. In addition, to develop a defensive or protection strategy for sensitive areas like estuaries and marshes, a hydrodynamic study was carried out by the University of Cantabria in all the estuaries of the region. The result of this study consisted of a boom deployment plan for each.

2005	The San Rafael de Laya oil spill: A case of cleanup and remediation in Venezuela	Correa, Padron, Petkoff	In November 1994, a 16-inch pipeline rupture resulted in a spill of about 10,000 barrels of crude oil extending on 4 hectares of agricultural land, including part of a freshwater lagoon. The spill was contained 2 kilometers away from the accident by a dike constructed across the lagoon during the first response operation. Oil cleanup activities included a bioremediation process (landfarming) where harrowing, water irrigation, and fertilization of contaminated soil were applied. Physical removal of the oil with sorbents, booms, and pads, as well as a drum skimmer, were used to clean up and restore the lagoon. Laboratory tests reported that total crude oil biodegradation rates were stabilized within 2 months, with a mean total hydrocarbons degradation of 80%.
1995	The technology windows-of-opportunity for marine oil spill response as related to oil weathering and operations	Nordvik	This paper identifies and estimates time periods as 'windows-of-opportunity' where specific response methods, technologies, equipment, or products are more effective in clean-up operations for several oils. These windows have been estimated utilizing oil weathering and technology performance data as tools to optimize effectiveness in marine oil spill response decision-making. The windows will also provide data for action or no-action alternatives. Crude oils and oil products differ greatly in physical and chemical properties, and these properties tend to change significantly during and after a spill with oil aging (weathering). Such properties have a direct bearing on oil recovery operations, influencing the selection of response methods and technologies applicable for clean up, including their effectiveness and capacity, which can influence the time and cost of operations and the effects on natural resources. The changes and variations in physical and chemical properties over time can be modeled using data from weathering studies of specific oils. When combined with performance data for various equipment and materials, tested over a range of weathering stages of oils, windows-of-opportunity can be estimated for spill response decision-making. Under experimental conditions discussed in this paper, windows-of-opportunity have been identified and estimated for four oils (for which data are available) under a given set of representative environmental conditions. These 'generic' windows have been delineated for the general categories of spill response namely: (1) dispersants, (2) in-situ burning, (3) booms, (4) skimmers, (5) sorbents, and (6) oil-water separators. To estimate windows-of-opportunity for the above technologies (except booms), the IKU Oil Weathering Model was utilized to predict relationships-with 5 m s-1 wind speed and seawater temperatures of 15°C. The window-of-opportunity for the dispersant (Corexit 9527®) with Alaska North Slope (ANS) oil was estimated from laboratory data to be

			the first 26 h. A period of 'reduced' dispersibility, was estimated to last from 26-120 h. The oil was considered to be no longer dispersible if treated for the first time after 120 h. The most effective time window for dispersing Bonnic Light was 0-2 h, the time period of reduced dispersibility was 2-4 h, and after 4 h the oil was estimated to be no longer dispersible. These windows-of-opportunity are based on the most effective use of a dispersant estimated from laboratory dispersant effectiveness studies using fresh and weathered oils. Laboratory dispersant effectiveness data cannot be directly utilized to predict dispersant performance during spill response, however, laboratory results are of value for estimating viscosity and pour point limitations and for guiding the selection of an appropriate product during contingency planning and response. In addition, the window of opportunity for a dispersant may be lengthened if the dispersant contains an emulsion breaking agent or multiple applications of dispersant are utilized. Therefore, a long-term emulsion breaking effect may increase the effectiveness of a dispersant and lengthen the window-of-opportunity. The window-of-opportunity of in-situ burning (based upon time required for an oil to form an emulsion with 50% water content) was estimated to be approximately 0-36 h for ANS oil and 0-1 h for Bonnie Light oil after being spilled. The estimation of windows-of-opportunity for offshore booms is constrained by the fact that many booms available on the market undergo submergence at speeds of less than 2 knots. The data suggest that booms with buoyancy to weight ratios less than 8:1 may submerge at speeds within the envelope in which they could be expected to operate. This submergence is an indication of poor wave conformance, caused by reduction of freeboard and reserve net buoyancy within the range of operation. The windows-of-opportunity for two selected skimming principles (disk and brush), were estimated using modeled oil viscosity data for BCF 17 and BCF 24 in combination with experimental performance data developed as a function of viscosity. These windows were estimated to be within 3-10 h (disk skimmer) and after 10 h (brush skimmer) for BCF 17. Whereas for BCF 24, it is within 2-3 d (disk skimmer) and after 3 d (brush skimmer). For sorbents, an upper viscosity limit for an effective and practical use has in studies been found to be approximately 15,000 cP, which is the viscosity range of some Bunker C oils. Using viscosity data for the relative heavy oils, BCF 17 and BCF 24 (API gravity 17 and 24), the time windows for a sorbent (polyamine flakes) was estimated to be 0-4 and 0-10 d, respectively. With BCF 24, the effectiveness of polyamine flakes, was reduced to 50%

			after 36 h, although it continued to adsorb for up to 10 d. For BCF 17, the effectiveness of polyamine flakes was reduced to 50% after 12 h, although it continued to adsorb for up to 4 d. The windows-of-opportunity for several centrifuged separators based upon the time period to close the density gap between weathered oils and seawater to less than 0.025 g/ml (which is expected to be an end-point for effective use of centrifugal separation technology), were estimated to be 0-18 (ANS) and 0-24 h (Bonnie Light) after the spill. Utilizing the windows-of-opportunity concept, the combined information from a dynamic oil weathering model and a performance technology data base can become a decision-making tool; identifying and defining the windows of effectiveness of different response methods and equipment under given environmental conditions. Specific research and development needs are identified as related to further delineation of windows-of-opportunity.
1984	Tidal area dispersant project: fate of dispersed and undispersed oil in two nearshore test spills	Page *et al.*	In 1981, an oil spill field experiment was done in Maine to assess the effects to the benthos of dispersant used in nearshore oil spills. Three test plots, each 60 by 100 m, were set up, each with an upper and lower intertidal sampling area. There were also five subtidal sampling stations in water depths from 5 to 20 m. One plot was exposed to 945 L (250 gal) of Murban crude oil released on an ebbing tide within containment booms and cleaned up by conventional mechanical methods 24 hr later. A second plot was exposed to 945 L of Murban crude oil premixed with 94 L (25 gal) of a widely available self-mix nonionic dispersant. The dispersant-treated oil was discharged over a 2 hr period around high water slack tide. During discharge, mixing gates augmented natural energy to provide a worst-case scenario for exposure of the benthos to the complete dispersal of a nearshore oil spill. During and after discharge, dispersed oil in water was monitored fluorimetrically.
2009	Towards optimum permeability reduction in porous media using biofilm growth simulations	Pintelon, Graf Von Der Schulenburg, Johns	While biological clogging of porous systems can be problematic in numerous processes (e.g., microbial enhanced oil recovery - MEOR), it is targeted during bio-barrier formation to control sub-surface pollution plumes in ground water. In this simulation study, constant pressure drop (CPD) and constant volumetric flow rate (CVF) operational modes for nutrient provision for biofilm growth in a porous system are considered with respect to optimum (minimum energy requirement for nutrient provision) permeability reduction for bio-barrier applications. Biofilm growth is simulated using a Lattice-Boltzmann (LB) simulation platform complemented with an individual-based bio-film model (IbM). A biomass detachment technique has been

			included using a fast marching level set (FMLS) method that models the propagation of the biofilm-liquid interface with a speed proportional to the adjacent velocity shear field. The porous medium permeability reduction is simulated for both operational modes using a range of biofilm strengths. For stronger biofilms, less biomass deposition and energy input are required to reduce the system permeability during CPD operation, whereas CVF is more efficient at reducing the permeability of systems containing weaker biofilms.
1986	Trials with net boom for corralling and recovering viscous oils at sea	Morris, North, Thomas	This paper describes experimental work conducted in the southern North Sea to collect viscous emulsion using a 1 km length of the 2 m wide Jackson netting as a semi-permeable boom. In one exercise 21. 5 tonne of viscous emulsion was put on the sea and some 20 tonne of this emulsion pumped back on board the recovery vessel RV Seaspring after having been surrounded by the net and left to float with the current for nearly 24 hours. The work was co-funded by the European Community and the Marine Pollution Control Unit (MPCU) of the UK Department of Transport.