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REPORT

A SHORT REVIEW OF THE STATE-OF-THE-ART OF PNEUMATIC OIL BARRIERS AND BUBBLE FLOTATION AT SEA

T.A. McClimans, S.H. Gjøsund, P.S. Daling, Ø. Johansen, B. Brørs, I. Leifer

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SINTEF REPORT

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TITLE

A SHORT REVIEW OF THE STATE-OF-THE-ART OF PNEUMATIC OIL BARRIERS AND BUBBLE FLOTATION AT SEA

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ABSTRACT

The authors have reviewed sources of information relevant to the use of air bubbles to develop new technology for combating oil spills at sea, including an overview of the status of oil spill response in Norwegian waters. The zooplankton 'Bubble trawl' flotation concept being developed by SINTEF Fisheries and Aquaculture demonstrates an approach with the potential to increase the efficiency of oil spill recovery operations, in particular by concentrating the surface emulsion layer and reducing the leakage under oil booms, but also by recovering dispersed oil and underwater spills at limited depths.

The size of the droplets to be floated, and the mechanisms by which they attach to air bubbles and coalesce, is decisive for the technique and equipment used for bubble generation. Oil properties may vary considerably for different types of oil, and the significance of oil properties for the cohesion and flotation efficiency needs to be studied further. Of several options, bubble generation by forced air injection is the preferred method to produce the desired larger bubbles with higher rise velocities and buoyant capacity. Natural flotation of oil also takes place at sites of underwater hydrocarbon seeps, where larger, oil coated gas (methane) bubbles rise to the surface and form natural oil slicks.

We need details on the coalescence and bubble capture on and in the wakes of rising droplets, especially the growth to larger slip speeds and more effective surfacing of the drops. On the basis of the information reviewed in this report, we will participate in a field study to gain valuable insight/data from a natural seep and a laboratory study is being made to provide useful data for the development of numerical tools that can help in the development of new technology for the application of bubbles to oil retrieval at sea.

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KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Environment	Miljø
GROUP 2	Offshore	Offshore
SELECTED BY AUTHOR	Oil spill contingency	Oljevern
	Air bubble flotation	Flotasjon ved luftbobler
	Pneumatic oil boom	Boblegardin oljelense

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1 Introduction

The Bubble Oil Boom (BOB) project is a collaboration between SINTEF Fisheries and Aquaculture, SINTEF Chemistry and Materials, Division for Marine Environment Technology, StatoilHydro and Eni Norway. The project is funded by the participants and the Norwegian Research Council's PETROMAKS program for the maximal utilization of petroleum resources. The project organization is shown in Appendix A.

The primary project objective is to investigate to what extent air bubbles can be used to improve the effectiveness of marine oil-spill recovery operations in coastal and environmentally sensitive areas, by creating 1) a pneumatic barrier ('bubble curtain') and/or 2) by flotation of oil particles/droplets attaching to rising air bubbles, see Fig. 1.1. Existing commercial pneumatic oil booms are fixed at the entrance of enclosed basins and pneumatic flotation processes are normally used in enclosed volumes of water.

A secondary objective is to develop numerical tools for the industrial development of such equipment by clarifying suitable applications and investigating the parameters necessary for the optimization of the design and operation of a BOB.

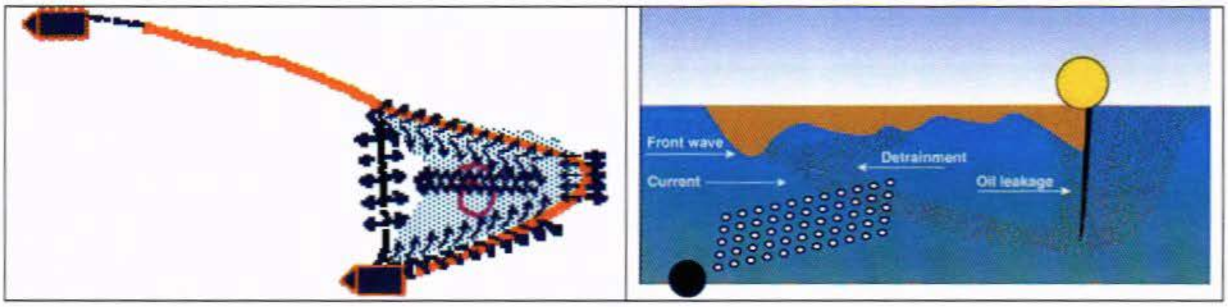


Figure 1.1. *Possible arrangements of 'bubble oil boom' in connection with traditional mechanical recovery operations. Left: plan view of surface outwelling (arrows) from bubble plumes being towed toward the left. Right: side view of flotation from sparse bubble clouds (white dots) produced at an air diffuser (black).*

This report is the first sub-task of BOB: To update the literature review that laid the groundwork for the project proposal. Results from internal discussions of the various sub-tasks (Appendix B) have revealed issues that justify this activity. Specific recommendations for the first year's sub-tasks, based on these additional inputs are summarized in the final section. We thank StatoilHydro for permission to use portions of SINTEF Report SFH80 F063075, "Air bubble flotation ('Bubble trawl') as part of offshore oil spill recovery – literature review" and CALANUS for information on the developments of the "Bubble trawl".

2 Background

Since the Bravo accident in 1977, Norway has developed oil spill contingency plans primarily based on mechanical recovery. The main operational limitations of traditional mechanical equipment are due to reduced performance for high surface or subsurface currents and sea conditions. As Norwegian petroleum activity has moved further north and closer to coastal and sensitive areas, combined with increased transport of Russian oil along the Norwegian coast, there is an increasing risk for oil spills affecting environmentally sensitive areas (*e.g.* Stortingsmelding nr, 8 2005/06). The coming years will be challenging for research and development related to oil spill response equipment. Future efforts should be based on existing knowledge, and further science-based results to develop oil spill response technologies that are founded on sound, proven and cost-effective solutions that are most beneficial environmentally.

In 1971, the U.S. Coast Guard reported on results of a large study to evaluate the feasibility of a bubble-curtain oil boom (termed pneumatic boom), and concluded that bubble curtain oil barriers were only feasible for low current conditions, *e.g.* protecting harbors and other fixed, protected installations (U.S. Coast Guard, 1971). There are several reasons why the conclusions of the 1971 study no longer are applicable and why the state-of-the-art remains unchanged since the late 1960s. Specifically, given the technological limitations of the era, optimization was obtained by trial and error. Also, knowledge of bubble processes and bubble-plume processes was highly simplified (and linearized). Similar limitations existed with respect to understanding, measuring and modeling oil slick processes. Needless to say, in the intervening 4 decades, enormous advances in measurement techniques and tools, including high speed, high-resolution video cameras and particle imaging velocimetry, as well as computational power, and the understanding of bubble and bubble plume processes provide equally enormous optimization potential. These advances have been paralleled by improvements in both compressor efficiency and shipboard power generation efficiency. We plan to leverage these advances through high quality measurement and numerical modeling of lab and field studies to allow optimization of the bubble-curtain oil-barrier, and additionally, by investigating oil particles/droplets flotation by attachment to rising air bubbles. We envision an adaptive system, which can respond to environmental conditions and application (*i.e.*, oil type, location) with built-in redundancy to control drifting oil over a wide range of conditions.

Our impetus for developing a bubble curtain oil barrier *now* is based on unpublished field observations in a natural marine hydrocarbon seep field near Santa Barbara where rising bubbles block thick brown oil slicks even under seas where winds and waves are significant. Aside from natural examples, the ideas behind the use of bubble curtains are not new, as mentioned above. Evans (1955) summarized the use of pneumatic breakwaters dating back to a patent from the early 1900's. Jones (1972) summarized the state-of-the-art for applying air bubbles to contain oil spills and ran a series of laboratory experiments to study the efficiency of this approach. Currently, commercial units are in operation in harbors and ports where power and operational constraints are minimal (Section 9). Details of the effectiveness of these with respect to bubble sizes, oil types and environmental conditions (wind, waves, currents, stratification) largely are undocumented and therefore are not useful in the development of new technology.

3 Oil spill contingency, equipment and limitations

3.1. Organization of the Norwegian oil spill preparedness

In Norway, the oil spill contingency comprises the following:

1. Municipal preparedness (Intermunicipal Committee for Acute Pollution - IUA)
2. National preparedness (Governmental – Norwegian Coastal Administration, NCA.)
3. Private Preparedness:
   - Operators on Norwegian Continental Shelf (Field contingency + NOFO)
   - Crude Oil terminals / Refineries (e.g. Sture terminal, Mongstad and Slagen refineries)

- Companies distributing oil products
- Major industrial companies

The Norwegian Coastal Administration (Kystverket) and the Inter-municipal Committee for Acute Pollution (Interkommunalt utvalg for akutt forurensning, IUA) have primary responsibility for the coastal zone- and shoreline oil spill contingency planning. IUA mostly has small 'harbor' oil booms at their disposal, while NCA also has heavier 'offshore'- and medium heavy 'coastal' oil booms. NCA has totally 16 national and 9 "intermediate" depots along the Norwegian coast. Additionally, NCA is responsible for the oil spill recovery systems on 10 Coast Guard vessels.

For accidental oil spills offshore, NOFO (Norwegian Clean Seas Association for Operating Companies) represents the petroleum industry and has the primary responsibility. NOFO is also responsible for coordinating the response operation if an *offshore* spill drifts into coastal areas.

3.2 Short description of the NOFO offshore mechanical equipment

During NOFO's 30-year history, there has been a continuous development and investment in its oil spill response equipment. New generations of offshore booms and skimmers were introduced both in the 80's and 90's. The last improvements of the NOFO response equipment took place in the period 2004 – 2007, with investments of more than 200 million NOK.

NOFO has divided the coast and the continental shelf into 5 "regions" (Fig. 3.1) with 5 depots along the Norwegian coast (Stavanger, Mongstad, Kristiansund, Træna, Hammerfest) - one connected to each "region". In addition, there is an ongoing re-organizing of the "first-line" offshore response into "area" contingency that also includes heavier mechanical recovery equipment and dispersants for boat and helicopter application. Table 3.1 summarizes the present oil spill response equipment organized by NOFO / offshore operating companies. 16 OR (Oil Recovery) vessels are at disposal. OR is a DNV (Den Norske Veritas) class notation with particular requirements on stability (typical oil/emulsion capacity of 1000 m^3) for handling oil with flash point below 60°C.

The main recovery system presently used by NOFO is the Norlense boom No-1200-R connected to the Framo TransRec 150 weir skimmer (Fig. 3.2) or the Hi-wax skimmer for response to waxy oils. The booms have 1.2 m freeboard and 1.3 m skirt (Fig 3.3) and a maximum towing velocity of 1 knot. Additionally, NOFO has purchased 3 systems of the NOFI Ocean Buster 1000, a boom system concentrating the oil in an aft chamber for pumping or skimming to the vessel, with a maximum towing velocity of 3-4 knots in calm sea conditions. The Ocean Buster can also be operated by one vessel with a "Boom Vane" replacing the towing vessel (Fig 3.4, right).

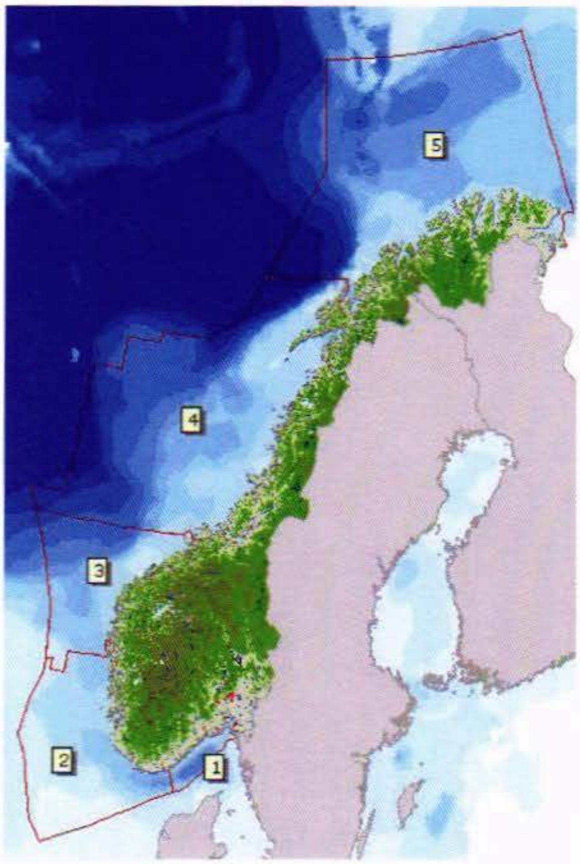


Figure 3.1. ***NOFO's 5 oil spill response regions (Source: http://planverk.nofo.no/.)***

Table 3.1. *Overview of the type and amount of oil spill response equipment in NOFO depots along the coast, and in the area contingency (Beredskapsområde).*

Depot	Booms: No-1200-R, lengde i m	Skimmers: TransRec- 150, (#)	Skimmer: Hi-wax, (#)	Oil spill radars (#)	Ocean Buster (#)	Dispersant (m^3)
Hammerfest	400 (1) *	0	0	1	0	0
Træna	1600 (4)	4	3	0	0	0
Kristiansund	800 (2)	2	2	0	1	59
Mongstad	1600 (4)	3	1	1	1	95
Stavanger	400 (1)	1	0	0	1	131
Beredsk.omr. Halten	400 (1)	1	1	1	0	89
Beredsk.omr. Troll/Oseberg	800 (2)	2	1	2	0	102
Beredsk.omr. Balder	400 (1)	1	1	1	0	100
Totalt	6400 (16)	14	9	6	3	576

**Numbers in parentheses represent the number of recovery systems, given a "standard" NOFO configuration with 400 m boom. (source: NOFO). An additional two new Transrec 150 skimmers will be in place in 2008.*

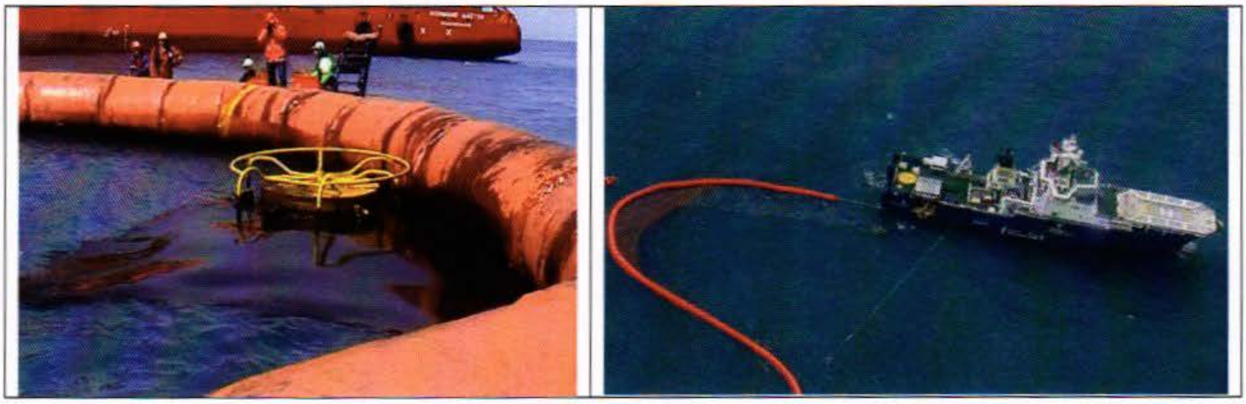


Figure 3.2. *Photos from testing of the Norlense boom No-1200-R connected to the Framo TransRec 150 weir skimmer (NOFO OoW exercises 2003 and 2005)*

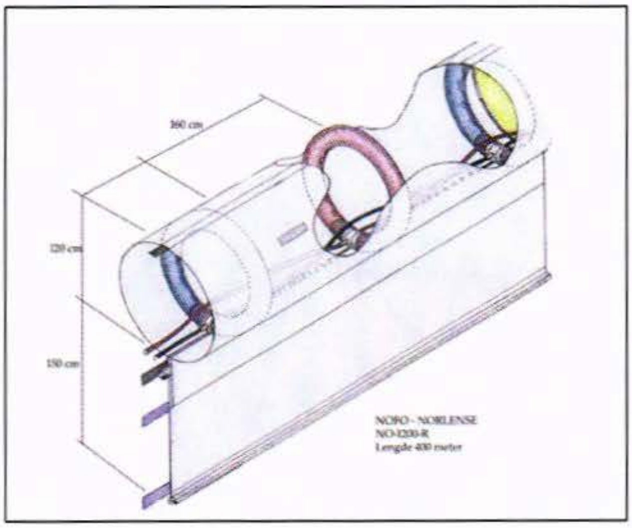


Figure 3.3. *Sketch of the Norlense boom No-1200-R ("Ringlense")*

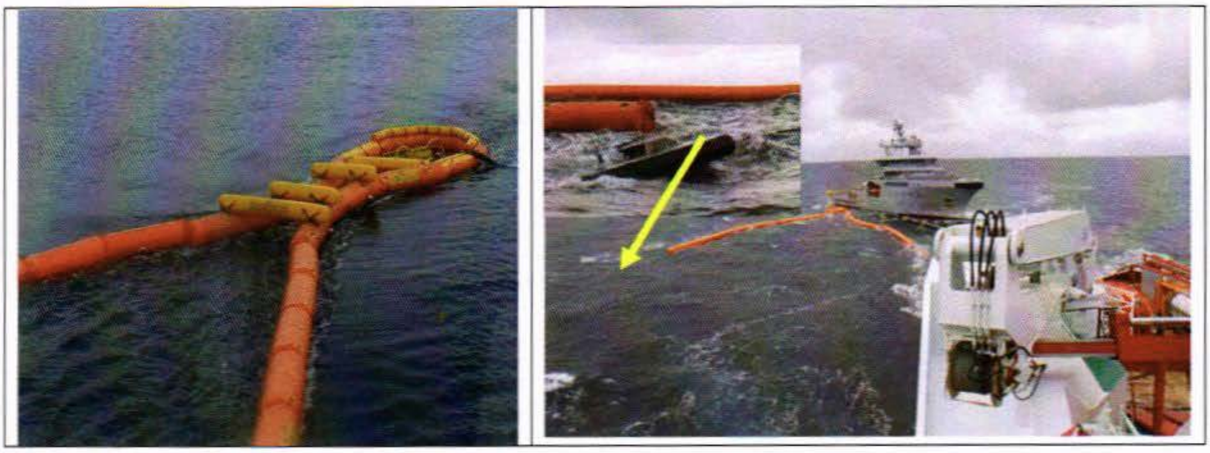


Figure 3.4. *Photos from testing of NOFI Ocean Buster. Right: One-vessel handling by use of a Boom Vane that replaces the towing vessel (NOFO OoW exercise 2008).*

3.3 Experience with boom leakage

3.3.1. General limitations for oil spill booms – mechanisms for oil leakage

The use of booms to contain and concentrate floating oil prior to its recovery by specialized skimmers is often seen as the ideal solution to a spill since, when effective, it removes the oil from the marine environment. Unfortunately, this approach suffers from a number of fundamental problems, not least of which is the fact that it is in direct opposition to the natural tendency of the oil to spread, fragment into patches and disperse under the influence of wind, waves and currents (Fanneløp, 1983). Booms vary considerably in their design, but normally all incorporate the following features:

1. freeboard to prevent or reduce splash-over;
2. a sub-surface skirt to prevent or reduce escape of oil under the boom;
3. flotation by air or a buoyant material;
4. longitudinal tension member (chain or wire) to maintain the shape and orientation of the boom under winds, waves, towing and currents. This member often provides ballast to keep the boom upright in the water.

There are many designs ranging from small, lightweight models designed for manual deployment in harbors, to large, robust units designed for open sea use that need cranes and sizeable vessels to handle and deploy. There are several mechanisms of boom leakage (Fig 3.5.).

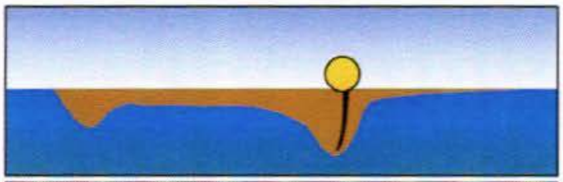
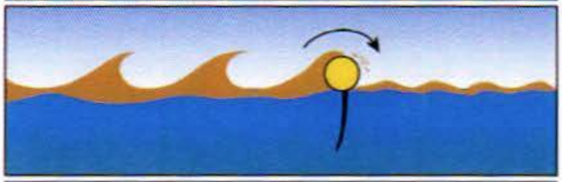
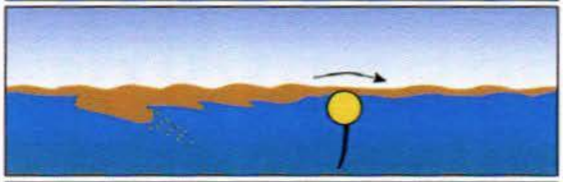
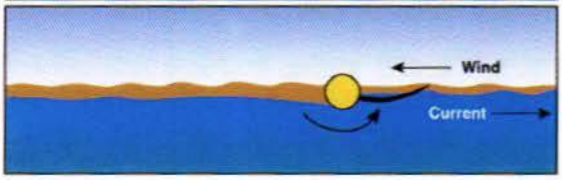
Over filling with oil	
"Splash-over" due to high waves	
Boom diving due to high towing speed and frontal detrainment (entrainment to the sea)	
Boom surfing due to a tail wind and opposing current	

Figure 3.5. *Some "traditional" causes of oil leakage from small boom systems.*

It is essential that a boom be sufficiently robust for its intended purpose. The most important characteristic of a boom is its oil containment or deflection capability, determined by its behavior in relation to water movement. It should be flexible to conform to wave motion yet sufficiently rigid to retain as much oil as possible.

NOFO offshore booms have been tested extensively during the annual oil-on water exercises, (NOFO OoW Exercises 2003, 2005, 2006, 2007 and 2008) and are believed to be among the most robust and reliable boom systems available. However, no boom is capable of containing oil against cross currents greater than typically 0.7 -0.8 knots, irrespective of boom size or skirt depth. Patches of surfacing oil or water turbulence appearing on the downstream side are indicative of boom failure. This results from various "detrainment" mechanisms (defined as leakage or *entrainment* to the ambient sea) as illustrated in Figure 3.6.

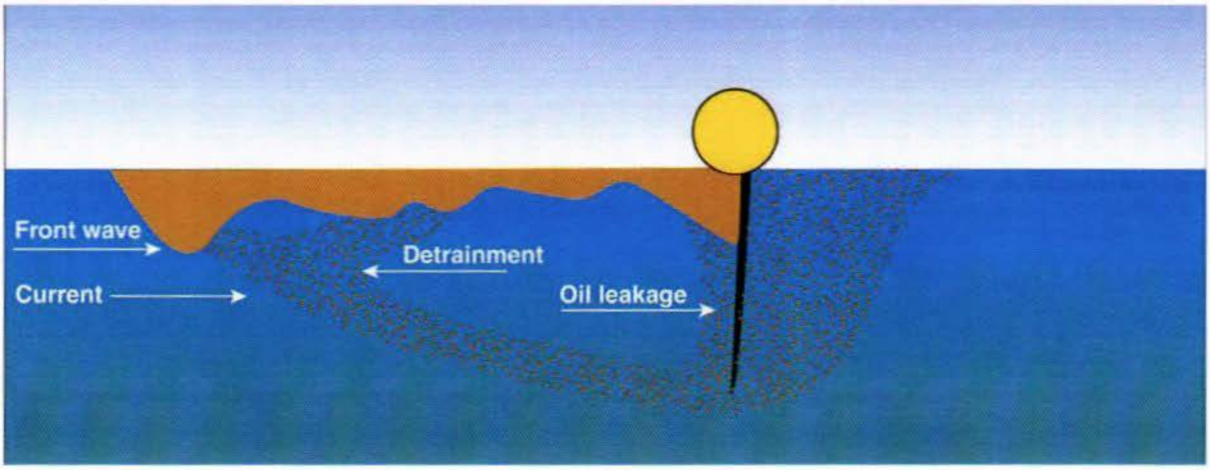


Figure 3.6. *Oil leakage from boom systems due to "detrainment" in high current conditions (> 0.7 – 0.8 knots).*

The general description of the limitations is as follows. The confined oil represents a significant change in the interfacial (immiscible) boundary condition (mobility, viscosity, *etc.*) Both because of confinement by the boom and, due to the nature of oil slicks, the oily interface is spatially discrete, leading to intense velocity shear at the slick edge. As a result, a downward wave front develops along the leading edge of the concentrated and thickened oil slick confined by an oil boom. The forward towing velocity (relative to the water below) can cause oil detrainment from the oil slick in the form of droplets, particularly from the leading wave area. Once the towing velocity exceeds the boom's critical towing velocity, the front wave 'breaks' and detrainment of oil droplets from the oil patch to the water below increases dramatically (Fig. 3.6.).

Waves are an important factor. The leakage under the skirt increases strongly as the significant wave height H_S approaches 3-4 m (OED, 2003, part 7-d) based on conservative analyses for oil spill contingency planning by SINTEF. Fig. 3.7 shows the algorithms used in the OSCAR (Oil Spill Contingency and Response) model to predict the relative confinement capability of the booms with respect to wind speed and H_S. Emulsions may constitute up to 90 % of the collected volume in oil spill recovery operations in calm weather and as little as 2 % in 3 m waves (Gaaseidnes and Turbeville, 1999). The leakage also depends on the oil viscosity. A "rule of thumb" is that the viscosity should be typically exceed 1000 cP for efficient boom operation. Droplet sizes are treated in more detail in Section 8.1. (*NB! The dynamic viscosity, μ, in centipoise (cP) is very close to the kinematic viscosity, ν, in centistokes (cSt) for liquids with density ρ near 1 g/cm^3, i.e., $\nu = \mu/\rho$.*)

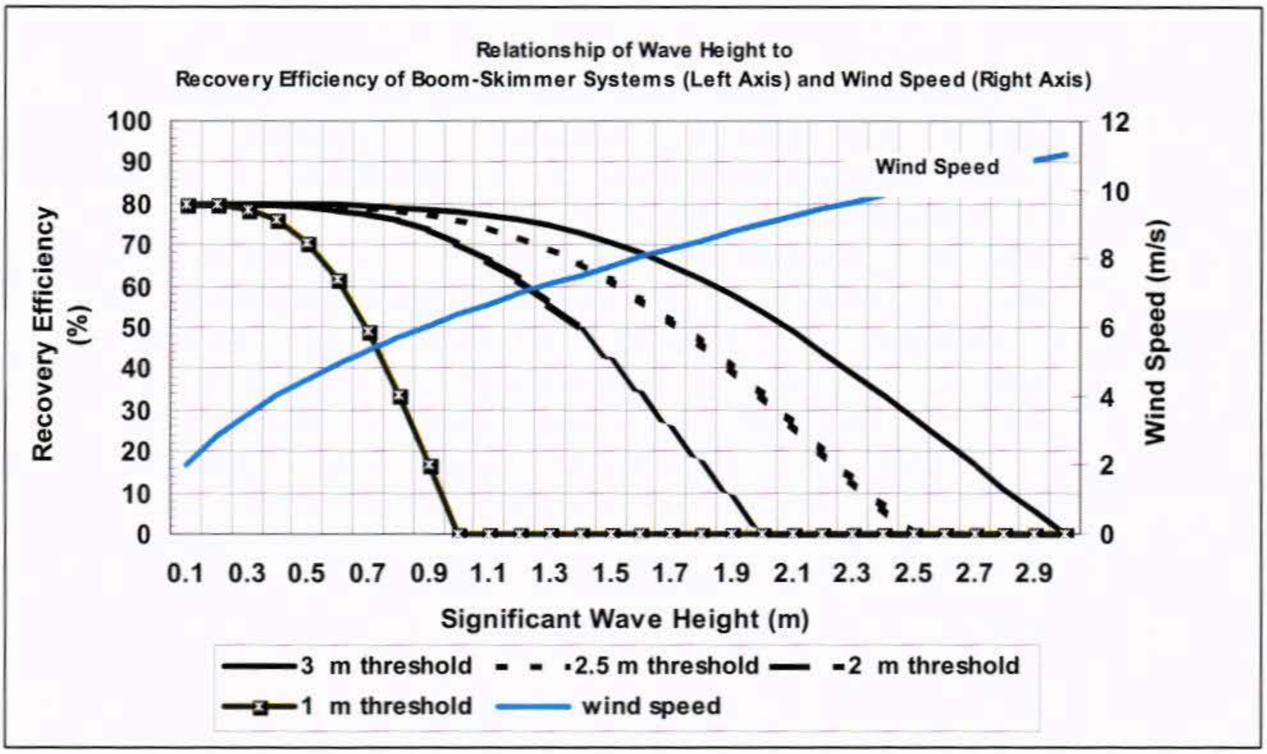


Figure 3.7. *Relationship between significant wave height, wind speed and the relative retention efficiency of booms with different design wave height thresholds, as applied in the OSCAR model system. The maximum retention efficiency is assumed to be 80% of oil encountered by the boom, regardless of sea state.*

3.3.2. Experience from the NOFO Oil-on-Water (OoW) exercises

Testing procedures for monitoring oil leakage:

For the recent OoW exercises, NOFO developed new field testing procedures for response equipment. The oil boom confinement effectiveness and leakage are quantified by combining ground-truth data and remote sensing monitoring. Fig. 3.8 describes the towing strategy and vessel formation while testing response equipment performance: note the secondary ("back-up") recovery system behind. Ground-truth (*in-situ*) monitoring takes place continuously during the testing. This includes measurements of the thickness of oil trapped inside the boom systems (see Fig. 3.9, left) and monitoring of oil leakage through the boom systems (Fig. 3.9, right).

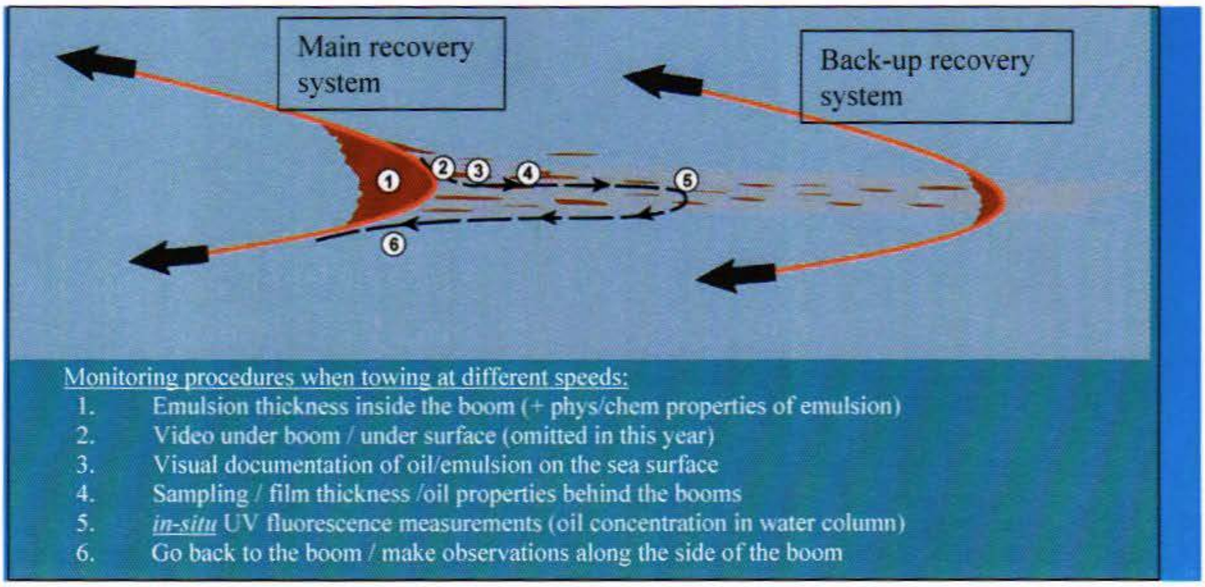


Figure 3.8. *Schematic of the NOFO strategy for the vessel formation when testing different mechanical countermeasures with a back-up recovery system downstream, and the ground-truth monitoring taking place during the testing.*

Figure 3.9. *Left: Measuring of oil thickness inside the boom systems, method: cylinder apparatus. Right: Measuring of oil leakage behind the boom system using oil adsorption pads to measure film thickness.*

Example of testing leakage from the Norlense boom

During the NOFO-2003 exercise, a systematic test-study was performed with the Norlense boom at different towing speeds under very calm wind and sea-state conditions. The viscosity of the emulsion used was ~ 2100 cP. The following documentation and qualitative/visual criteria were developed to characterize and quantify the degree of boom leakage (Figs. 3.10 – 3.13):

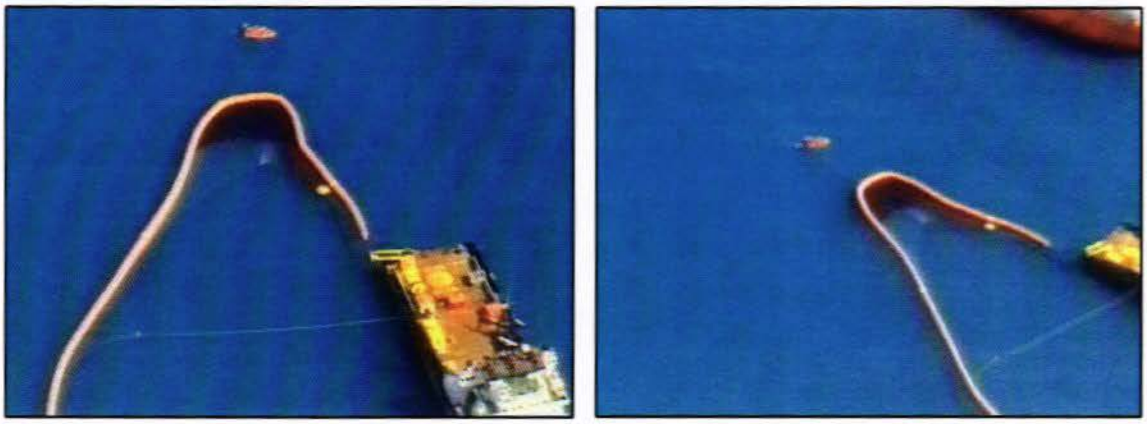


Figure 3.10. *Towing speed: approx. 0.4 -0.5 knots: Virtually no boom leakage: No oil droplets emerge behind the boom (only sheen/rainbow, i.e. < 1-5μm thick). Tentative leakage released: < 10-50 l/hour (< 0.2-1 l/min.).*

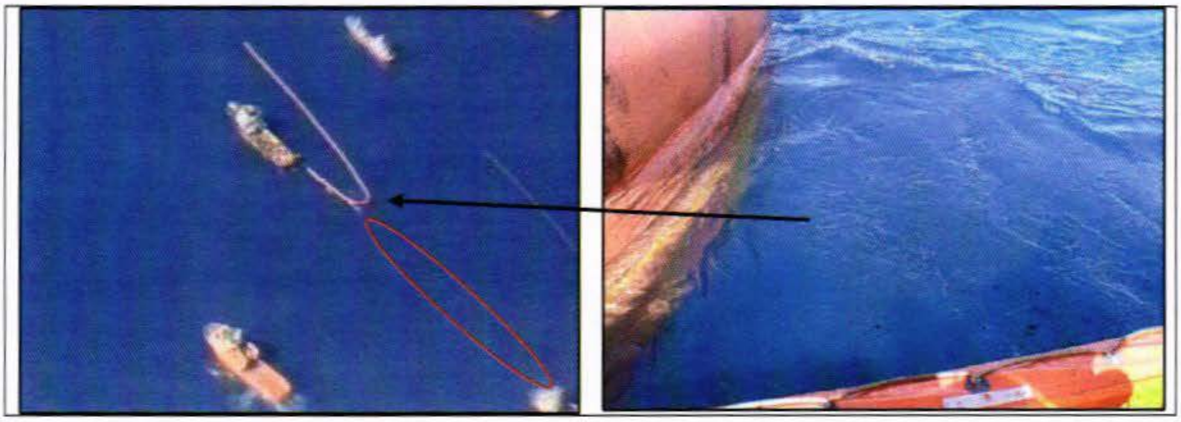


Figure 3.11. *Towing speed: approx. 0.6 – 0.7 knots: "Small" boom leakage: Small oil droplets (< 1cm diameter) surface behind the boom, in the region encircled by a red line, causing small areas of sporadic / spotty oil / emulsion (discontinuous true oil, < 0.5 mm average oil thickness) surrounded by "metallic" film (5-50μm thick). Tentative leakage < 1 m^3/hour (< 10-20 l / min.). (Assumptions: 0.1 mm average thickness, towing speed of 1 km/ hour and width of 10 m)*

Towing speed: approx. 0.8 - 1 knots:
"Significant" boom leakage*:*
Significant numbers of oil droplets / blobs surface behind the boom, causing significant areas of high density oil/emulsion on the water (discontinuous & continuous true oil, 0.2 – 1 mm average oil thickness) surrounded by "metallic" film (5-50µm thickness). ***Tentative leakage: < 2-10 m³/hour (< 30-150 l/min.).***

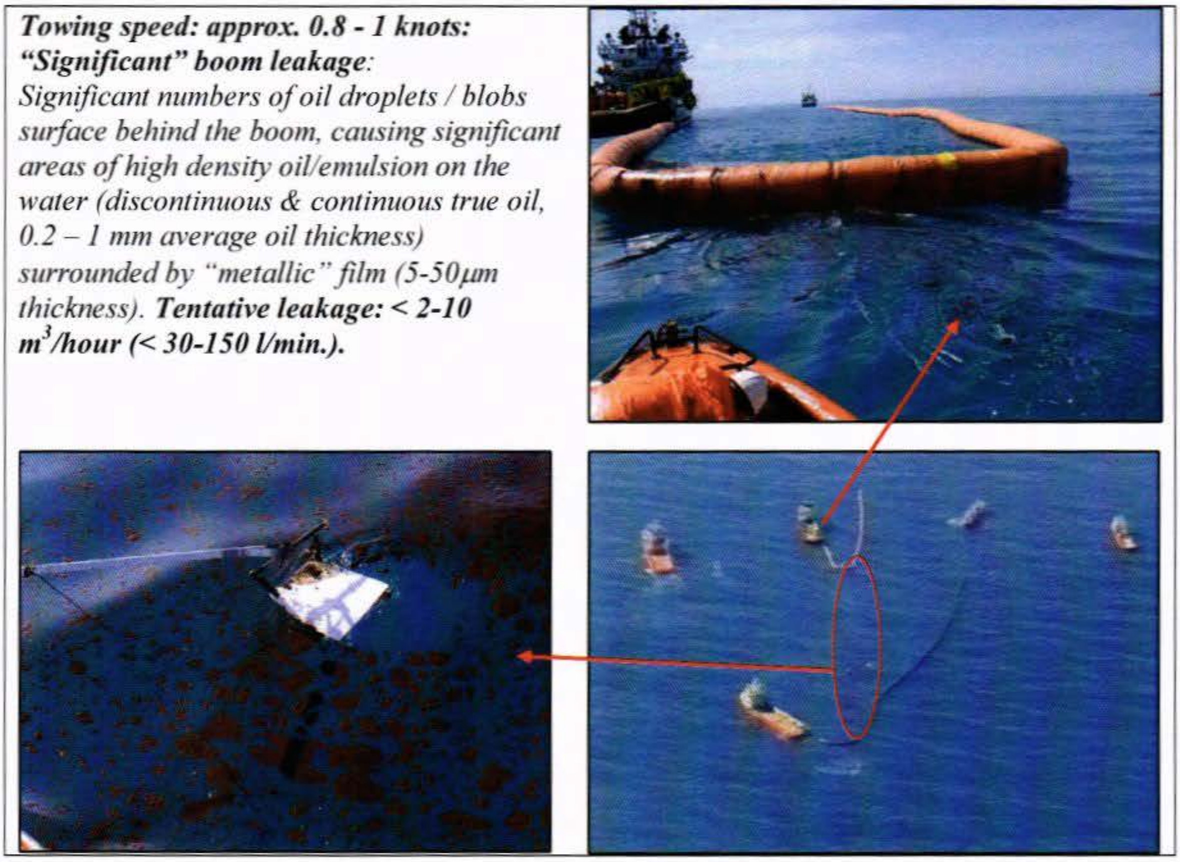


Figure 3.12: *Towing speed: approx. 0.8 - 1 knot. "Significant" boom leakage.*

Towing speed: approx. 1.2 – 1.4 knots
"Large" boom leakage:
Large quantities of oil surface behind the boom, causing areas with high density – a more or less continuous strip of oil/emulsion (continuous true oil, > 1-2 mm average oil thickness). Surrounded by "metallic" film. Intense water eddies on the down-current side (see picture below).
Tentative leakage: > 10 m³/hour (> 150 l / min.).

Figure 3.13. *Towing speed: approx. 1.2 – 1.4 knots. "Large" boom leakage.*

<u>Example from testing the Nofi Ocean Buster</u>
During both NOFO OoW exercises in 2006 and 2007, significant, large-scale leakage was observed bypassing the containment booms during the release of the emulsion into the Ocean Buster system (Fig. 3.14). Leakage was observed primarily at the "connections" between the floating elements (Leirvik and Melbye, 2007), possibly due to eddies formed at the junctions. However, leakage was not observed from the Ocean Buster when towing at 3 knots with emulsion in the "separator" (Daling and Leirvik, 2006 and Leirvik and Melbye, 2007).

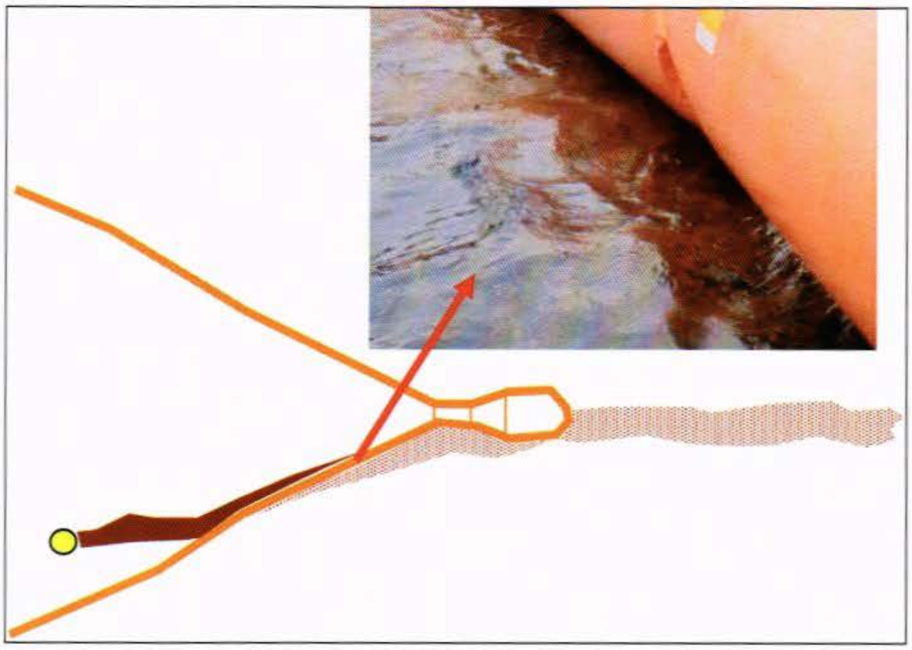


Figure 3.14. Schematic picture of the leakage from the containment boom during release of emulsion into the Ocean Buster system (NOFO OoW exercises in 2006 and 2007). The separation unit is to the right (downstream) of the main boom.

In the NOFO OoW exercise in 2008, the weather conditions were significantly rougher (significant wave heights of 2.5 – 3 m, and 10 – 12 m/s wind). When operating the Ocean Buster up-wind, significant "splash-over" was observed (Fig 3.15 below).

Figure 3.15. "Splash-over" of emulsion from the separator chamber of the Ocean Buster system (NOFO OoW exercise in 2008) operating "up-wind" at 2.5 – 3 m significant wave heights. Picture to right is taken just after the picture to left, showing that the emulsion "rained" on the sea-surface behind the OB-system.

3.3.3 Conclusion – oil spill boom limitations

In conclusion, present oil spill recovery equipment is used to recover oil (emulsion) from the surface with wave height and towing velocity as two of the more severe limitations with respect to applicability and capacity. In this context, our study of using air bubbles to improve the effectiveness of oil spill recovery operations may contribute significantly to improving response capabilities. A BOB can be deployed in coastal and environmentally sensitive areas where its pneumatic barrier ('bubble curtain'), and/or flotation of oil particles/droplets attaching to rising air bubbles, presents an environmentally beneficial approach to oil spill response. There is no need to clean massive boom surfaces after operations and to dispose of the waste. However, the effects of currents and waves must be evaluated and tested.

4 Quantifying the boom failure mechanisms

In theory, three basic principles govern the efficiency of oil containment by a boom:

1. Oil must be buoyant in water, *i.e.* the density of oil is less than the density of water ($\rho < \rho_w$)
2. Oil must be immiscible in water, with the tendency to separate into a distinct surface layer.
3. The resultant forces induced by a counter current and buoyancy forces will tend to thicken the contained oil slick.

Efficient containment primarily implies minimization of oil leakage (oil passing under the boom), while maximizing the thickness of the contained oil in the boom in the vicinity of the skimmer to increase actual recovery. With reference to the sketch shown in Figure 4.2, the maximum attainable slick thickness will be limited by the draft of the boom, the oil properties, primarily density and rheology, and the current speed relative to the boom. Further thickening of the oil slick causes drainage losses (oil escaping under the boom).

A first-order estimate of the expected thickness of a contained oil slick can be made by considering the balance between the major forces acting on the slick, *i.e.* the buoyancy and the friction or drag forces. If the boom is presumed to be straight, enclosing the oil in a channel with a fixed width B (m), the oil volume V (m^3) contained by the boom can be expressed more in terms of contained oil volume per unit width of the channel, *i.e.*, as the unit volume $v = V / B$ (m^3/m). The density difference between water and oil, $\Delta\rho$ (kg/m^3) can be expressed as the reduced gravity $g' = g\,\Delta\rho / \rho_w$, where g (m/s^2) is the acceleration of gravity and ρ_w (kg/m^3) is the density of water. For a straight boom, a simplified force-balance model indicates that a relationship between slick length X (m), contained oil volume v, and the density difference between oil and water can be expressed in terms of two non-dimensional variables, X / L and $\mathrm{Fr} = U / \sqrt{g' L}$, where U (m/s) is the towing speed and L (m) the length scale $L = \sqrt{v}$ (Johansen and Brørs, 2008). These non-dimensional variables have been found useful for comparing experimental data from boom tests with different oils, varying oil volumes and tow velocities (Figure 4.2).

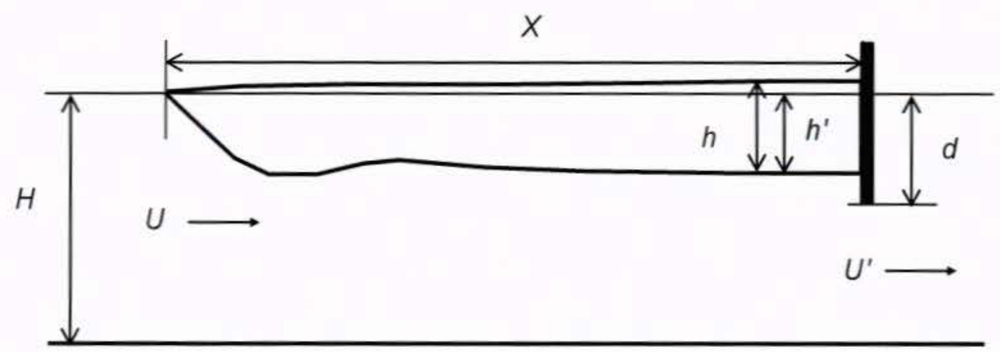


Figure 4.1. *Definition sketch of an oil slick contained against a stagnant boom in a counter flow U. X is the length of the slick, h is the slick thickness, h' is the draft of the slick, and d is the draft of the boom. A finite water depth H will cause an enhanced velocity below the boom:* $U' = U\,H/(H-d)$.

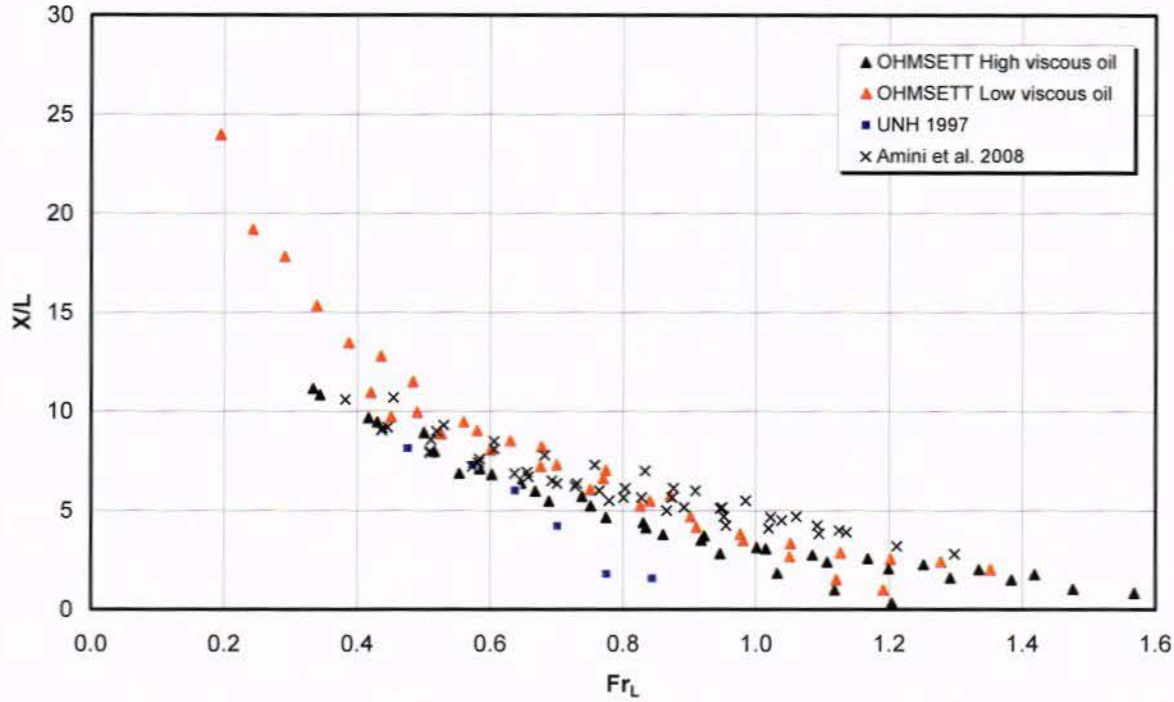


Figure 4.2. *Normalized plot of results from boom tests in the OHMSETT tank and results from small scale tests at University of New Hampshire (UNH) – both reported by Grilli et al. 2000), supplemented with data reported by Amini et al. (2008).*

Figure 4.2 indicates that a general relationship exists between slick length, towing speed and reduced gravity, *i.e.* for a given unit volume v (m^3/m), the slick length X will shorten with decreasing density difference between oil and water – expressed in terms of reduced gravity, g', and increasing tow velocity U. However, at a certain point, further shortening of the oil slick causes oil leakage below the draft (drainage loss). By assuming a rectangular cross-section of the contained oil slick, this condition can be expressed as $X_{\lim} = v / D$, where D (m) is the boom draft. This implies that under otherwise equal conditions, more oil can be contained by simply increasing the boom draft. In spite of the friction force mentioned above, the result should be insensitive to oil viscosity. However, aside from the work of Cross and Hoult (1971) showing an increase in thickness with a 15-fold increase in oil viscosity at large scales, little has been done to study this effect in detail.

A further increase in the towing velocity above a certain limit will cause an abrupt loss of oil from the boom (catastrophic failure). This failure mechanism is linked to suction forces generated by water flowing beneath the boom not balanced by the buoyancy of the oil layer (Fanneløp 1983). A complicating factor for the 3-D situation is the development of vortices in the boom that increase the suction locally (*e.g.* Fig. 3.13, lower left).

In theory, the situation may be defined in terms of a critical velocity $U_c = \sqrt{2g'D}$, depending on the density difference between oil and water (expressed in terms of reduced gravity g') and boom draft *D*. The corresponding critical Froude number will be $Fr_L = \sqrt{2D/L}$, where *L* is the length scale derived from the unit volume, $L = \sqrt{v}$.

In addition to these major failure modes, oil droplets peeling off the head wave of the slick may cause a gradual leak of oil beneath the boom (entrainment loss to the sea). This mechanism is explained as instabilities at the oil water interface known as Kelvin-Helmholtz (KH) instabilities (Amini *et al.* 2008), and is related to a characteristic velocity

$$U_{KH} = \left[2\sqrt{\sigma\,\rho_w\,g'}(\rho+\rho_w)/(\rho\,\rho_w)\right]^{1/2},$$

which depends on the interfacial energy σ. Experiments reported by Lee and Kang (1997) and more recently by Amini *et al.* (2008) have shown that the initial failure velocity U_f, where droplets starts to pass beneath the boom, can be related to this characteristic velocity. For the test oil used in the experiments conducted by Amini *et al.*, (rapeseed oil with $\rho = 910$ kg/m^3 and $\sigma =$ 0.03 N/m), the threshold velocity was reported to vary from 30 to 33 cm/s for different contained oil volumes and boom drafts. This velocity range was found to be about twice the KH-velocity. The authors propose a relationship for the threshold velocity based on the KH-velocity and the boom draft. However, a close inspection of the reported results indicates that the threshold velocity is more sensitive to the contained oil volume and less influenced by the boom draft. The same observation was made by Lee and Kang (1997), who wrote:

"Despite the common anticipation that the oil leakage could be expedited by a large volume of oil, the experimental results show a contrary phenomenon. The reason is due to the fact that as the length of the oil layer stretches ahead of the boom, the droplets separated from the arrow-like head of the layer have longer distance to travel to reach the boom, during which the droplets have a good chance of reattaching to the layer above"

Droplet size is treated in more detail in Section 8.1.

As shown in Fig. 3.16, a close relation exists between the contained oil volume and oil slick length – larger contained oil volumes imply longer slicks. Taking this into account, we have found that the reported threshold velocities correspond to a Froude number $\mathrm{Fr} = U_f / \sqrt{g'L}$ close to 1. For towing velocities above this threshold, $U > U_f$, the loss rate was found to increase in an exponential manner with the differential velocity $\Delta U = U - U_f$, m/s (Figure 3.18).

If the Froude number-based relationship is valid, velocity scales to the square root of length and the threshold velocity for entrainment loss will be significantly larger for ocean going booms with contained volumes on the order of cubic meters per unit width, compared to the threshold values of 30 cm/s observed in the laboratory tests. This is to some extent an established fact, since ocean going booms have been operated successfully at towing speeds up to and even above 1 knot (50 cm/s), but it may still be questionable to extend the laboratory scale findings to ocean going applications with boom drafts on the order of 1 m and contained oil volumes in the range of several cubic meters per unit width. Again, the effects of viscosity and surface tension have not been sufficiently tested.

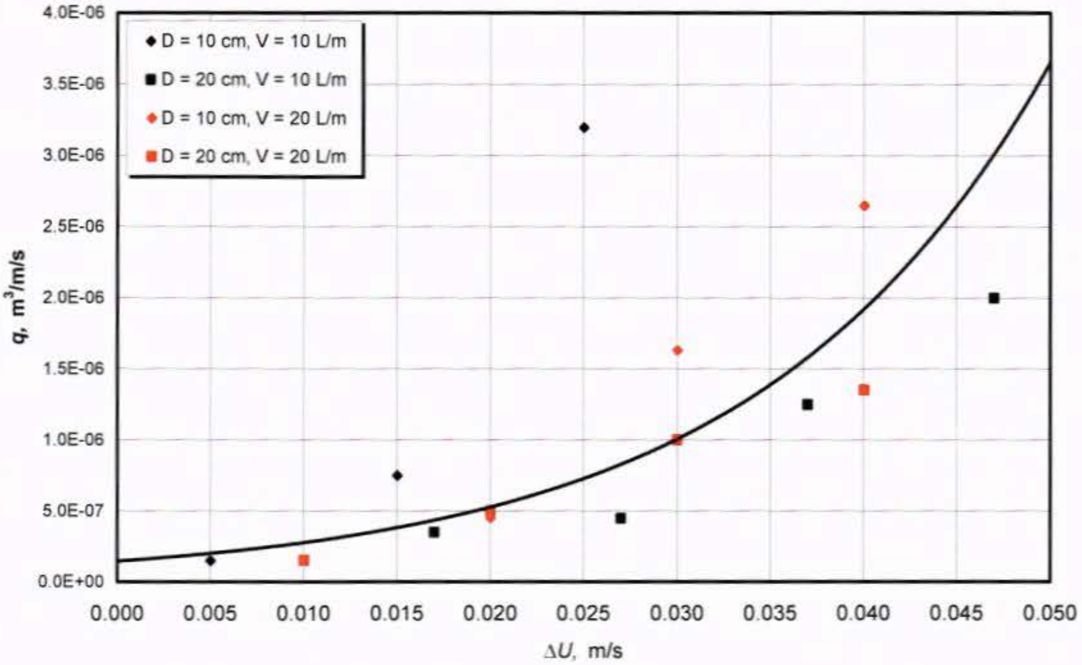


Figure 3.18. *Leak rates plotted as a function of differential velocity* $\Delta U = U - U_f$ *based on experimental data reported by Amini et al. (2008). The boom draft D varies from 10 to 20 cm, while the contained volume V varies from 10 to 20 l/m. The solid line shows an exponential curve fit to the data.*

In summary, we may note that three major modes of boom failures have been addressed in the literature:

- Drainage failure occurs when the oil layer thickness exceeds the boom draft. The tow velocity at which this will happen for a given boom draft will depend on the contained oil volume per unit width, and the buoyancy of the oil, expressed in terms of the density difference between oil and water.
- Entrainment failure occurs when oil droplets generated at the head wave of the slick passes beneath the boom. Recent findings from laboratory tests indicate that the threshold velocity for initiation of entrainment failure depends on two main factors – the buoyancy of the oil and the contained oil volume per unit width.
- Catastrophic failure occurs when a critical tow velocity is exceeded. Above this velocity, the buoyancy of the oil is no longer strong enough to withstand the suction force generated by the water flow beneath the boom. This critical velocity depends on the buoyancy of the oil and the boom draft. 3-D vortices enhance this mode.

Thus, in order to avoid significant losses of oil from the booms, they must be operated below the smallest of these three threshold velocities. For ocean-going booms, rough calculations indicate that entrainment failure may be the limiting factor: With boom drafts on the order of 1 m, the tow velocities where theory implies that drainage failure and catastrophic failures should not occur until far above the present operational tow velocities. In spite of early attempts to estimate the size of entrained droplets, there are few relevant data to guide the work on flotation at sea.

5 Bubble size and separation: the basics

The vertical rise (slip speed, or terminal velocity, u_s) of bubbles in water at rest depends in a complicated way on their diameter and on the purity of the ambient water (Haberman and Morton, 1954). More recently, Maxworthy, *et al.* (1993) showed how this behavior leads to 5 well-defined flow regimes in clean water, depending on the physical properties, including the viscosity of the ambient. Leifer and Patro (2002) focused on the difference between clean (laboratory only) and contaminated water, as is the case in the ocean, demonstrating the importance of bubble surface state. Patro *et al.* (2002) measured bubble behavior in natural waters and found that bubbles larger than 1 mm radius (approximately), in seawater behaved clean.

Surface tension σ of water increases with increasing salinity S (ppt) and decreasing temperature T (°C) according to the Flemming-Revelle formula (Neumann and Pierson, 1966):

$$\sigma = (75.64 - 0.144T + 0.0215S)\cdot 10^{-3}\ \text{N/m}.$$

The surface tension of sea water is higher than for fresh water, so air bubbles will be smaller in sea water than in fresh water if generated in the same manner (see also Sverdrup *et al.*, 1942, Asher *et al.*,1997, Johansen and Jansson, 2005, and the comprehensive overview of water structure and behavior, with references, on web site http://www.lsbu.ac.uk/water/explan5.html).

Behavior of bubbles in a plume is more complex than individual bubbles because they interact with each other, particles, and dissolved substances. We define a bubble plume as a region where bubble density is sufficiently high for frequent interacts and sparse where they do not interact. Grammatika and Zimmerman (2001) propose that a separation distance over 20 diameters is enough to cause a small interaction. In comparison, to simulate the updraft in a plume, *e.g.* a submerged fresh water discharge at sea, the separation distance is only 3 to 4 diameters. Most studies of bubbles are made with individual bubbles. Because of wake persistence, to ensure no interaction requires significant distance (*i.e.*, time) between bubbles. Vaquez, *et al.* (2008), for example, studied bubbles released in a column with 3 minute intervals to avoid any residual wake effects.

When bubbles are sufficiently densely packed, they interact synergistically, producing a bubble plume with properties distinct from the surrounding fluid (Leifer *et al.*, 2006). Here, the local bubble rise accelerates the fluid in its vicinity creating a significant wake that encounters other bubbles (Leifer *et al.*, 2008). When the upwelling flow reaches the sea surface, it "outwells". (See Section 6.) Bubble plume upwelling and outwelling flows are driven collectively by the individual rising bubbles, each of which transfers momentum to the surrounding fluid. With respect to a BOB, the outwelling flow is most important. This is the engineering purpose of the bubble curtain used in pneumatic breakwaters as well. Taylor (1955) treated this as a continuum driven by the buoyancy flux of the air, but found an upwelling 1.73 times greater than that observed in experimental bubble curtains. He suggested that this discrepancy was due to the bubble slip speed (see Section 6). Thus, the behavior of bubbles is a central issue for understanding the behavior of a BOB.

The behavior of bubbles is described in detail in the review paper by Leifer and Patro (2002). Upon formation, bubbles accelerate very rapidly until they rise at their terminal rise velocity (u_s) relative to the surrounding fluid. They also create an upwelling flow (Asher and Farley, 1995; Leifer *et al.*, 2000a). As the bubble rises it changes size due to the decreasing hydrostatic pressure and due to gas exchange. With increasing size, bubbles equilibrate slower (Leifer, 1995), since their surface area to volume ratio is less, and they have shorter subsurface lifetimes due to their larger rise speeds. The three main factors affecting bubble rise are equivalent spherical radius, r, temperature, T, and surface-active substances (surfactants). Leifer *et al.* (2000b) found that the theoretically predicted temperature dependency of the rise velocity was wrong for large bubbles in clean water. Patro *et al.* (2002) found that small bubbles behaved dirty and large clean (Fig. 5.1) with a transition that was dependent on the type of water, consistent with the stagnant cap model (Sadhal and Johnson, 1983). Because bubble rise can only be predicted for very small (*i.e.*, spherical) bubbles from basic theory (*e.g.* Alves *et al.*, 2005), empirical parameterizations are used, modified to account for surfactants (Fig. 5.1, B). The flow around very small bubbles (r <100 µm) is laminar. Larger clean bubbles have an increasingly turbulent wake. The rise velocity peaks at $r \sim 700$ - 1000 µm depending on T, due to the onset of trajectory and shape oscillations due to large vortex shedding and wake instabilities. In this range, bubbles are most sensitive to surfactants. Larger bubbles (1 mm < r < 2mm) rise more slowly, have more complex motion and are less sensitive to surfactants and T. For $r > 2$ mm, bubbles rise faster, but bubbles larger than 1 cm generally are unstable and fragment.

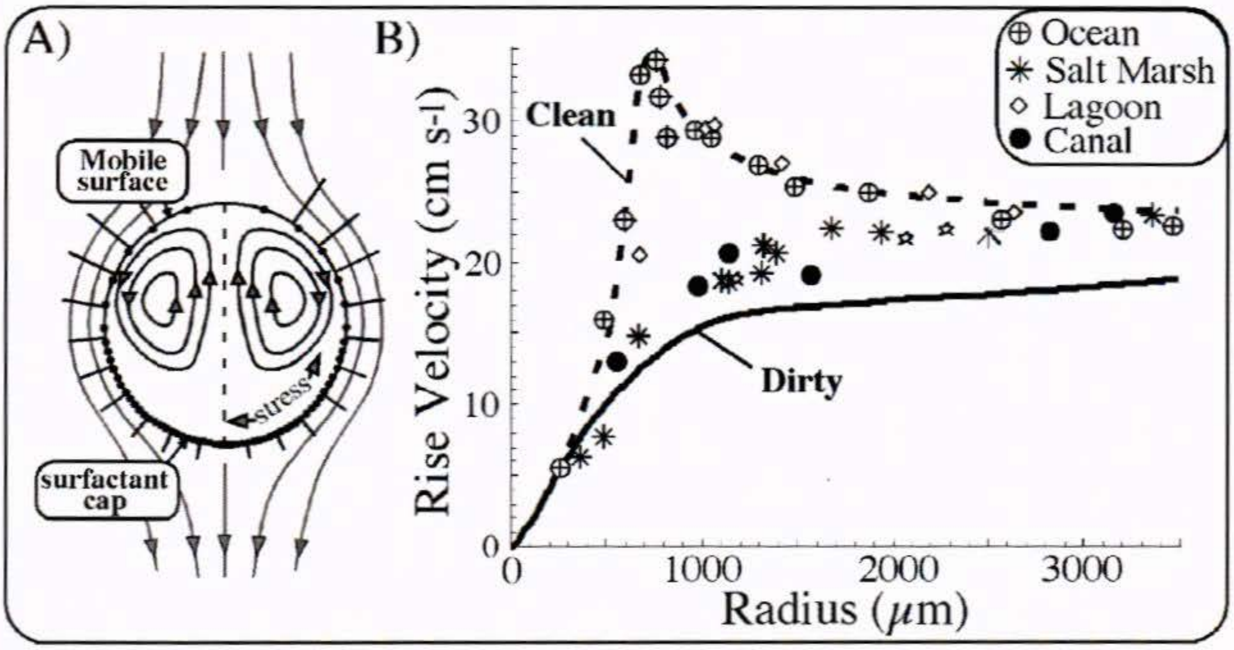


Figure 5.1. *A) Schematic of the stagnant cap model. Line length indicates surface tension from Leifer and Patro (2002). B) Observed bubble rise velocity vs. radius in natural waters, and clean and dirty bubble rise velocity parameterizations. Adapted from Patro (2000). Data key on figure.*

5.1 From distributed source to a plume

Fanneløp and Webber (2003) analyzed the development of bubble plumes from a distributed (wide) source. In the extreme, an infinitely wide source is equivalent to a flotation cell (Section 8). At some normalized distance above the source (much less than the width of the source), the buoyancy causes the updraft to "neck", that is, a location of minimum cross section and maximum vertical velocity. Most plume models invoke a self-similarity hypothesis and consider the source to be a virtual point somewhere below the "neck". As the rising bubbles collect, they cause an entrainment of surrounding fluid and induce a significant ambient flow.

For a plume, the upwelling flow is the integrated total momentum transfer to the surrounding fluid, including the fluid entrainment into the plume, detrainment from the plume and effects from fluid stratification. In the field, currents and wave orbital motions affect the formation of an upwelling flow, in large part by flow disruption – i.e., enhanced entrainment/detrainment. Finally, the surface spreading depends on the density difference between the upwelled fluid and the surrounding near-surface waters, including stratification. Work on pneumatic breakwaters is relevant (*e.g.*, Taylor, 1955; Bulson, 1961). Many studies have investigated plume-associated vertical fluid motions in small-scale laboratory settings, generally with confining walls (Aseda and Imberger, 1993, Simiano *et al.*, 2006, Rensen and Roig, 2001; Riess and Fanneløp, 1998; McDougal, 1978, Fischer *et al.*, 1979). These studies generally report Gaussian flow fields. This distribution is realized only when the local variability is averaged over a sufficiently long time (see Fischer *et al.*, 1979, Ch. 9 for single-phase plumes). Fewer laboratory studies have been conducted where walls have minimal effect, and again, depths are at most a few meters. Studies of large-scale bubble plumes and associated vertical fluid motions in the field are largely associated with aeration of lakes (*e.g.*, Wüest *et al.*, 1992; Singleton *et al.*, 2007), with the exception related to natural seeps (Leifer *et al.*, 2000a; Leifer and Boles, 2005; McGinnis *et al.*, 2006). Field observations suggest that small-scale lab studies highly simplify plume characteristics. For example, seep field observations (Leifer *et al.*, 2008), and larger tank observations (see Fig. 5.2 A) indicate that bubble flows oscillate and organize into clouds or puffs after rising meter scale distances. These puffs are likely significant for entrainment-detrainment.

A B C

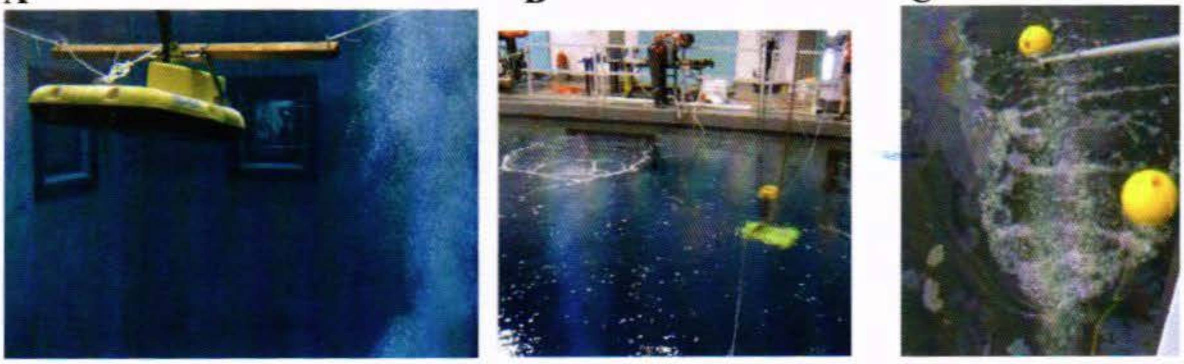


Figure 5.2. *A) and B) Images of bubble plumes from the MBARI saltwater test tank during a sonar study of rising bubble plumes. Note unevenness of outwelling rings showing plume puffs. C) First field test of a bubble oil boom deployed at 0.5 m depth below an oil slick.*

5.2 Dirty bubbles

Surface active materials (surfactants) are ubiquitous in marine waters, most commonly from algae (Zutic *et al.*, 1981). Surfactant contamination of bubbles is usually due to a monolayer that covers a portion of the bubble surface – *e.g.*, the stagnant cap model shown in Fig. 5.1A. Surfactants slow the bubble rise by decreasing the bubble's interface mobility thereby changing the bubble boundary layer. As a result, the effect of surfactants is reduced where turbulence in the bubble's boundary layer is imposed by external sources – in this case, the wakes of other bubbles. As a result, it has been noted that surfactant effects are diminished in bubble swarms (Hill, 1974).

Although oil is surface active, its effect on bubbles is different because it forms layers that are significantly thicker than monomolecular (Leifer and Wilson, 2007). In this case, decreased bubble buoyancy results in a decrease in associated fluid motions. Bubbles are efficient spargers of surfactants; thus bubble plumes effectively "purify" the plume water. As a result, only some bubbles will have reduced buoyancy from oil adhesion. Critical to the oil droplet flotation process is their attachment to bubbles. Attachment is a multi-step process. First the oil droplets and bubbles must collide; then the oil must adhere rather than bounce. *Collision efficiency is approximately greatest for similar sized particles, because where one particle is much larger than a second, the smaller tends to follow streamlines around the larger*. Decreases in rise velocity due to oil adherence would increase collection efficiency by tightening flow streamlines and increasing the residence time.

6 Bubble curtain

A bubble curtain may be considered as the two-dimensional equivalent of a single, axi-symmetric bubble plume. Most of the hydrodynamics of these different plumes are quite similar. A simple sketch of the plume is shown in Fig. 6.1. Among the applications, pneumatic breakwaters were mentioned. The theory of bubble curtains is similar to that of one-phase plumes deriving their buoyancy from heat or freshwater in seawater. There are, however, significant differences. The width of the bubble plume is less than the momentum plume as sketched in Fig. 6.1.

The effectiveness of the two-phase (bubble) plume can be viewed as the ratio of the width of the buoyancy distribution compared with the width of the induced flow, often called λ. For single phase, 3-D plumes, $\lambda \sim 1.2$ (Fischer *et al.*, 1979). For bubble plumes, usually $\lambda < 1$. Indeed, most investigators use a value close to 0.8 in their plume model (*e.g.*, Milgram, 1983; Brevik and Kristiansen, 2002). This is due to the tendency for (especially large) bubbles to remain in the center of the plume (Leitch and Baines, 1989). Rowe *et al.* (1987) show a range of λ from less than 0.8 for weak air flows to greater than 1 for strong forcing.

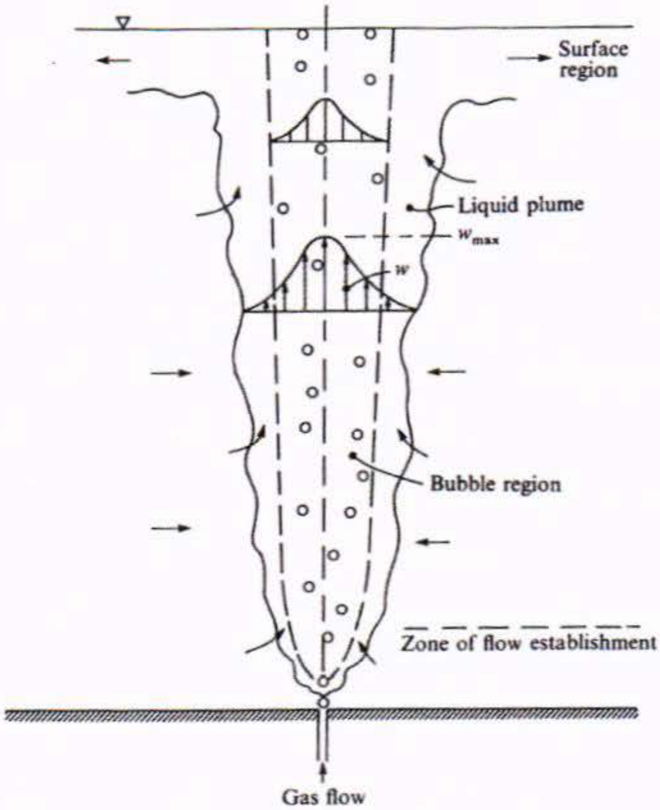


Figure 6.1. *Sketch of a weak bubble plume (from Leitch and Baines, 1989).*

These differences can be seen as a result of the larger scale turbulent eddies formed by single phase plumes – a series of vortices (Fischer *et al*., 1979) forming thermal-like billows on their way to the surface (similar to the bubble puffs in Fig. 5.2). The eddies transport buoyant fluid to the side, where the rotational motion contributes a negative velocity defect (relative to their ascension), thereby giving a relatively more narrow velocity profile compared to the buoyancy profile. It is suggested that the buoyancy in this outer part is important for the entrainment (increase of volume flux). For *bubble plumes*, there is not as much buoyancy delivered to the outer parts of the puffs due to the behavior described by Leitch and Baines (Fig. 6.1). For weak bubble plumes, they found that volume flux is proportional to the square root of air flow and increases linearly with height. Their laboratory bubbles were on the order of r = 2 mm. For these conditions the individual bubble wakes make an important contribution to the entrainment.

Following Taylor's (1955) suggestion of a reduction of effectiveness due to bubble rise velocity, Milgram (1983) computed a reduced entrainment as a function of the reduced bubble residence time in the plume. Rowe *et al*. (1989) show an increase in entrainment of more than 50% as the plume strength increases. This reduces the relative importance of bubble residence time. Recently, Male (2008) showed an increase in entrainment efficiency by using small bubbles ($r < 500$ μm) to increase the residence time, but the increase in efficiency was overwhelmed by the energy required to press the air through a sparger. Seol *et al.* (2007) confirm that the entrainment coefficient increases with buoyancy flux and decreases with increased slip velocity. They collapsed their data to the parameter $u_s/(g'Q/z)^{1/3}$, where $g'Q$ is the buoyancy flux and z is distance above the bubbler. Curiously, their laboratory measurements show a top-hat distribution in total bubble velocity, with a Gaussian distribution in the plume momentum. They assume a Gaussian distribution of void fraction as sketched in Fig. 6.1.

The largest plumes all have bubbles at the limits of stability (r = 1 – 2 cm), with slip speeds on the order of ¼-½ m/s. For strong bubble plumes, the volume flux is nearly proportional to the cubic root of the air flow as is the case for the single-phase plume.

For the BOB, the air bubble source will be shallow with short rise times so the effects of compressibility and dissolution can be neglected. Diameter increases from 5-m depths to the surface are only 15%, while buoyancy increases by 50%.

When the bubble plume reaches a depth comparable to the surface expression diameter, the upwelling flow feels the surface and the vertical momentum changes to horizontal momentum. This conversion creates angular momentum and, due to the unsteadiness and instability, also to intense turbulence. The dome at the surface where the outflow starts is often called a "boil". Bulson (1961) was more concerned with the maximum exiting outflow from the edge of the boil rather than the velocity structure within to assess its effect on surface waves. This is also of interest for the present application. These results, which have been verified by several other authors and also for single-phase plumes, are that the maximum outflow velocity is proportional to the cube root of the air flow *and* the depth of the bubble source. This assumes no (or negligible) stratification. In this review we will consider this for a wider range of conditions, including stratification. More recently, Friedl and Fanneløp (2000) and Brevik and Kristiansen (2002) have studied the details of the boil.

There can be variability in bubble curtain operation due to the large vortices generated during rise, and the tendency of bubble plumes to form structures or billows, as well as effects from environmental factors like waves, currents, and stratification. Understanding sources and magnitudes of variability is important for a BOB since random openings in the outwelling may allow leakage. However, because the outwelling flow derives from an ensemble contribution of the bubbles in the plume near the sea surface and comprises water with significant momentum, highly transient variability in the bubble flux has minimal effect. For example, lab studies for the project showed that after a bubble pulse of just a few seconds, the outwelling flow persists (in quiescent water) for about a minute. Therefore, it is important to look at the variability that upon time averaging creates the engineering concept of a Gaussian distribution (see also Fisher *et al.*, 1979, Ch. 9).

Jones (1972) presented laboratory data that showed how oil breaks through a bubble curtain in a cross flow, and how effective a bubble curtain can be to steer surface oil spills toward the side of a flowing channel. Also, Delvigne (1984) reported results from laboratory experiments with pneumatic barriers to protect water intakes from oil, concluding that such barriers are inefficient for preventing break-through, but may be effective in deflecting the surface current, as sketched in Fig. 1.1 (left).

Ambient stratification *reduces* the effect of the buoyancy flux in a bubble curtain. For weak air flows, the entrained water will peal off and form intrusions at one or more depths (*e.g.* Aseada & Imberger, 2002). Sægrov (1975) showed that air flows sufficiently strong to break down the barrier of a freshwater layer near the surface gave an outflow with maximum velocity close to the homogeneous situation tested by, *e.g.* Bulson (1961) and Kobus (1968). For the present, we consider BOB where thermal stratification does not create a significant effect. Thus, our focus is on conditions where the air-sea temperature difference is small and there is no strong stratification in the upper few centimeters.

7 Bubble trawl

SINTEF Fisheries and Aquaculture has recently described a new trawl-concept for harvesting marine zooplankton, primarily with the crustaceans *Calanus finmarchicus* in mind. The essence of the concept is that air bubble flotation concentrates the vertically distributed zooplankton, which typically are 2-3 mm long and 0.5 mm thick, at or near the ocean surface, thus reducing the necessary vertical opening and towing resistance of the trawl/collector and increasing the energy efficiency and profitability of the fishery, as well as providing species selectivity. The trawl system in essence consists of a submerged air bubble diffuser and a surface collection unit similar to an offshore oil skimmer, with or without a fine meshed net bottom. The diffuser is towed at a depth ~ 20-40 m at a velocity ~ 0.5-1.0 m/s. The required horizontal spreading of the gear is ensured by kites instead of traditional heavy trawl-doors/deflectors. The catch may be accumulated in a cod-end or skimmed/pumped continuously to the vessel.

The obvious similarity with oil spill recovery equipment initiated an interest in evaluating the applicability of the 'bubble trawl'-concept to increase the operational efficiency of such, in particular by reducing the leakage under oil booms during towing and/or operating in waves. The concept also may be of interest in cases when natural dispersion of surface oil slicks takes place, but is unwanted or unacceptable due to environmental concerns, as an alternative in environmentally sensitive areas to chemical dispersants, and in cases of underwater spills at limited depths or to protect resources against submerged oil (*e.g.*, mouth of a fjord, fish farms).

For the zooplankton 'Bubble trawl' (Johansen and Jansson, 2005; Fig. 7.1), tests were carried out using a porous pipe air sparger centered inside a short pipe/bend of somewhat larger diameter. The sparger injects air into the water flow in the pipe/bend, hence producing bubbles. Smaller sparger orifices generally yield smaller bubbles, but there is a limit on hole size as very small holes may clog due to impurities. Higher water flow velocity through the pipe/bend also yield smaller bubbles, since then the water flow pinches off the bubbles developing earlier than at lower velocities. The water-bubble mixture then flows into a reinforced hose or flexible pipe where a number of holes are drilled along as well as circumferentially around the hose. The hose acts as a diffuser, injecting the water-bubble mixture into the sea with the goal of producing a uniform emission of bubbles from its entire length, rather than one where sources closest to the hose inlet produce the most bubbles. The circumferential placing of holes along the hose prevents a uniform flow separation pattern from developing along the hose when towed transversely through water, thus avoiding vortex-induced vibrations and increased drag of the hose and it reduces trapping of air bubbles inside the hose. The resulting bubble size distribution is relatively broad. For particular oil and ocean conditions, there will be a specific bubble size that is optimal. Thus, the ability to narrow the bubble size distribution and control its peak in real-time in this otherwise simple, robust and low-cost system is unclear. As stated above, sparger orifice and water inflow velocity can be used to vary bubble size, but this needs to correspond to the total capacity and air volume required. The flow conditions in and design of the diffuser may also influence bubble size. Fig. 7.2 shows the sparger (without hose/diffuser) placed in a free flow at three different velocities.

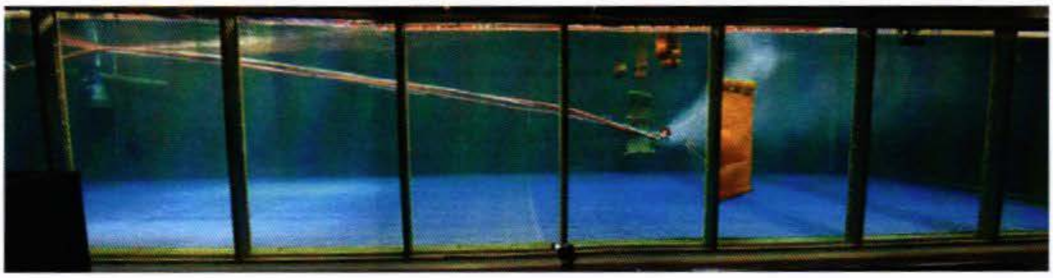


Figure 7.1. Experimental set-up for bubble sparging. The air diffuser is attached to two kites providing the desired spread. Photo: Stig Jansson / Vegar Johansen, SFH (from SINTEF Hirtshals flume tank laboratory).

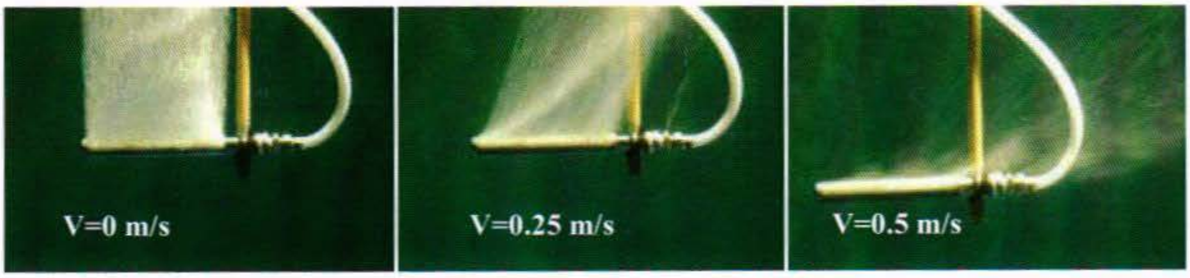


Figure 7.2. IAF bubble sparger. Gas inside porous pipe (grey). Axial water flow reduces bubble size. Photos: Stig Jansson/Vegar Johansen, SINTEF.

One flotation method need not disqualify another. A multimodal approach may be taken, *e.g.* releasing larger bubbles to initially lift the larger oil droplets, aggregates and plumes, followed by smaller bubbles to collect the smaller droplets, possibly followed by another release of large bubbles to enhance further aggregation and increase rise velocity, as well as multiple parallel curtains. Also, the rising bubbles imply some degree of upwelling, which in turn implies a diverging outflow from the surfacing area and a converging inflow towards the area where the bubbles are generated. The surface outflow may have implications for the configuration and operation of the surface oil boom and skimmer.

8 Flotation of dispersed oil droplets

Oil drops in water behave in a similar way to bubbles (Fig. 5.1). Fig. 8.1 shows the terminal velocities of fluid drops obtained by Hu and Kintner (1955). Several of the results that were cited for bubbles are therefore relevant to oil droplets, only at different strengths, although upon adhesion to a bubble, the behavior will be some combination of the two extreme cases – pure bubbles and pure oil droplets.

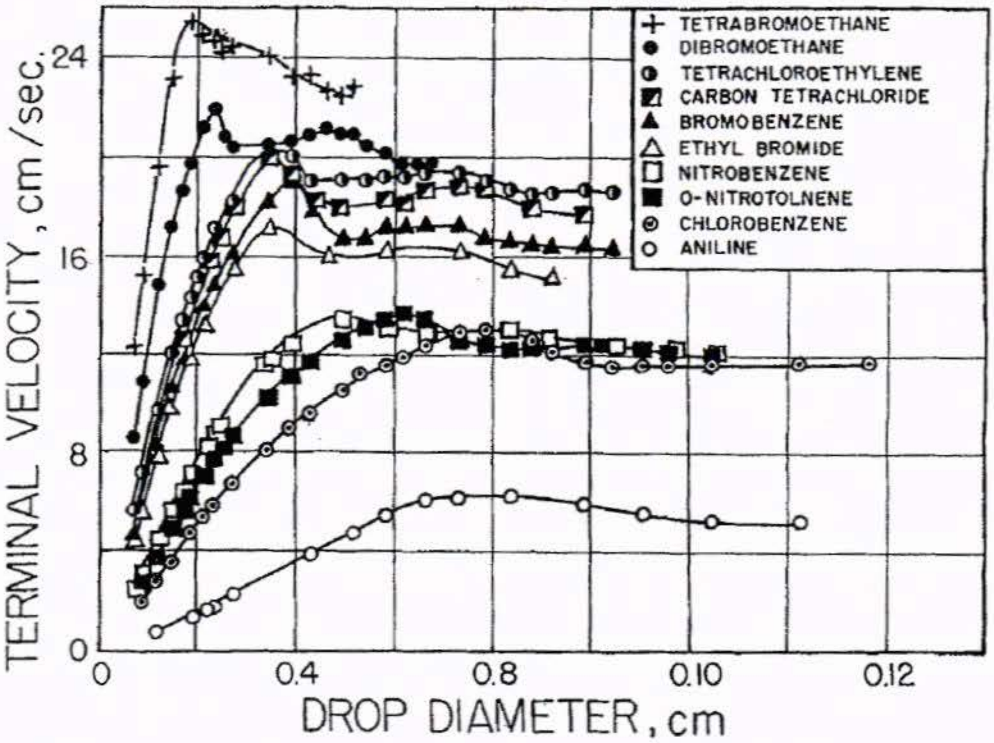


Figure 8.1. *Variation of terminal velocity of immiscible fluid drops in water (Hu and Kintner, 1955).*

8.1 Oil droplets

Of particular interest for air bubble flotation of oil spills are models for the spatial distribution and size of dispersed oil droplets, *i.e.* release- and weathering models. RIKZ (the Dutch Institute for Coastal and Marine Management) has recently evaluated and compared 5 oil spill/weathering models (Vos, 2005). These include the two SINTEF models OWM and DREAM, the two US National Oceanic and Atmospheric Administration (NOAA) models GNOME and ADIOS, and RIKZ own model SIMPAR. Since the models have somewhat different content and applications direct comparison is not necessarily relevant. For the specific weathering processes OWM was found to be overall most reliable, although with some comments on the oil-in-water dispersion results. The dispersion is based on Delvigne and Sweeney (1988) in all models except GNOME. The primary dispersion result from the models is the entrainment rate (dispersed/detrained oil mass per unit time) for a specified type of oil under specified environmental conditions. However, the model of Delvigne and Sweeney (1988) also allows more detailed predictions of droplet size distribution and intrusion depth as a function of oil type, oil layer thickness, breaking wave energy (*i.e.* sea state) and temperature.

In case of submerged spills, dispersion into oil droplets is generated by turbulence. For submerged spills Delvigne and Sweeney (1988) draw the following general conclusions:

- most of the dispersed volume of oil is comprised droplets with diameters in the range 50-1000 μm
- the mean droplet size increases with viscosity and decreases with turbulence energy and time
- the droplet size distribution is independent of water salinity and whether the oil is added as a surface film or as submerged parcels
- the oil-water interfacial (surface) tension is likely to influence the droplet size distribution, but their experiments were conducted with oil types with similar values of interfacial tension and thus unable to provide such a relationship

Delvigne and Sweeney (1989) used two crude oils in their breaking wave tests – Ekofisk, and Prudhoe Bay (PB). The former oil was tested only in fresh state, but at different temperatures, while the latter also was tested in weathered states, i.e. weathered by evaporation and emulsification. The effect of weathering was mainly to increase the viscosity of the oil. For the fresh Ekofisk oil, the viscosity was in a range from 8 to 12 cSt depending on temperature (varied between 4 and 20 °C). For the PB oil, the viscosity ranged from about 90 to about 200 cSt for the fresh oil and the samples weathered by evaporation, while the viscosity of the emulsified sample was measured in a different range; 56 000 cSt at a shear rate 0.03 s^{-1} (non-Newtonian). It should be noted that tests with this sample did not provide any dispersion results, so in reality, the results were limited to the viscosity range from 8 to about 200 cSt.

The importance of interfacial (surface) tension is demonstrated *e.g.* by chemical dispersants, which reduce both the interfacial tension and the droplet size by an order of magnitude (Delvigne and Sweeney, 1988). Surfactants prevent small bubbles from coalescing.

For surface spills dispersed by breaking waves, Delvigne and Sweeney (1988) draw the following general conclusions:

- the droplet size distribution and oil concentration is quite uniform over the entire intrusion depth, for oil droplet size intervals not affected by resurfacing, implying a quite sharply defined (wave dependent) intrusion depth $z_i < (1.50 \pm 0.35)\ H_b$, where H_b is the height of the breaking wave. In laboratory experiments with oil intrusion due to breaking waves, single as well as series of spilling breakers, Nilsen *et al.* (1985) found that $z_i = (1.5 - 2)\ H_b$. They considered crude oil, 70/30 water-in-oil-emulsion and chemically dispersed oil. The droplets were in the range 0.2-1.6 mm, and the chemically dispersed droplets were generally smaller than the others.
- the oil entrainment and droplet size distribution are independent of oil slick thickness, and the maximum droplet size can be considerably larger than the slick thickness
- even when all of the surface oil is submerged by a breaking wave, the larger globs and droplets resurface quickly with only a fraction of the oil remaining. The stability of the dispersion depends on the injection depth, the rise velocity of the oil droplets as function of size and buoyancy, and on the vertical turbulent diffusion. The fraction of resurfacing droplets in a given size and time interval increases with increasing size. The results and discussion in Delvigne and Sweeney (1988) suggest that that many of the droplets with diameter > 1000 μm will resurface quickly while droplets with diameter < 200 μm will require far longer to resurface, but this also depends on the time, intrusion depth, wave breaking intensity and ambient ocean turbulence.

8.2 Models

Spill models

Oil spill models may include hydrodynamic release- and transport modules, oil weathering modules, oil property modules (data base), environmental consequence modules and response-scenario modules. SINTEF Materials and Chemistry, Department of Marine Environmental Technology offers among others the following models:

OWM (Oil Weathering Model) - Predictions of the behavior of spilled oil at sea under different weather conditions.

DREAM (Dose-related Risk and Effects Assessment Model) - The model can account for releases of complex mixtures of chemicals, such as those associated with produced water.

OSCAR (Oil Spill Contingency and Response) – A scenario-based and 3-D statistical approach to objective evaluations of alternative response strategies and environmental risk assessment. Both physical and biological measures of success and effectiveness are provided. It uses the SINTEF OWM for weathering calculations.

DeepBlow - Computes the physical behavior of oil well blowouts in both deep and shallow water. A plume with entrained sea water, hydrate where appropriate, oil and dissolved gas rises and spreads from the release point, while droplets of oil detrain from the bubble plume forming a separate plume that rises towards the surface. In water exceeding about 400 m depth, hydrate formation and depth dependant gas solubility effects may significantly affect the plume dynamics.

Bubble models

DeepBlow is a 3-D bubble plume model. For the modeling of a 2-D bubble curtain, it is deemed better to apply a computational fluid dynamics (CFD) model. An example of such a simulation is shown in Fig. 8.1. For this demonstration simulation, discrete particles were modeled in a weak cross-flow, showing the consequences of currents on oil breaching (break-through). The results are similar to those reported by Jones (1973). Plume models must parameterize the bubble and plume properties to be viable within existing computational technology.

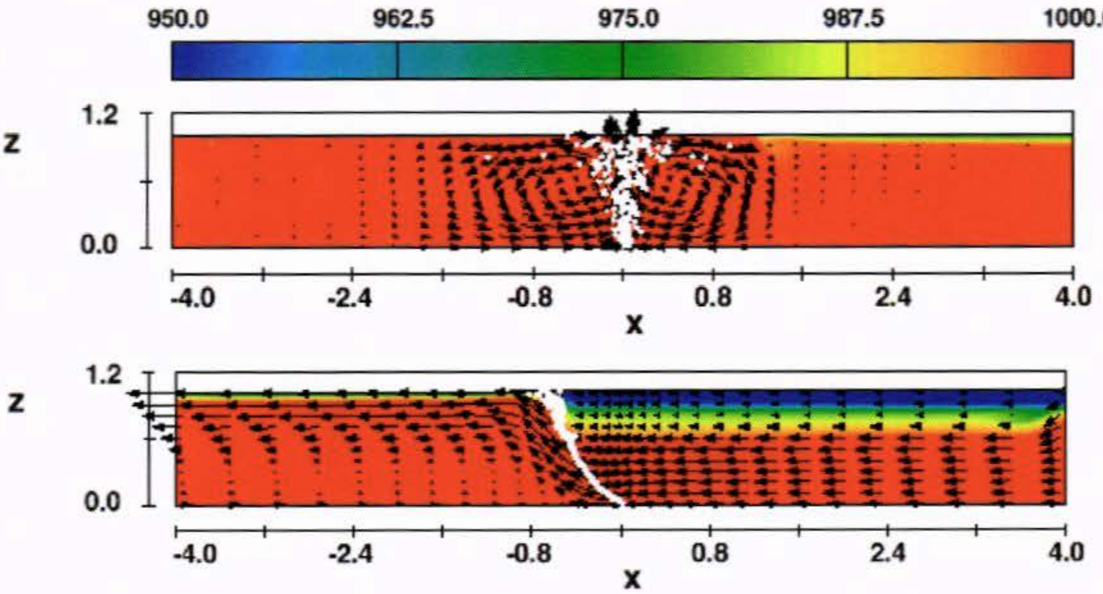


Figure 8.1. *Simulating bubble curtains with FLOW 3D. Top: Density scale, kg/m^3; middle: quiescent ambient; bottom: cross flow of 0.1 m/s.*

8.3 Flotation techniques

Air bubble flotation is a well known technology for confined oil-water separators (see Rubio *et al.*, 2002), and is also used for separation of (recovered) oil and seawater from oil spill recovery operations (see *e.g.* Gaaseidnes and Turbeville, 1999 and Nordvik *et al.*, 1996). Flotation may be described as a gravity separation process, where gas bubbles attach to oil droplets and decrease the density of the bubble-droplet body. Air-flotation in wastewater treatment and land-based oil-water separation is described and reviewed in Bennet (1988), Zabel (1992) and Rubio *et al.* (2002). Note that the methods and bubble sizes referred to below presumably pertain to fresh water. A bubble generated in the exact same manner in sea water will have a smaller diameter than in fresh water.

The bubble size is important for the efficiency of the flotation. For a given total volume of gas confined in bubbles, the total bubble surface area increases with decreasing bubble size and increasing number of bubbles. On the other hand, the buoyancy and nominal rise velocity of bubbles increase with size, for small bubbles (Fig. 5.1). Hence the appropriate bubble size and flotation method depends on the size distribution of the oil droplets and in which manner the air bubbles and oil droplets attach. Aggregation of multiple oil droplets (and air bubbles) also often plays an important role in the flotation process, and may increase the rise velocity considerably (see Section 5). Chemicals may be used to enhance flocculation as well as the attachment process between individual oil droplets and air bubbles.

Three different methods for bubble generation lead to the three traditionally most important flotation methods: electro(-lytic) flotation (EF), dispersed (induced) air flotation (IAF) and dissolved (pressure) air flotation (DAF). In EF bubbles of hydrogen and oxygen are generated by electrodes in an aqueous solution. Typical bubble diameter is 20-100 μm. An often mentioned advantage of EF is that the bubble generation does not require pressure or velocity differences, hence the bubble generation itself does not induce turbulence and shearing, which may disrupt aggregates/flocs. In IAF bubbles are generated by mixing water and injected air mechanically with a rotor/impeller, introducing intense turbulence. The bubble diameter is typically 700-1500 μm. So-called froth flotation may be considered a special case of IAF, where air is released directly into the fluid by a sparger. The bubble size here mainly depends on the orifice diameter and normally the bubbles are relatively large. In DAF bubbles are generated by a reduction of pressure of water pre-saturated with air, which then nucleates on particles producing bubbles with diameters 20-100 μm. For open ocean applications relevant to the BOB, we conclude that IAF is more appropriate. Turbulence produced from this method may form emulsions, which, under some circumstances are easier to collect than low-viscosity oils.

In removal of oil from wastewater by air flotation, the wastewater is pumped to a gravity separator, where most of the oil droplets rise to the surface to be skimmed off. Emulsified and dissolved oil components still remain. Chemical agents (emulsion breakers) are then used to break the emulsion followed by air flotation treatment (Bennet, 1988; Gopalratnam *et al.*, 1988). The flotation process consists of four steps that are also essential for open-ocean applications:

1. Bubble generation in the oily wastewater
2. Contact between the gas bubble and the oil droplet suspended in the water
3. Oil droplet attachment to the gas bubble
4. Rise of the air/oil combination to the surface where the oil is skimmed off

Stokes law is used extensively to describe the rise velocity and thus the efficiency in oil-water separation. However, it should be recalled that Stokes law is for the drag on solid spheres under creeping flow conditions ($Re \ll 1$), and that it gives incorrect results for the rise velocity as the bubble/droplet size increases, as the bubbles/droplets deform and become subject to impurities and surfactants, and as flocculation takes place (see *e.g.* Gaaseidnes and Turbeville, 1999). Typically, inappropriate application of Stokes law under-predicts the rise velocity.

Zheng and Zhao (1993) present a mathematical model for the oil removal rate (decrease in mg/l/s) in IAF separator cells. They state that the flotation of oil droplets depends on 1) the opportunity for contact/collision between oil droplet and air bubble and 2) if the kinetic energy of the oil droplets is high enough for them to 'break through the water film and enter the gas bubble' and thus become attached to and lifted by the air bubble. The model also accounts for the inability of IAF to recover droplets below a specific size (2 µm is indicated as a limit). Their model in its present form applies to separator cells only. The basic formulation and derivation appear quite general, however, and a model for the removal rate under open sea conditions may be developed in a similar way. The 'catching factor' appears to account for the 'attachability' between oil droplets and air bubbles, allowing for modeling the effect of adding chemicals. This process has to be studied in more detail for open sea applications.

Two more recent flotation methods that appear promising for oil-water separation are nozzle flotation and jet flotation. These produce medium sized bubbles of 400-800 µm and 100-600 µm, respectively (Rubio *et al.*, 2002, Bennet, 1988). It is unclear if these methods and the possible advantages they offer compared to EF, IAF and DAF rely on the flotation process taking place within a closed tank/separator cell.

8.4 Bubble flotation in open sea conditions

For application of air bubble flotation to aid recovery of oil spills at sea, it is essential to be able to describe and predict the oil droplet intrusion and size distribution, since the efficiency of the flotation and the appropriate method and equipment for bubble generation is determined by the required bubble size. These aspects may be different for different types of oil and different oil spill situations. In general larger droplets are easier to float than smaller ones. Adding chemicals is one way of increasing the efficiency for small oil droplets; generating sufficiently small air bubbles and subjecting the oil droplets to a sufficiently high number and concentration of bubbles, possibly in a sequence of releases, is an alternative. However, the attachment process is complex, and reported efficiencies of different methods and bubble sizes are not unambiguous. The need, feasibility and approval for using chemicals to enhance the flotation process also must be clarified. Note that, in contrast to chemical dispersants, the 'flotation enhancing' chemicals will also float to the surface and are thus in principle recoverable.

With respect to the traditional flotation techniques, IAF has the advantage of larger bubbles yielding a higher rise velocity and a greater potential for increasing capacity and efficiency by increasing the total volume of air released without application of chemicals (which may be neither feasible nor acceptable). IAF is further simpler than DAF since a pressurizer/saturator is not needed, and the cost of IAF is generally lower than that of DAF (Gopalratnam *et al.*, 1988). EF and DAF, on the other hand, may be better suited to lift the smaller dispersed oil droplets, although these may constitute only a small fraction of the dispersed oil volume.

Aside from attachment flotation, the bubble plume also creates an upwelling flow which will lift bubbles towards the sea surface. Oil droplets entrained in the upwelling flow and those that detrain on the upstream side, will be effectively brought to the sea surface even if they remain unattached. However, droplets that detrain on the downstream side of the bubble curtain will not.

To address this leakage mechanism may require multiple BOB curtains. Even attached bubble-oil droplet complexes face the risk of detrainment if the bubble buoyancy and hence upwelling velocity is sufficiently small.

9 Lessons from the literature review

The project plan for BOB is shown in Appendix B. This report is the first task to improve the basis for the remaining work. The primary BOB research tasks are:

A. Bubble-driven fluid motion: Laboratory experiments of bubble plume upwelling and outwelling flows (Fig. 1.1, left) and the development and validation of a semi-empirical numerical model of bubble curtain barrier efficiency, defined as percentage of oil recovered from a given spill.
B. Oil advection and flotation: Laboratory experiments with sparse bubbles and oil, (Fig. 1.1, right) integration of bubble-plume model with oil (spill) advection model and with models of flotation efficiency.
C. Prototype development and testing: Develop prototype from A and B, laboratory and field demonstration of prototype.

An existing test facility is being modified to reproduce the conditions for the present study (Fig. 9.1). In particular, a nearly uniform, turbulence-free flow must be achieved. Appropriate measures will be made to remove all oil upstream of the impeller.

The present literature review is intended to summarize the state-of-the-art to identify the needs for basic data/information that will enable the development of numerical models and possible new technology using air bubbles. The information from the literature will help to choose the range of current, oil and air forcings in the model studies.

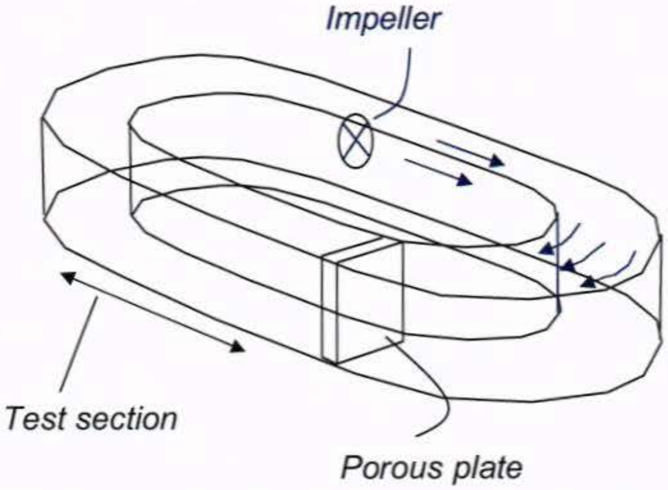


Figure 9.1. SINTEF experimental facility for the project. The test section is 50 cm wide, 100 cm high and approximately 150 cm long.

9.1 State of the art: (Commercial ventures)

Bubble oil barriers are produced, among others, by the German industries:
Hydroteknik Lübeck (http://www.hydrotechnik-luebeck.de/html/pneumatic_bubble_barriers.php) and AGOberlin (http://www.agoberlin.de/hydroair/gew_anl_schutz/ago_gwa002_e.html). There are very few technical data or performance results available from these to assess their applicability

to the present tasks. Some qualitative information on several commercial ventures, including cost analyses can be found in the (undated) RPI term project by B.M. Durham at web site http://www.rpi.edu/dept/chem-eng/Biotech-Environ/Environmental/boom.html.

The project objectives are reviewed here and amended to take into account newer information derived from the literature and idea exchanges at internal project meetings. In the reformulations, emphasis is placed on the realities of accomplishing real progress within the existing budgets of the project.

9.2 Research task A – Bubble-driven fluid motions

Many parameters affect the efficiency of a bubble oil barrier; however, our initial focus is on parameters that can be changed adaptively in the field: bubble size distribution, depth, and geometry. In real marine applications, booms can be designed to contain series of orifices that upon selective activation can create bubble size distributions spanning customized ranges as well as curtain geometries. Further, booms can be automatically lowered or raised.

Newer work shows that bubble processes are highly sensitive to bubble size, thus initial experiments will examine flows and bubble-curtain barrier efficiency for a range of bubble plumes spanning key bubble hydrodynamic behavior; turbulent ($r \sim 600$ µm), oscillatory ($r \sim 1250$ µm), erratic ($r \sim 2000$ µm) and spherical cap ($r \sim 5000$ µm). Conditions will be as close to appropriate field conditions as feasible – cold (but clean) seawater, with concern for tank wall adhesion. For each condition, associated fluid motions will be measured over the relevant spatial domains. Experiments will be conducted for point releases of chosen oil droplets and a range of bubble emission rates and configurations ranging from minimally interactive, to highly interactive (interactive is defined as wake-wake and wake-bubble). Because with increasing bubble rate, the plume dimensions grow (increased low momentum fluid entrainment), bubbles will be produced from a plate with a large number of nozzles spanning an area comparable to the depth-averaged plume cross section. From these experiments, the optimum bubble size for the given depth, with respect to emission rate, will be determined. The highly interactive regime will induce currents in the flume (Fig. 8.1).

Numerical modeling, has been discussed (Section 8.2). There are several theories for choosing appropriate parameters for modeling bubble plumes. The flow characteristics in the boil are particularly evasive (see *e.g.* Brevik and Kristiansen, 2002). The CDF studies (Fig. 8.1) will be used in conjunction with the planned laboratory tests.

9.3 Research task B – Oil flotation at sea.

Here, a sparse matrix of bubble orifices will be used to study the interactions (collisions) of bubbles and oil droplets in a laboratory setting. This (minimally interactive) scenario is of particular interest in terms of evaluating efficiencies for flotation in open sea conditions. Details of the modifications of the facility shown in Fig. 9.1 for these studies are being decided at this stage, as well as the choice of oil characteristics and drop sizes.

9.4 Research task C – Prototype development and testing.

At the present stage of the project, it is too early to amend the goals of the project as they are formulated in the proposal.

9.5 Summary

The present literature review is not exhaustive, but rather is focused on the possibilities of developing new technology for enhancing offshore oil spill recovery using bubbles. The zooplankton 'Bubble trawl' flotation concept developed by SINTEF Fisheries and Aquaculture may help to increase the efficiency of oil spill recovery operations, in particular by concentrating the surface emulsion layer and reducing the leakage under oil booms, but also by recovering otherwise dispersed oil and underwater spills at limited depths.

The size of the droplets to be floated, and the mechanisms by which they attach to air bubbles and coalesce, is decisive for the technique and equipment used for bubble generation. Oil properties may vary considerably for different types of oil, and the significance of oil properties for the cohesion and flotation efficiency needs to be studied further. Bubble generation by forced air injection is the preferred method to produce the desired larger bubbles with higher rise velocities and buoyant capacity. All methods may in principle be used for flotation of oil, as they are all in use in different types of industrial and wastewater oil-water separators. 'Natural flotation' of oil also takes place at sites of underwater hydrocarbon seeps, where larger, oil coated gas (methane) bubbles rise to the surface and form natural oil slicks.

The zooplankton to be surfaced in the bubble trawl are typically 0.5 mm in diameter and 2-3 mm in length (i.e. 500 μm and 2-3000 μm). The bulk of the oil to be floated is likely to be constituted by droplets with diameters in the range 50-1500 μm. Smaller and larger droplets also occur. The larger droplets may resurface themselves (but on the wrong side of the boom) while the smaller ones will not. Hence, although oil droplets are generally smaller, the size ranges of the most interesting zooplankton species and oil droplets to float are comparable, and considerable benefits may be gained from mutual development of zooplankton and oil spill flotation technologies.

We need details on the coalescence and bubble capture on and in the wakes of rising droplets, especially the growth to larger slip speeds and more effective surfacing of the droplets. On the basis of the information reviewed in this report, we will participate in a field study to gain valuable insight/data from a natural seep and a laboratory study is being made to provide useful data for the development of numerical tools that can help in the development of new technology for the application of bubbles to oil retrieval at sea.

10 Acknowledgements

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11 References

Alves, S.S., S.P. Orvalho and J.M.T. Vasconcelos, 2005. Effect of bubble contamination on rise velocity and mass transfer, *Chemical Engineering Science*, **60**, 1-9.

Amini, A, E. Bollart, J-L. Boillat and A.J. Schleiss, 2008. Dynamics of low-viscosity oils retained by rigid and flexible barriers. *Ocean Engineering*, in press.

Aseda, T. and J. Imberger, 1993. Structure of bubble plumes in linearly stratified environments. *J. Fluid Mechanics* **249**, 35-57.

Asher W.E. and P.J. Farley, 1995. Phase-Doppler anemometer measurement of bubble concentrations in laboratory-simulated breaking waves. *J. Geophys. Res.* **100,** 7045-7056.

Asher, W. E., L. M. Karle and B. J. Higgins, 1997. On the differences between bubble-mediated air-water transfer in freshwater and seawater, *Journal of Marine Research* **55**, 813-845.

Bennet, G.F., 1988. The removal of oil from wastewater by air flotation: a review, *CRC Critical Reviews in Environmental Control* **18,** 189-253.

Brevik, I. and Ø. Kristiansen, 2002. The flow in and around air-bubble plumes. *Int. J. Multiphase Flow* **28,** 617-634.

Bulson, P.S., 1961. Currents produced by an air curtain in deep water. *The Dock and Harbour Authority,* **42,** 15-22.

Clester, S.M., J.S. Hornafius, J. Scepan and J.E. Estes, 1996. Quantification of the relationship between natural gas seepage rates and surface oil volume in the Santa Barbara Channel. *EOS Transactions of the American Geophysical Union* **77**, 420.

Cross, R.H. and D.P. Hoult., 1971. Collection of oil slicks. *ASCE J. Waterways, Harbors and Coastal Eng. Div.* **97**, 313-322.

Daling, P. and F. Leirvik, 2006. Dokumentasjon og karakterisering av olje på sjø I forbindelse med testing av mekanisk oljevern – og dispergeringsutstyr ved NOFOs OPV-øvelse, 10-11 mai, 2006. – Tokt-/Observasjonsrapport. *SINTEF Report* STF80MK F06185. 64 pp. (In Norwegian.)

Delvigne, G.A.L., 1984. Oil spill protection of industrial water intake in harbour areas. *The Dock and Harbour Authority* **645(759)**, 237-241.

Delvigne, G.A.L. and C.E. Sweeney, 1988. Natural dispersion of oil, *Oil and Chemical Pollution* **4**, 281-310.

Evans, J.T., 1955. Pneumatic and similar breakwaters. *Proc. Roy. Soc. London, A* **231,** 457-466.

Fanneløp, T.K., 1983. Loss rates and operational limits for booms as barriers. *Applied Ocean Research*, **5**, 81-92.

Fanneløp, T.K. and K. Sjøen, 1980. Hydrodynamics of underwater blowouts. *Norwegian Maritime Res.* **8,** 17-33.

Fanneløp, T.K. and D.M. Webber, 2003. On buoyant plumes rising from area sources in a calm environment. *J. Fluid Mech.* **497,** 319-334.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger and N.H. Brooks, 1979. *Mixing in inland and coastal waters*, Academic Press. 483 pp.

Friedl, M.J. and T.K. Fanneløp, 2000. Bubble plumes and their interaction with the water surface. *Applied Ocean* Research **22,** 119-128.

Gopalratnam, V.C., G.F. Bennet and R.W. Peters, 1988. The simultaneous removal of oil and heavy metals from industrial wastewater by joint precipitation and air flotation, *Environmental Progress* **7**, 84-92.

Grammatika, M. and W.B. Zimmermann, 2001. Microhydrodynamics of flotation processes in the sea surface layer, *Dynamics of Atmosphere and Oceans* **34**, 327-348.

Grilli, S.T., T. Fake and M.L. Spaulding, 2000. *Numerical modelling of oil containment by a boom/barrier system: Phase III,* Final Technical Report submitted to U.S. Department of Transportation, Cambridge, MA, 185 pp.

Gaaseidnes, K. and J. Turbeville. 1999. Separation of oil and water in oil spill recovery operations, *Pure Appl. Chem.* **71**, 95-101.

Haberman, W.L. and R.K. Morton, 1954. An experimental study of bubbles moving in liquids. *Proc. Am. Soc. Civ. Eng.* **80(387)**, 379-427.

Hills, J.H. 1974. Radial non-uniformity of velocity and voidage in a bubble column. *Trans. Inst. Chem. Eng.* **52**, 1-9.

Hornafius, J.S., D. Quigley and B.P. Luyendyk, 1999. The world's most spectacular marine hydrocarbon seeps (Coal Oil Point, Santa Barbara Channel, California): Quantification of emissions, *J. Geophys. Res.* **104**, 20,703-20,711.

Hu, S. and R.C. Kintner, 1955. The fall of single liquid drops through water. *A.I.Ch.E. J.* 1:42-48.

Johansen, Ø. and B. Brørs, 2008. CFD simulations of oil boom containment. Submitted to *Ocean Engineering*.

Johansen, V. and S. Jansson, 2005. *Utvikling av bobletrål for fangst av raudåte*, SINTEF Fisheries and Aquaculture report no. SFH 80 FO.53049, Nov. 2005. 42 pp.

Johansen, Ø., 2000. DeepBlow – a Lagrangian plume model for deep water blowouts, *Spill Science & Technology Bulletin* **6**, 103-111.

Jones, W.T., 1972. Air barriers as oil spill containment devices. *J. Pet. Eng.* April, 1972, 126-142.

Kobus, H.E., 1968. Analysis of the flow induced by air-bubble systems. Ch. 65, part 3 Coastal Structures. Vol. II, *Proc. 11th Conf. on Coastal Engineering, London.*

Lee, C.M. and K.H. Kang, 1997. Prediction of oil boom performance in currents and waves. *Spill Science & Technology Bulletin,* **4**, 257-266.

Leifer, I.S., 1996 A *validation study of bubble-mediated air-sea gas transfer modeling*, Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA. 218 pp.

Leifer, I. and J. Boles, 2005. Measurement of marine hydrocarbon seep flow through fractured rock and unconsolidated sediment, *Marine and Petroleum Geology* **22**, 551-568.

Leifer, I. and R.K. Patro, 2002. The bubble mechanism for methane transport from the shallow sea bed to the surface: A review and sensitivity study, *Continental Shelf Research* **22**, 2409-2428.

Leifer, I and K. Wilson, 2007. Tides and the emission of oil and gas from an abandoned oil well: Nearshore, Summerland, California. *Mar. Poll. Bull.* **54**, 1495-1506.

Leifer, I., J.F. Clark and R.F. Chen, 2000a. Modifications to the local environment by natural marine hydrocarbon seeps, *Geophys. Res. Let*. **27**, 3711-3714.

Leifer, I., J.F., Clark and R.F. Chen, 2000a. Modifications to the local environment by natural marine hydrocarbon seeps, *Geophys. Res. Let.* **27**, 3711-3714.

Leifer, I., H. Jeuthe, S.H. Gjøsund and V. Johansen, 2008. Engineered and natural marine seep, bubble-driven buoyancy flows. *Journal of Physical Oceanography, Submitted*

Leifer I., R. Patro, and P. Bowyer, 2000b. A study on the temperature variation of rise velocity for large clean bubbles. *J. Atm. and Ocean. Tech.* **17(10)**, 1392-1402.

Leirvik, F. and A.G. Melbye, 2007. Evaluering av effektiviteten til oppsamlingsutstyr under NOFOs Olje På Vann Øvelse 2007. *SINTEF Report* STF80MK F07179. 25 pp.

Leitch, A.M. and W.D. Baines, 1989. Liquid volume flux in weak bubble plume. *J. Fluid Mech.* **205,** 77-98.

Male, S.L., 2008. *New bubble curtain for Svartisen hydropower plant.* Thesis, Dept. of Hydraulic and Environmental Engineering, NTNU, Trondheim. 110 pp.

Maxworthy, T., C. Gnann, M. Kürtem and F. Durst, 1996. Experiments on the rise of air bubbles in clean viscous liquids. *J Fluid Mech.* **321,** 421-441.

McDougall, T., 1978. Bubble plumes in stratified environments. *J. Fluid Mech.* **85**, 655-672.

McGinnis, D.F., J. Greinert, Y.Artemov, S.E. Beaubien and A. Wüest, 2006. Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? *J. Geophys. Res.* **111**, CO9007 doi:10.1029/2005 JC003183.

Milgram, J.H., 1983. Mean flow in round bubble plumes. *J. Fluid Mech.* **133,** 345-376.

Neumann, G. and W. Pierson, Jr., 1966. *Principles of Physical Oceanography.* Prentice-Hall, 545 pp.

Nilsen, J., A. Næss and Z. Volent, 1985. *Measurements of oil concentrations in the water column under breaking waves*, Norwegian Hydrotechnical Laboratory Report No. STF60 A85079, Trondheim, Norway. 37 pp.

NOFO: web site http://planverk.nofo.no/ (In Norwegian)

NOFO OoW Exercises 2003, 2005, 2006, 2007 and 2008. SINTEF reports STF66 F03052 (36 pp.), STF80MK F06011 (23 pp.), STF80MK F06185 (64 pp.), STF80MK F07179 (25 pp) and (In press, 18 pp.) (In Norwegian.)

Nordvik, A.B., J.L. Simmons, K.R. Bitting, A. Lewis and T. Strøm-Kristiansen, 1996. Oil and water separation in marine oil spill clean-up operations, *Spill Science & Technology Bulletin* **3**, 107-122.

Norlense: web site http://www.norlense.no/?id=76038470.

OED, 2003. *Utredning av konsekvenser av helårlig petroleumsvirksomhet i området Lofoten-Barentshavet. Sammendragsrapport*, Olje- og energidepartementet (Ministry of Petroleum and Energy) (In Norwegian). 120 pp. The summary report OED(2003) and all thematic sub-reports can be found at:
http://odin.dep.no/oed/norsk/p30006318/olje_gass/026031-080002/dok-bn.html

Patro, R. K., 2000. *The Hydrodynamics of Large Bubbles and Air-Sea Gas Exchange.* PhD Thesis, National University of Ireland, Galway, Ireland. 269 pp.

Patro, R. K., I. Leifer and P. Bowyer, 2002. Better bubble process modeling: Improved bubble hydrodynamics parameterization, *Gas Transfer at Water Surfaces*, **127**, 315-320.

Rensen, J. and V. Roig, 2001. Experimental study of the unsteady structure of a confined bubble plume. *Int. J. Multiphase Flow* **27**, 1431-1449.

Riess, I.R., and T.K. Fannelop, 1998. Recirculating flow generated by line-source bubble plumes. *J. Hydraulic Engineering* **124**, 932-940.

Rowe, R.D., J.Y.C. Poon and C.J. Laureshen, 1989. A simple method for predicting bubble plume properties. *Proc. 23rd Int. Assoc. Hydr. Res.*,Ottawa, D-23-30.

Rubio, J., M.L. Souza and R.W. Smith, 2002. Overview of flotation as a wastewater treatment technique, *Minerals Engineering* **15**, 139-155.

Sadhal, S. and R.E. Johnson, 1983. Stoke's flow past bubbles and drops partially coated with thin films. *J. Fluid Mech.* **126**, 237-250.

Seol, D.G., Bhaumik, T., C. Bergmann, and S.A. Socolofsky, 2007: Particle image velocimetry of the mean flow characteristics in a bubble plume. *J. Engr. Mech.* **33**, 665-676.

Simiano, M., R. Zboray, F. De Cachard, D. Lakehal and G. Yadigaroglu, 2006. Comprehensive experimental investigation of the hydrodynamics of large-scale, 3D, oscillating bubble plumes. *Int. J. Multiphase Flow* **32**, 1160-1181.

Singleton, V.L., P. Gantzer and J.C. Little, 2007. Linear bubble plume model for hypolimnetic oxygenation: Full scale validation and sensitivity analysis. *Water Resources Research,* **43**, W02405, doi:10:1029/2005WR004836.

Singsaas, I., Ø. Johansen, S.Ramstad, T. Nortug, J.L. Resby and P.S. Daling, 2008. Helhetlig forvaltningsplan for Norskehavet – sector petroleum og energi. SINTEF rapport F5443. (In Norwegian) 108 pp.

Sommerville, M., 1999. Orimulsion containment and recovery, *Pure Appl. Chemistry*, **71**, 193-201, cf. http://www.oil-spill-web.com/flemingco/articles/orimulsion1.htm also.

Stortingsmelding nr. 8 2005/06. The white paper management plan for Lofoten-Barents Sea. 140 pp. (In Norwegian) See also web site: http://www.regjeringen.no/Rpub/STM/20052006/008/PDFS/STM200520060008000DDDPDFS.pdf

Sverdrup, H.U., M.W. Johnson and R.H. Fleming, 1942. *The Oceans; Their Physics, Chemistry and General Biology*, Prentice-Hall. 1087 pp.

Sægrov, S., 1978. *Boblegardin i sjiktet vann.* SINTEF Report STF60 F78015. 30 pp.

Taylor, G.I., 1955. The action of a surface current used as a breakwater. *Proc. Roy. Soc. London,* ***A*** **231,** 466-478.

Topham, D.R., 1975. Hydrodynamics of an oil well blowout. *Beaufort Sea Project, Frozen Sea Research Group, Dept. of the Environment, Victoria, B.C. Technical Report 33.* 52 pp.

U.S. Coast Guard, 1971. *Heavy-duty oil containment systems: pneumatic barrier system.* Report No. 714102/A/094, U.S. Coast Guard Office of R&D Contract DOT-CG-00-490-A to Oil Containment Div., Wilson Industries, Inc., 322 pp. + App.

Vazquez, A., R.M. Sanchez and I. Leifer, 2008. Analysis of bubble growth phases on the related dynamic forces. (Submitted)

Vos, R.J., 2005. *Comparison of 5 oil-weathering models*, RIKZ report no. RIKZ.ZD/2005.011w, July 2005. 49 pp.

Wüest, A.J., N.H. Brooks and D.M. Imboden, 1992, Bubble plume modeling for lake restoration. *Water Resources Res.* **28**, 3235-3250.

Zabel, T.F., 1992. Flotation in water treatment, pp. 431-454 In: *Innovations in Flotation Technology*, P. Mavros and K.A. Matis (eds.), Kluwer Academic Publishers.

Zheng, Y.-Y. and Z.-Z. Zhao, 1993. A study of kinetics on induced-air flotation for oil-water separation, *Separation Science and Technology* **28**, 1233-1240

Zutic, V.B., B. Cosovic, E. Marcenko and N. Bihari, 1981. Surfactant production by marine phytoplankton. *Marine Chemistry* **10**, 505-520.

Appendix A. Organization of the bubble oil boom (BOB) project.

Institution	**Person**	**Competence**	**Role**
SINTEF Fisheries and Aquaculture (SFH)	Svein Helge Gjøsund	Hydrodynamics, wave kinematics, bubbles, project manager for similar ongoing project	Project manager, participate in most research activities
	Eduardo Grimaldo	Experimental techniques	Participate in lab and field activities
	Pål Lader	Hydrodynamics, experimental and imaging techniques, DPIV	Co-responsible for lab- and field tests
	Thomas McClimans	Hydrodynamics and physical oceanography	Scientific advisor, member of steering committee
SINTEF Marine Environmental Technology (SMET)	Per Daling	Behavior of oil on water and oil spill response technology	Sub-project leader literature review and laboratory testing
	Øistein Johansen	Oil spill modeling, numerical modeling	Sub-project leader numerical models & modeling
	Bård Brørs	Hydrodynamics, numerical modeling	Co-responsible for numerical modeling
	Merete Ø. Moldestad	Chemical properties of oil and oil spills Research leader Oil Spill Contingency	Quality assurance SMET
	Tove Strøm	Chemical properties of oil and oil spills, Research Manager SMET	Project leader SMET Member of steering committee, Project QA
	Frode Leirvik	Chemical engineering, experimental setup	Planning and carrying out of laboratory experiments
UCSB, Marine Science Institute	Ira Leifer	Bubble theory and processes, measurement techniques	Participate in most research activities
University (TBD)	NN (TBD)	Numerical modelling (fluid mechanics; chemical engineering; mathematics)	PhD student
StatoilHydro	**Frode Engen**	Advisor for oil spill contingency	Financing partner , member of steering committee
Eni Norway	**Ole Hansen**	Advisor for environment and oil spill response	Financing partner , member of steering committee
NOFO	**Hans Valter Jensen**	R&D-leader NOFO. Oil spill response	Member of steering committee
NOFI Tromsø AS	**Olav Småbakk**	Development of Oil spill response technology / manufacturer	Observer in steering committee
NorLense AS	**Hugo Svendsen**	Development of Oil spill response technology / manufacturer	Observer in steering committee

Appendix B. Task-timeline organization of BOB (from project proposal).

		2008				2009				2010				2011			
	Activities	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	Year 1 (2008)																
1	Literature review	x															
2	Preliminary numerical model studies, concept evaluation		x														
3	Initial flotation experiments		x														
4	Initial barrier experiments		x	x													
	Summarize and conclude from Year 1				1												
	Year 2-4 (2009 -2011)																
5	Extended flotation experiments					x	2		x	3							
6	Extended barrier experiments						x	4		x	5						
7	Numerical modeling					x	x	x	x	x	x	6					
8	Model analyses, design prototype										x	x					
9	Full scale prototype test – field tests											x	x		7		
10	Final reporting and publication													x	x		
11	PhD study					x	x	x	x	x	x	x	x	x	x	x	x
	Industrializing the results (e.g. IFU-project)						x	x	x	x	x	x	x	x	x		