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A STUDY OF FACTORS INFLUENCING OIL SUBMERGENCE

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ABSTRACT

A series of experiments is described which had the general objective of elucidating the factors which cause oil from a spilled slick to break up into drops or "pans" and subsequently become partially submerged and thus less detectable on the ocean surface. The experiments included studies of the break up of a slick on prolonged weathering on a turbulent water surface in the laboratory and studies of the submergence behaviour of simulated oil masses (using a wood block and bags of ballasted lard) and simulated oil drops (using plastic balls). The results are discussed and a tentative model proposed. It is suggested that the conventional concept of oil existing on the water surface primarily as a continuous slick is often erroneous and that substantial quantities of oil may exist, at times, as discrete masses varying in size from millimetres to tens of centimetres, distributed on and under the water surface. An explanation is proposed to acount for this behaviour.

RÉSUMÉ

On a décrit une série d'expériences ayant pour but général de déterminer les raisons pour lesquelles, lors d'un déversement d'hydrocarbures, la nappe de pétrole peut se briser en gouttes ou en "poêlons" et devenir ensuite partiellement submergée, ce qui la rend moins décelable à la surface de l'océan. Les expériences comprenaient des études en laboratoire sur le bris d'une nappe à la suite d'une altération prolongée à la surface d'une eau tubulente ainsi que des études sur la submersion de quantités de pétrole simulées (à l'aide d'un morceau de bois et de sacs de lard lestés) et de gouttes de pétrole simulées (des balles de plastique). Les résultats sont discutés, et un modèle provisoire est proposé. On avance l'hypothèse que le pétrole déversé dans l'eau ne forme pas toujours une nappe continue, comme on le croyait, et que d'importantes quantités de pétrole peuvent parfois former des masses discrètes, d'une épaisseur variant entre la surface et la subsurface de l'eau. Une explication est proposée pour expliquer ce phénomène.

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1 INTRODUCTION

1.1 BACKGROUND

It has been observed that under certain environmental conditions, some viscous and dense oils may form large "blobs" or "rafts" or "pans" which tend to "float" just under the water surface. Such behaviour was observed in the "Kurdistan" incident in 1979 (Reimer et al., 1981, Vandermuelen 1980). This phenomenon is important because it may render the oil invisible to the eye or to remote sensing systems, thus it may be impossible to plan appropriate countermeasures or provide adequate warning of impending oil arrival to locations which may be impacted. There is also a lack of fundamental understanding of the mechanism of formation of these "pans". It is important to document the factors which combine to create conditions in which an oil forms pans rather than a slick. Further, it would be useful to understand what factors influence the size of these pans, and the extent to which they are submerged.

Environment Canada has sponsored a number of studies to elucidate this phenomenon, notably the reports by Juszko et al. (1983), Juszko (1985) and Wilson et al. (1986). While considerable progress has been made, many unanswered questions remain. For example, Wilson et al., noted that when a large pan of simulated oil of specific gravity in the range 0.9 to 1.0 was tethered in a wave field it was continually overwashed by water and gave the appearance of being submerged. In this study a series of experiments has been designed and conducted to further elucidate these phenomena. In particular, the study addressed three issues.

(i) Is it possible to measure, quantify and correlate the effects of oceanic and oil properties on the submergence or overwashing phenomena observed by Wilson et al. (1986)?

(ii) Is it possible to conduct laboratory experiments to investigate the onset of pan formation and thus elucidate what combination of factors contribute to pan formation at sea?

(iii) Can a mathematical model be developed?

(iv) Recognizing the impossibility of simulating oceanic conditions in the laboratory, can this laboratory work form a basis for the design of at-sea experiments which will provide more reliable data about the behaviour of oil pans during exposure to real oceanic conditions?

1.2 EXPERIMENTAL APPROACH

To answer these questions a series of experiments was designed and conducted (and are described in subsequent sections) as follows.

(i) Overwashing

Initially it was proposed to construct "oil pans" of variable size and density from wood, hollowed out to accept ballast, and study their behaviour, both tethered and free-flowing, in a wind wave tank. Maximum raft width was constrained by the available tank width, to 60 cm. The degree of submergence was measured optically by determining the absorption of light between the raft and the surface by dyed water. Three approaches were envisaged.

(a) Illumination from above, reflection at the raft, then sensing from above.

(b) Illumination from a light source within the raft and sensing above.

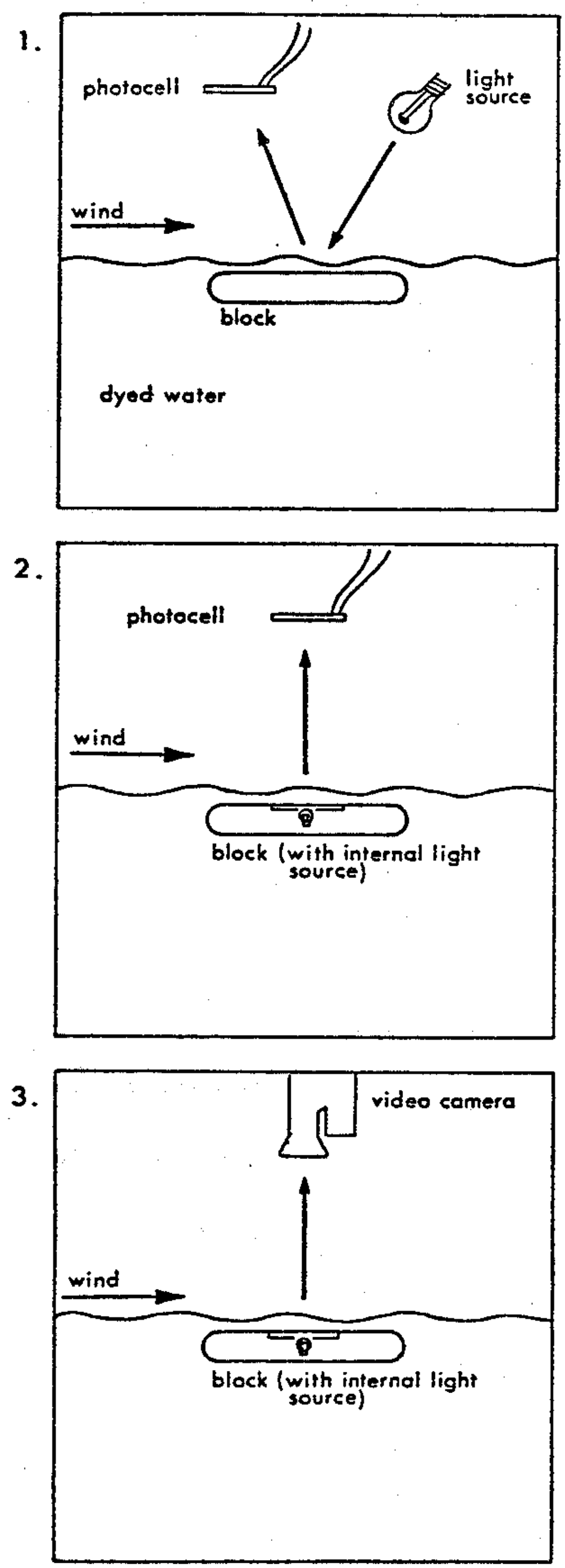
(c) Direct video photography from above with calibration.

These methods are shown in Fig. 1.1. Method (a) has the disadvantage that some light is reflected from the water surface, but it is very simple. Method (b) is more reliable but requires a light source in the raft. Method (c) is less quantitative but it gives a good, direct picture of the raft including time and position variations in water thickness over the raft.

Results were obtained using system (a) but a number of problems became apparent. The signal changes rapidly as waves wash over the surface, as reflection occurs at the water surface, and as the pan tilts. It is difficult to conduct the experiments with a free-flowing untethered pan. It was also time-consuming to construct a large number of pans.

Accordingly it was decided to investigate the use of direct video photography using various densities and sizes of pans in an untethered condition. It was impractical to use actual oil pans, thus a simulated material was sought. Some effort was devoted to the use of gelled mixtures of water and an alcohol such as methanol or ethanol which could be made up to the required density. A dye could also be added to enhance visibility. Suitable cross linking polymers were obtained and some success was achieved but it became clear that the development of a recipe for the preparation of plastic

Figure 1.1: Three Methods of Determining the Extent of Overwashing



gelled pans of a variety of properties and sizes was a study in itself requiring more time than was available. A simple solution was to make pans out of lard (used in domestic cooking) contained in heat-sealed plastic bags with no air space. These pans could be made in almost any size or shape greater than a few centimeters. Density could be increased by adding lead weights or another suitable ballast material such as sand. This approach has the additional advantage that lard is not an environmentally noxious substance thus there should be little concern with its use in field trials.

For smaller particles, plastic spheres of high density polyethylene were purchased and used directly, or in some cases weighted by gluing sand to their surface.

It was thus possible to investigate the submergence behaviour of a variety of sizes of pans of varying density with a view to establishing quantities such as average or maximum depth of submergence, or time of submergence. These results are reported later.

In a separate complementary study, a series of experiments was conducted to investigate pan formation. It was believed that oil slicks experience one of, or a series of, several fates or behaviour regimes depending on their susceptibility to several competing processes, and on their changing physical chemical properties. Oil spill models have been developed by several workers, including us, in an attempt to simulate this behaviour but none has been totally successful. The basic processes which control behaviour are;

(i) Evaporation (especially of volatiles)

(ii) Dissolution (especially of aromatics)

(iii) Water uptake to form mousse

(iv) Shearing or dispersion into small oil drops

(v) Recoalescence of oil drops to form larger masses

The oil's density and inherent viscosity strongly influence the rates of these processes, as do weather, temperature and salinity conditions. The formation of oil pans was suspected to be due to the predominance of process (v) which implies that the oil has a chemical/interfacial composition which favours coalescence and is sufficiently viscous that it resists deformation and dispersion (Process iv).

To elucidate these phenonmena an apparatus was assembled consisting of a glass walled tank of dimensions 120 cm deep by 47 cm square with an oscillating hoop wave generator. Various oils were investigated in the system, observations and appropriate analyses being made as a function of time.

The final tasks were the interpretation of the results, the assembly of the results into a mathematical model, the suggestion of conditions for oceanic tests and the recommendation of further research.

2 EXPERIMENTAL SECTION

2.1 OVERWASHING TESTS: BALLASTED WOOD PANS

In this study an attempt was made to investigate the depth of overwashing by using a simulated oil pan consisting of a ballasted wood block. The pan was fashioned from maple wood to give a disc of diameter 25 cm, and thickness of 5 cm, with rounded edges. It is shown in Fig. 2.1. The block contained a cavity to allow ballast, in the form of ball bearings, to be added without changing the volume. A rubber stopper compression plug was used to seal the opening to the cavity. The specific gravity of the block could thus be set at a minimum of 0.750 to a maximum of 1.000 by adding the appropriate number of ball bearings. The wind-wave tank (Fig. 2.2), contained the floating pan, and had wind speeds set by the insertion of screens of different porosity into the intake of the fan. Runs were carried out at four wind speeds of 13.5, 10.5, 6 and 0 m/s. Since the wind speeds are non-uniform along the length of the tank, these should be considered as average velocities, with a variation of 5%. The still water depth in the tank was established at 61 cm.

The waves were generated only by wind action and had a relatively low amplitude of a few cm. After this series of tests it was decided to install a wave generator to increase the wave amplitude. All wood pan tests were done with wind-waves only.

After initial observation and picture-taking, the amount of water washing over the block at each different condition was measured. The first attempt to measure water cover involved floating the tethered block under the photocells. This allowed the block to be kept in a relatively stationary

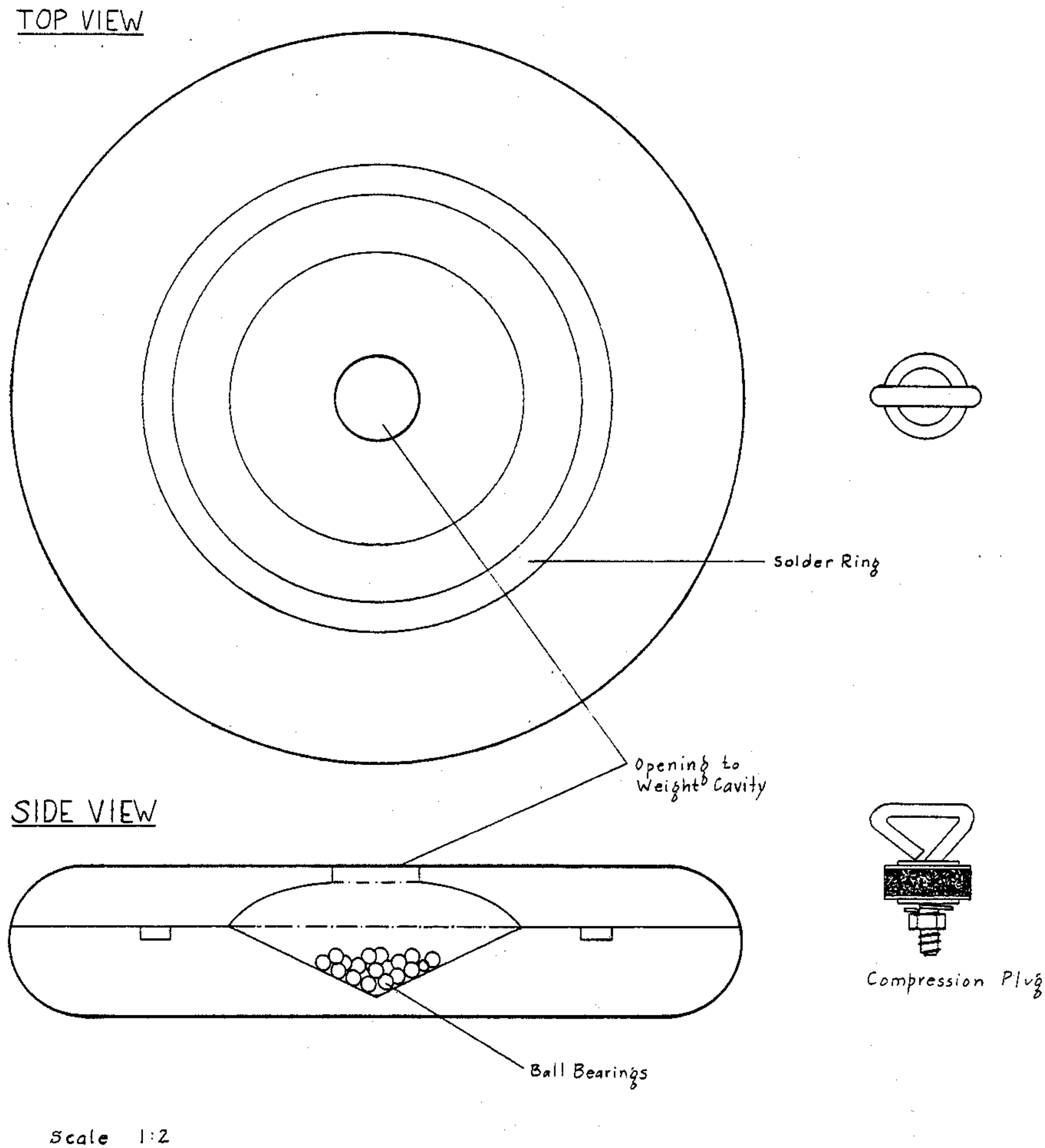


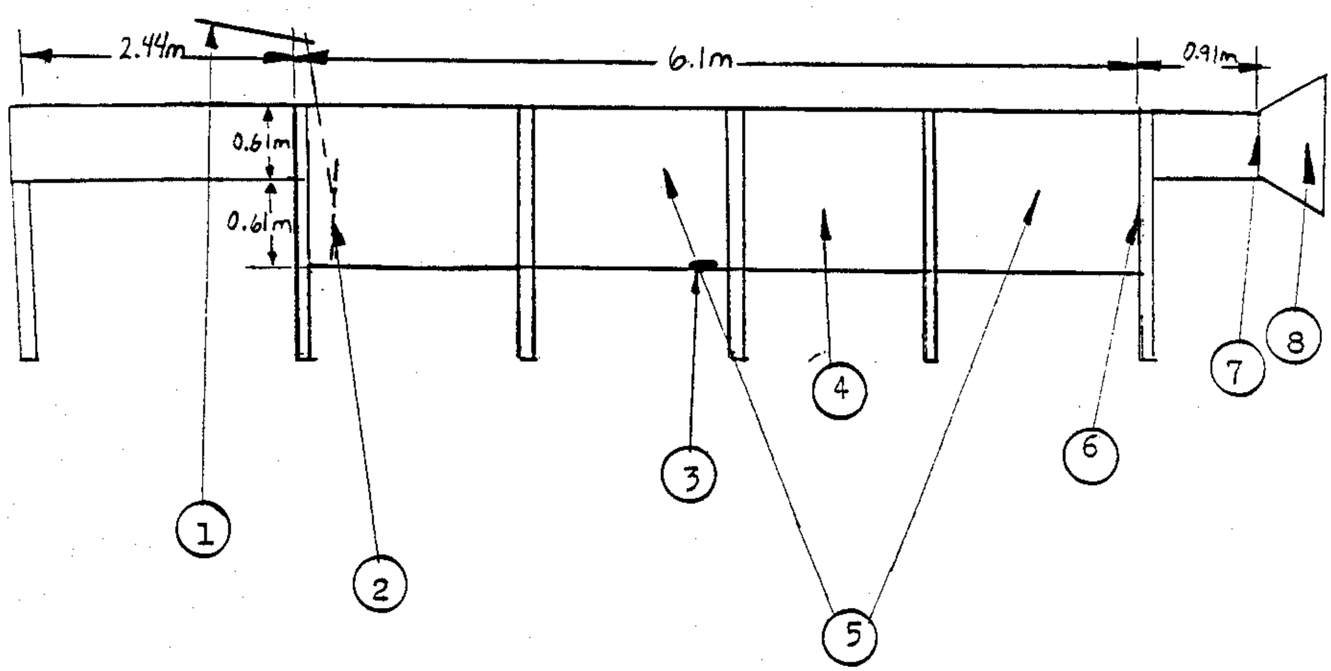
Figure 2.1: Ballasted Wood Block

Figure 2.2: The Wind Wave Tank

1) Wave Generator Push Rod
2) Wave Generator Paddle
3) Drain
4) Measurement Grid
5) 1/2" Plate Glass Walls
6) Wave Reflecting Wall
7) Air Flow Reducing Mesh Plate
8) Aerovent LS-248 Fan

* The wind speed is controlled by various screens

Screens	Wind Speed (m/s)
0	13.5
2	10.7
5	6.0



position beneath the cells. A 150 W General Electric reflector floodlight was placed 25 cm from the surface of the water, and 2 photocells (Eftonscience No. D31,276, 10 cm diam., 2 amps, 0.42 volts) connected in series were connected outside the tank to a Dynascan 283 Digital Multimeter. The cells faced the upper surface of the pancake, and were placed 63 cm above the water surface and 4.32 m from the front end of the tank. A red filter was placed directly in front of the cells, and methylene blue was added to the water in order to filter out the red component of the floodlight. The effect of this was a decrease in the voltage output of the cell as more water covered the block, since the cells responded to the intensity of the reflected red component of the light.

The block and cells were calibrated in still water conditions by fixing the block to a moveable arm permitting precise vertical movement. By measuring the vertical displacement of the block above the water surface, the voltage output of the cells could be plotted against depth of water cover to give the required calibration curve. Three 220 uF capacitors connected in series provided a 660 uF smoothing capacitance across the cells. The block was placed at the upper end and allowed to float down the tank when the fan was turned on. By adjusting the length of the tether, the block was brought into a position under the cells, where a voltage reading was taken. In the experimental readings, the voltage measured at each condition was compared to that on the calibration curve for the block in still water, and the average still water depth for each condition determined.

It was believed that the tethering of the block will produce different results from that of untethered conditions, especially at sea. To investigate this, the cells were connected to a Honeywell Electronik 196 chart recorder, and the block was floated under the cells, starting from a stationary position at the end of the tank. There was no tethering. A 75 W light replaced the previous lamp, and the cells were recalibrated. For these runs, the tank was refilled with fresh water, to which 1.7 g of methylene blue were added. In order to ensure that the block passed under the cells at the point where calibration took place, two strands of wire were placed on either side of the block during calibration, and left as markers during the runs. The block was floated under the cells several times in an effort to induce it to pass unhindered through the markers. The recorded output appeared as a period of noise, corresponding to surface reflection, followed by a sharp peak when the block was underneath the cells, followed by more noise. The maximum output for the run was compared with the calibration curve to give the approximate depth of wash over the block. An additional change for these runs was the removal of the capacitors, since the block was not underneath the cells long enough for the maximum volatage to be reached, due to the large time constant of the photocell system. In order that the maximum voltage obtained during the run was the reading to be used for the comparison, the block was placed in such a position during calibration that the maximum cell outputs were obtained, i.e. the block's position corresponding to maximum cell output during the run was the same location at which calibration took place.

For the untethered situation, the block was floated down the tank under the action of wind and waves only. The velocities of the block were measured at each wind speed and density, and the surface drift velocities were calculated by measuring the time for small pieces of wax paper to float a distance of 3 m down the tank.

The results are given later in section 3.2.

2.2 OVERWASHING TESTS: DEVELOPMENT OF AN OIL SIMULANT

It was decided to devote some effort to developing a relatively inexpensive and environmentally acceptable method of simulating oil masses.

The first idea was to prepare methanol-water solutions of known specific gravity and heat-seal these solutions into polyethylene bags of the desired size and shape. This was successful, but tests in the tank showed that the bags deformed easily in response to wave action, thus they did not simulate the behavior of more rigid oil pans. The effect of this elasticity is not known but it is judged to be an undesirable (and ultimately unnecessary) variable.

A thickening agent was sought to "gel" the solution. Solid polyvinyl alcohol was obtained from the Baker Chemical Company, dissolved in hot water to give a 7% w/v solution and saturated boric acid solution was added as the gelling agent. A cross-linked borate ester gel formed on the addition of sodium hydroxide solution. Various proportions of the reagents and temperatures were tested. The gels obviously did not have a homogeneous degree of cross-linking since they varied in stiffness with some lumps of hard gel and other more fluid parts. Air bubbles were also inadvertantly trapped in the gel, significantly affecting the mean density.

It is believed that with proper control it should be possible to make gelled pans of any desired density, size and shape. These pans could be enclosed in heat-sealed bags or they could be used directly. Presumably, they could be coloured with dyes to improve visibility.

Another idea was to use large concentrations of gelatine to increase the rigidity of the pan material. A number of other stiffening agents are used in the food, paint and general chemical industries which could be investigated, but time did not permit this to be pursued.

The most successful system tested was the use of lard in polyethylene bags, heat-sealed and allowed to solidify, the shape being adjusted as desired. The specific gravity of lard is 0.91, thus to increase and vary the density, sand was added. It proved to be difficult to add the sand evenly, thus the pans became "lop-sided" when floated in the water. Another problem was that some residual air was always left in the bag, but this could be removed by pricking a small hole and resealing. This problem ultimately proved to be advantageous because it was found that the final pan density could be adjusted to close density tolerances by injecting some air with a syringe and resealing. The best ballast was found to be flat rectangular pieces of lead, 0.16 cm thick which could be cut to the desired size, inserted into the bag and positioned centrally within the lard. A final density adjustment could be made by injecting or removing air and pans of specific gravity, 0.91 to 0.99 could be made. The pans were white and thus could be easily seen in the tank. The depth of submergence was best determined by dying the water with methylene blue and observing the depth of colour with a calibration. Fig. 2.3 shows two typical lard pans with lead ballast.

The calibration consisted of a piece of stiff white graduated plastic inserted at an angle in a container of dyed water, thus giving a variation of depth and colour which could be compared with the submerged pan.

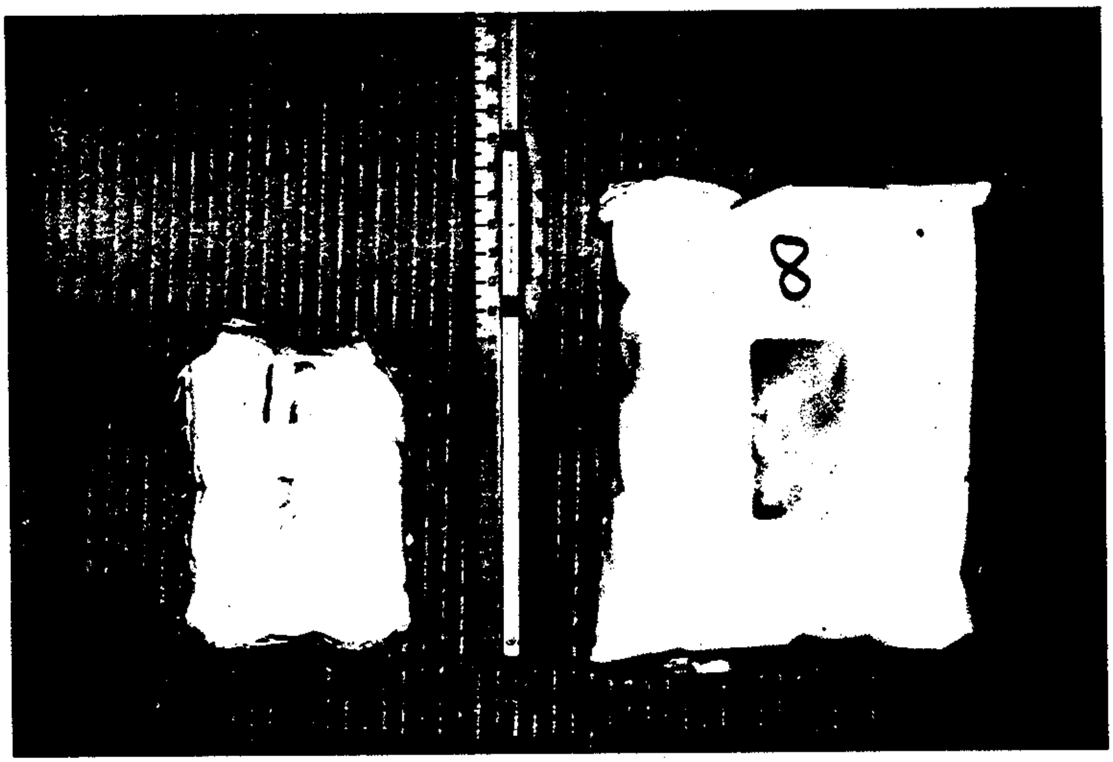


Figure 2.3: Photograph of Lard Bans with Lead Ballast

2.3 OVERWASHING TESTS: LARD PANS

A number of tests was conducted in the wind wave tank with various pans, wind speeds (but mostly 5 m/s) and wave frequencies (but mostly 1.4 Hz). The wave height was 15-20 cm. The pans were observed from above and the side by eye and by video (Kodak Camcorder 2400) and a judgement made of the depth of overwash by comparison of the mean colour intensity over the pan with the calibration. The use of the naked eye proved to be preferable because the colours could be better discriminated and there were fewer problems with stray light and reflections. A wide angle camera lens would have been desirable to enable the pan and the calibration strip to be viewed simultaneously.

Some pan rising velocities were also measured by timing the journey from release at the bottom to the surface.

2.4 OVERWASHING TESTS: PLASTIC BALLS

After some investigation, it was discovered that a range of solid plastic balls of various sizes (1/8 inch to 2 inches diameter) and densities were available commercially from PC Product Components Corporation, 30 Lorraine Avenue, Mount Vernon, N.Y. 10553. Quantities of low and high density polyethylene balls were obtained of various sizes (0.317 cm to 2.54 cm) and of specific gravity appoximately 0.90-0.95. It was found that there was typically a 1% variation in specific gravity between supposedly identical balls.

Measurement of diameter and mass proved to be inaccurate, and the best method of determining density involved floating the balls in water, then adding methanol with stirring, until the ball became neutrally buoyant. The solution density was then measured with a hydrometer.

The balls were painted, i.e. colour coded, to facilitate identification. To obtain higher densities, the balls were coated with epoxy glue, rolled in sand and allowed to set. In this way specific gravities in the range 0.93 to 0.996 could be obtained. Densities could be reduced by breaking off the sand particles. Before and after each experiment the ball densities were measured to check that they had remained constant. Table 2.1 gives the ball dimensions.

A number of tests was conducted in the wind-wave tank under similar conditions to those used for lard pans.

It was hoped that the use of lard pans and plastic balls would cover the spectrum of oil pan or droplet sizes which are relevant to this study.

2.5 OIL PAN FORMATION TESTS

The studies were conducted in a glass walled tank 120 cm deep by 47 cm square as shown in Fig. 2.4 An oscillating hoop system was used to generate waves at the water surface and confine the oil to the centre. The hoop was oscillated with an amplitude of 0.25 cm with a frequency of 3.7 Hz using a cam system driven by a 1/4 HP electric motor coupled to a Zero Max variable speed drive. The temperature was 20°C.

In the experiments, a known volume of crude oil or crude oil mixture was added to the water surface and oscillation started. Visual and photographic observations were made at various times to monitor the condition of the oil. Oil samples were taken periodically for analysis by gas chromatography. At the end of the test, which varied from 2 to 7 days, the oil was recovered and its density, water content and composition were measured. The oils studied were

Table 2:1 Ball Dimensions

Colour		Diameter (cm)	Density (g/cm³) Run 1,2	Density (g/cm³) Run 3,4,5,6,7,8
Blue (B)	1:	2.54	0.918	0.993
	2:	1.905	0.918	0.993
	3:	1.27	0.918	0.987
	4:	0.635	0.927	0.965
	5:	0.3175	0.915	0.934
Red (R)	6:	2.54	0.918	0.985
	7:	1.905	0.918	0.990
	8:	1.27	0.918	0.980
	10:	0.3175	0.918	0.946
Yellow (Y)	11:	2.54	----	0.973
	12:	1.905	----	0.955
	13:	1.27	----	0.969
	15:	0.3175	----	0.969
Green (G)	16:	2.54	----	0.978
	17:	1.905	----	0.964
	18:	1.27	----	0.995
	20:	0.3175	----	0.955
Orange (O)	21:	2.54	----	0.950
	22:	1.905	----	0.981
	23:	1.27	----	0.996
	24:	0.635	0.930	0.930
	25:	0.3175	----	0.982
Silver (S)	26:	0.635	----	0.994
	27:	1.27	----	0.959
Purple (P)	28:	0.635	----	0.984
	29:	1.27	----	0.984
Dark Brown (DB)	30:	0.635	0.917	0.982
	31:	1.27	----	0.992
Light Brown (LB)	32:	0.635	----	0.980
	33:	1.27	----	0.992

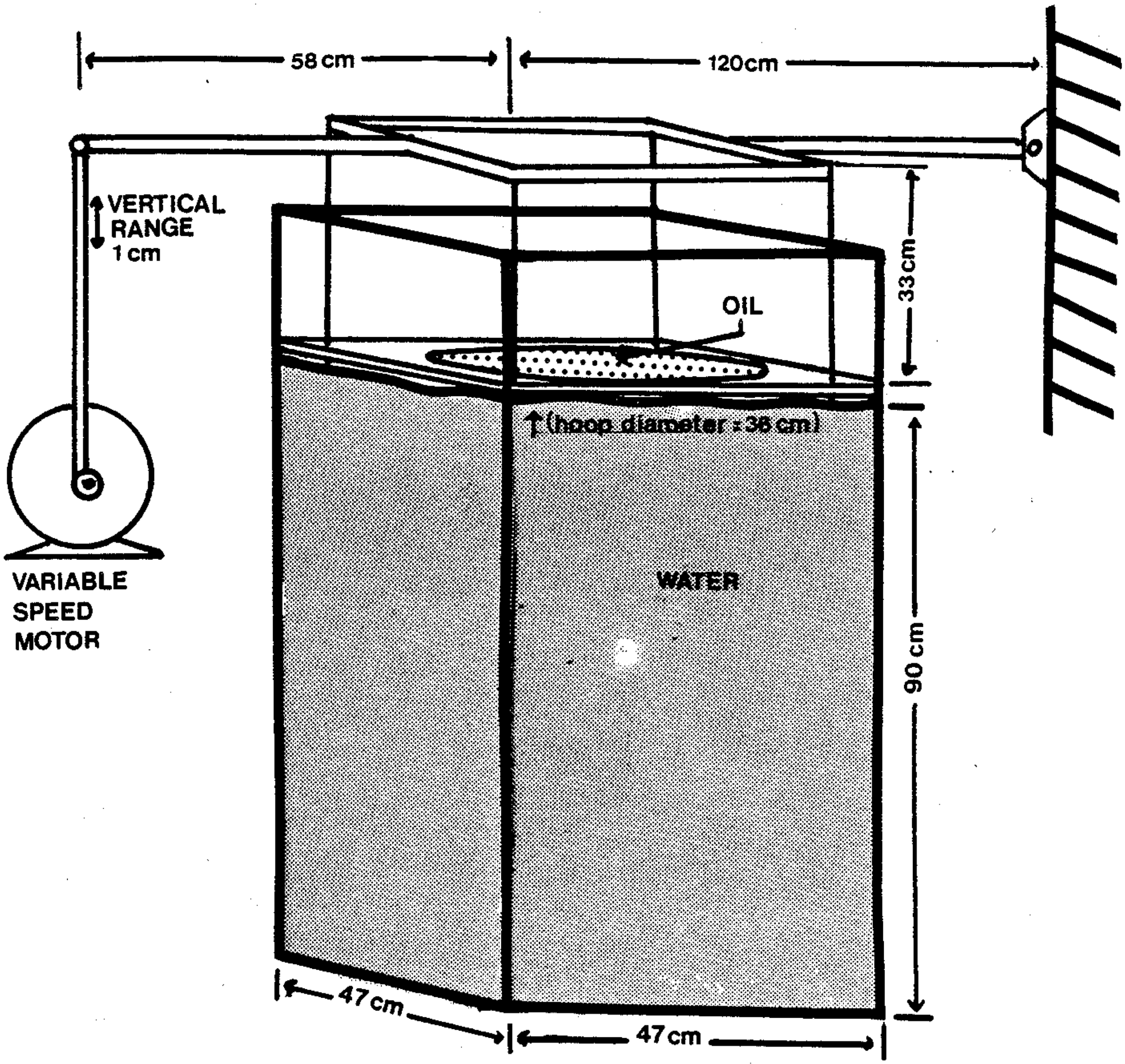


Figure 2.4: Diagram for Glass Tank for Oil Pan Formation Tests

principally weathered EPS Standard oil and mixtures of that oil with various other hydrocarbon components which are believed to influence pan formation.

Some tests were done in beakers in an attempt to obtain more results faster but this proved to be impractical. Tests were also done with UV light to investigate the influence of photolysis. Specific oils and test conditions were as follows (Table 2.2.).

Table 2.2: Oil Pan Formation Test Conditions

Experiment	Oil	Initial Oil Volume
1	EPS-10% Weathered	50 mL
2	EPS-10% Weathered	50 mL
3	EPS-10% Weathered	100 mL
4	EPS-10% Weathered, 4.3% Paraffin Wax	212 mL
5	EPS-10% Weathered, 25% Cold Lake Oil (i.e. high in asphaltenes)	260 mL
6-10	EPS-10% Weathered (beaker tests)	20 mL
11	EPS-10% Weathered	120 mL
12	EPS-10% Weathered (UV light)	120 mL
13	EPS-10% Weathered (UV light)	120 mL

2.6 OIL ANALYSIS

Crude oil samples were analysed using a Hewlett-Packard Model 5700 gas chromatograph equipped with a FID detector, a 30 m long and 75 mm diameter glass capillary column coated with Supelco SPB-55. Peaks were recorded by a Hewlett-Packard 3390 integrator and identified by comparing to a chromatogram of a calibration sample. The chromatographic conditions were: initial oven temperature - 50°C; time held at initial temperature - 8 min.; temperature programming rate - 5°C/min.; final oven temperature - 220°C; injector port temperature - 250°C; FID temperature - 300°C.

When oil and water emulsions were analysed, the emulsion was first dissolved in pentane to separate the oil from the water, then followed by gas chromatographic analysis.

Density measurements were made using a hydrometer. Water compositions were measured by first inserting a flask containing a known volume of the oil-in-water emulsion in a water bath at 100°C to break the emulsion.

3 RESULTS

3.1 OVERWASHING: GENERAL COMMENTS

Prior to presenting the results it is useful to review briefly the nature of the data that was expected in this exploratory study, and compare it with that which was in fact found.

First, it was desired to determine if overwashing occurred, and if so, what the approximate mean overwash depth was as a function of hydrodynamic conditions. It was found that overwashing did occur, often to a depth of several centimetres. There was, however, a considerable variation in depth with position and time. Further the upper pan surface rarely drained completely of water, thus there was almost always a layer of water of depth approximately 1 mm on the surface.

Second, it was noted that the interfacial properties of water spreading on the pan surface appeared to play a role in the submergence behaviour. The plastic balls were not "wetted" by water, thus they tended to resist submergence. It is suspected that water flow over the surface of the pans may be impeded by this "non wetting" tendency. But whether or not this effect occurs with real oil pans is not known.

Third, it had been hoped that it would be possible to express submergence as a probability function of the type shown in Fig. 3.1 in which cumulative frequency was plotted against depth of submergence for a given oil-ocean system. This would enable statements to be made of the following type.

"An oil pan of density A and size B, when floating on a water surface at a wind speed C and wave height D will

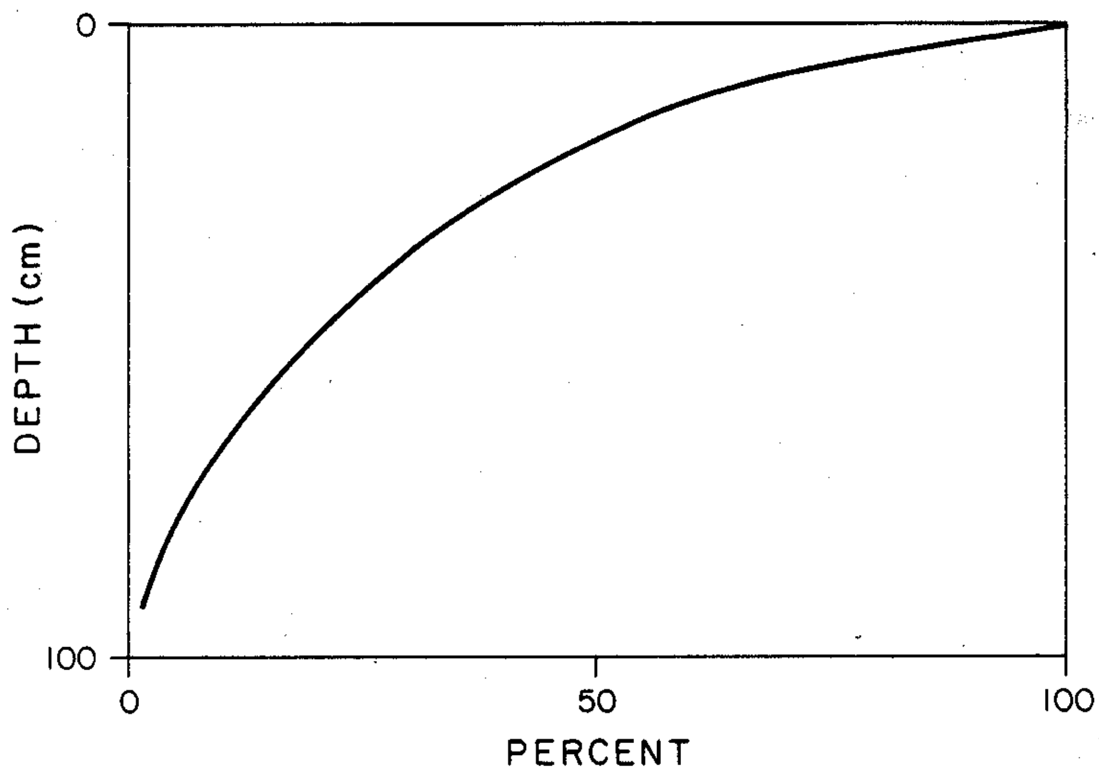


Figure 3.1: Plot of Cumulative Frequency Percent vs Depth of Submergence. The percent is the fraction of the time that the oil pan or drop lies below the stated depth.

generally spend 65% of the time essentially at the surface, i.e. submerged from a depth of 0 to 2 cm, 20% of the time submerged in the range 2 to 3 cm, 10% in the range 3 to 4 cm and the remaining 5% will be spent at depths below 10 cm. As a result, for a given slick it is expected that 65% of the oil will be essentially at the surface and 35% submerged.".

An attractive approach would be to fit a probability density function to the data to express this mathematically, for example, the above data could be expressed by a Weibull type of function of the form

$$P = \exp\left(-(d/D)^x\right)$$

where P is the probability that the pan is below the depth d cm, and D is a constant with dimensions of depth corresponding to the depth of 37% submergence (since when d equals D, P equals 0.37) and x is a second constant reflecting the steepness of the probability curve. For example if D was 2 cm and x was 1.5 the statistical submergence condition would apply as shown in Table 3.1.

Table 3.1: Hypothetical Depth-Probability Data

Depth d	P	Difference in P
0	1.0	0
1	0.70	0.300
2	0.37	0.330
3	0.16	0.210
4	0.06	0.100
5	0.02	0.040
6	0.005	0.015
≧6		0.005
Total		1.000

The pan would thus be at a depth from 0 to 1 cm for 30% of the time, 1 to 2 cm - 33%, 2 to 3 cm - 21%, etc. until it would only be at a depth exceeding 6 cm, 0.5% of the time.

In practice it was found that, as expected, large, low density pans spent almost all their time close to the surface. As pan size is reduced and density increases, the pans were occasionally subjected to episodes of submergence in which, under the action of a breaking wave, they plunged to a depth of perhaps 20 cm then drifted slowly back to the surface at a "Stokes Law" rising velocity.

Viewing the video record enabled estimates to be made of the frequency of these "deep episodes", but it was very difficult to judge fractions of time at various depths. Even if this could be done accurately the results may not be meaningful because hydrodynamic conditions in the tank do not mimic those at sea. Emphasis was thus placed on obtaining approximate submergence results, on determining what data can be easily obtained and on suggesting experiments for oceanic conditions.

3.2 BALLASTED WOOD PAN

Table 3.2 gives the drift velocity of the pan and the water surface at various wind speeds. The surface velocity was approximately 3% of the wind speed. The block drifted more slowly because of its submergence, generally in the range of 1.0 to 1.8% of the wind speed, the denser more deeply submerged blocks being slower. The result is that the block is subject to a water surface drift velocity of 1.2 to 2.0% of the wind speed. There is thus a current of surface water which tends to flow up and over the block at a

Table 3.2: Drift Velocities of Wooden Block and Water Surface Velocities as a Function of Wind Speed

Specific Gravity	Wind Speed u(m/s)	Drift Velocity (cm/s)
0.80	5	8.8
	10	15.3
	13	19.7
0.85	5	8.3
	10	14.6
	13	18.8
0.90	5	7.8
	10	13.4
	13	16.7
0.95	5	7.2
	10	12.0
	13	14.9
0.975	5	6.8
	10	11.5
	13	13.9

Wind Speed u(m/s)	Water Surface Velocity (cm/s)
5	15.8
10	18.3
13	34.5

velocity of typically 10 cm/s plus or minus a factor of two. This velocity corresponds to an energy of 0.005 J/kg (i.e. half of velocity squared) which further corresponds to a potential height of 0.5 mm, (i.e. gravity times height). The water surface, when deccelerated will thus tend to rise by 0.5 mm which is small and probably insufficient to cause overwashing, but possibly sufficient to enhance the overwashing.

The principal cause of overwashing must be the action of waves rather than the drift velocity. This was not appreciated until later, at which time it was decided to build a wave generator.

Table 3.3 and 3.4 give the estimated depths of submergence for tethered and untethered blocks. At low velocities and specific gravities, the block was not submerged and floated consistently above the water surface. At 10 m/s the block was consistently submerged with typical average overwashing of 1 to 8 mm. Tethering caused an increase in submergence, probably because the relative velocity between block and water was increased, and because there was a tendency for the tether to pull the block down under the water surface.

Due to the varying wave profile, the depth of water cover appeared to be greater at the downwind end of the tank where larger waves were present. This probably resembles real conditions most closely; however, reflection from the end of tank appeared to increase the water cover. The readings from the photocells were taken near this end of the tank, but outside of the region where wave reflection became a dominant factor.

In both test situations, at densities close to that of water, the block would be covered with a thin layer of water, and a much thicker layer at high wind speeds. In the tethered case; however, the block displayed a tendency to

Table 3.3: Depth of Water Cover Over Wooden Block - Tethered Case

Specific Gravity	u(m/s)	Depth (mm)
0.80	0	7.6 above
	5	7.6 above
	10	0.2
	13	1.4
0.85	0	5.4 above
	5	5.4 above
	10	1.6
	13	3.6
0.90	0	3.2 above
	5	3.2 above
	10	2.4
	13	2.8
0.95	0	0.8 above
	5	0.8 above
	10	4.4
	13	6.2
0.975	0	0.4 above
	5	0.0
	10	5.8
	13	7.6

Note: "above" indicates top of block above water surface, i.e., no submergence

Table 3.4: Depth of Water Cover Over Wooden Block - Untethered Case

Specific Gravity	u(m/s)	Depth (mm)
0.80	0	
	5	no water cover
	10	no water cover
	13	≈ 1
0.85	0	
	5	no water cover
	10	≤ 1
	13	1.5*
0.90	0	
	5	no water cover
	10	1*
	13	2*
0.95	0	
	5	no water cover
	10	1.4
	13	2.0
0.975	0	
	5	0.0
	10	2.4
	13	5.8

Note: * are estimates of water depth and are subject to error incline downwards into the wind. This condition was not observed when tethering did not take place. At mid-densities and low wind speeds, the inclination of the block prevented waves from forming a continuous water cover. Tethering thus creates atypical conditions and is not desirable. The untethered case is of most interest since it more closely mimics real behaviour.

For the untethered case, water cover was observed in all but the low velocity cases. Quantitative measurements for these runs; however, could not be obtained in several cases. It is observed that there was significant water cover, but not as much in the tethered case. Comparison of the voltages for these runs to the calibration curve often indicated that no water cover was present. These runs were repeated several times, with the same data being obtained. The conditions in which this problem occurred were at specific gravities of 0.9 or less, at all wind speeds.

Many problems were encountered trying to obtain reproducible results with untethered pans and while it is believed that it may be possible to develop an optical measurement system, time was not available for the appropriate experimental work. It was therefore decided to pursue another approach using lard pans.

An approximate correlation of submergence depth S for the untethered block is

$$S\ (\text{cm}) = 0.0015\ U^2/(\text{SGD})^{0.8}$$

where U is wind speed (m/s)

SGD is specific gravity difference between water and block.

This has the correct properties that as SGD tends to zero S becomes large.

3.3 LARD PANS

Table 3.5 gives the dimensions of the pans and the pan submergence behaviour expressed as the average overwash depth, the maximum depth of submergence and the frequency of the deep episodes. The pan rising velocity is also given for those pans which were subject to deep episodes.

The pans spent virtually all the time (90%) in a state of submergence with perhaps 20 to 25% of the surface exposed to the air but covered with a thin layer of water. The average submergence depths were clearly dependent on density difference. An approximate correlation is

$$S \text{ (cm)} = 0.009\ U^2/(SGD)^{0.8}$$

The constant is considerably larger than that of the wooden block, but it must be remembered that there was induced wave action in this case whereas in the case of the wooden block there was only wind-induced waves. It is clear that it is primarily the impact of relatively large waves which induces overwashing.

During a typical deep episode the pan would submerge for 5-15 seconds and reach a depth of 15 cm. The episodes were more frequent for smaller, denser pans, varying from 75 per hour to 24 per hour. The submergence time was typically 10 seconds thus the fraction of the time that these episodes applied is quite small, i.e. 7 to 20% of the total. But at higher wind speeds the frequency increased, especially for the smaller pans.

Table 3.5: Experimental and Calculated Data from Lard Pan Tests

Experimental Data

Raft No.	Density (g/cm^3)	Density Differerence (g/cm^3)	Length (cm)	Width (cm)	Thickness (cm)	Volume (cm^3)	Overwash Average	Depth Maximum (cm)	Frequency[2] of Deep Episodes
1	0.958	0.041	13.5	12.0	3.4	551.0	3.2	≥ 10.4	24.0
2	0.980	0.019	16.0	13.0	2.0	416.0	5.8	≥ 10.4	36.0
3	0.964	0.035	16.0	10.5	2.0	336.0	4.2	7.4	Ø ND
4	0.952	0.047	12.5	10.5	2.0	262.0	4.5	7.1	Ø WD
5	0.973	0.026	16.0	12.5	2.0	400.0	4.5	7.8	Ø WD
6	0.977	0.022	20.5	15.0	2.5	769.0	4.2	10.0	0 ND
7	0.982	0.017	16.0	13.0	2.0	416.0	7.1	≥ 10.4	30.0
8	0.990	0.009	16.0	12.5	2.5	500.0	6.0	7.8	Ø ND
9	0.986	0.013	14.0	12.0	3.0	504.0	6.8	≥ 10.4	15.0
10	0.986	0.013	13.0	6.5	2.0	169.0	7.8	≥ 10.4	75.0
11	0.982	0.017	10.5	7.0	1.5	110.0	5.8	≥ 10.4	75.0

It appears that the pans are subject to a frequency of deep submergence events with a spectrum of eddy sizes and velocities, with smaller eddies being more frequent. An interpretation of the data is that the frequency (per hour) of these events is approximately

$$N = 500/L$$

where L is the equivalent diameter (cm) in the horizontal plane and the constant 500 depends on wind speed and breaking wave frequency. An alternative and intuitively more satisfying relationship is of the form

$$N = No \exp(-L/M)$$

where No is the total frequency of all submergence episodes and M is the length scale constant. If an episode lasts 10 seconds it can be argued that No will approach a maximum of 360 per hour. An approximate correlation is

$$N = 360 \exp(-L/5) \text{ per hour}$$

The two correlations agree fairly well in the 2 to 12 cm range but the exponential expression gives a faster (and intuitively more reasonable) fall off in frequency with increasing size. Assuming a mean submergence time of 10 seconds gives the fraction of the time that the pan is underwater and experiencing submergence as

$$10N/3600 \text{ or } \exp(-L/5)$$

Thus a 10 cm pan will be submerged 14% of the time at this wind speed.

The pan rising velocities are typically 3 to 7 cm/s but depend on the pan configuration. It appears that during a typical episode the pan is propelled downwards at 10 cm/s but decelerates to zero velocity in about 3 s and a depth of 15 cm, then rises to a velocity of 5 cm/s and reaches the surface in some 6 s. During this process it may be subjected to lateral movement and even a second submergence. At very high turbulences, there is clearly a spectrum of water currents which generally exceed the pan rising velocity, thus the pan is well mixed into the water column.

3.4 PLASTIC BALLS

The plastic balls, which it is hoped simulate oil drops, were observed to reside at or near the water surface then occasionally plunge into the water column as a result of a breaking or spilling wave. When there was no wind the low density (SG = 0.92) balls rode with the waves and showed little tendency to submerge. As the ball density increased the balls tended to become more frequently and deeply submerged. It was impossible to record the behaviour accurately in the top 5 cm of the water column because of the fluctuating water level. As the water level rose and fell as waves passed the balls rose and fell, but occasionally rising out of the surface and occasionally plunging below the surface. Only a maximum depth could be determined above which the balls spent perhaps 90% of the time. Behaviour was very erratic thus multiple measurements were made in an attempt to obtain some statistical significance.

Figs. 3.2 to 3.5 give some results with maximum depth as a function of ball diameter and density.

Fig. 3.2 at zero wind speed shows that the maximum depth of submergence was some 3 cm for the less dense balls and 5 cm for the denser balls. Fig. 3.3 at 6 m/s shows an increase in these low and high densities to approximately 5 to 20 cm but there is considerable scatter. At 10.7 m/s (Fig. 3.4) the depths are mostly less than 3 cm even for the higher density balls. It appeared that at the very high wind speed the balls "stuck" to the water surface as a result of their high drift velocity of 8 to 20 cm/s (Fig. 3.5).

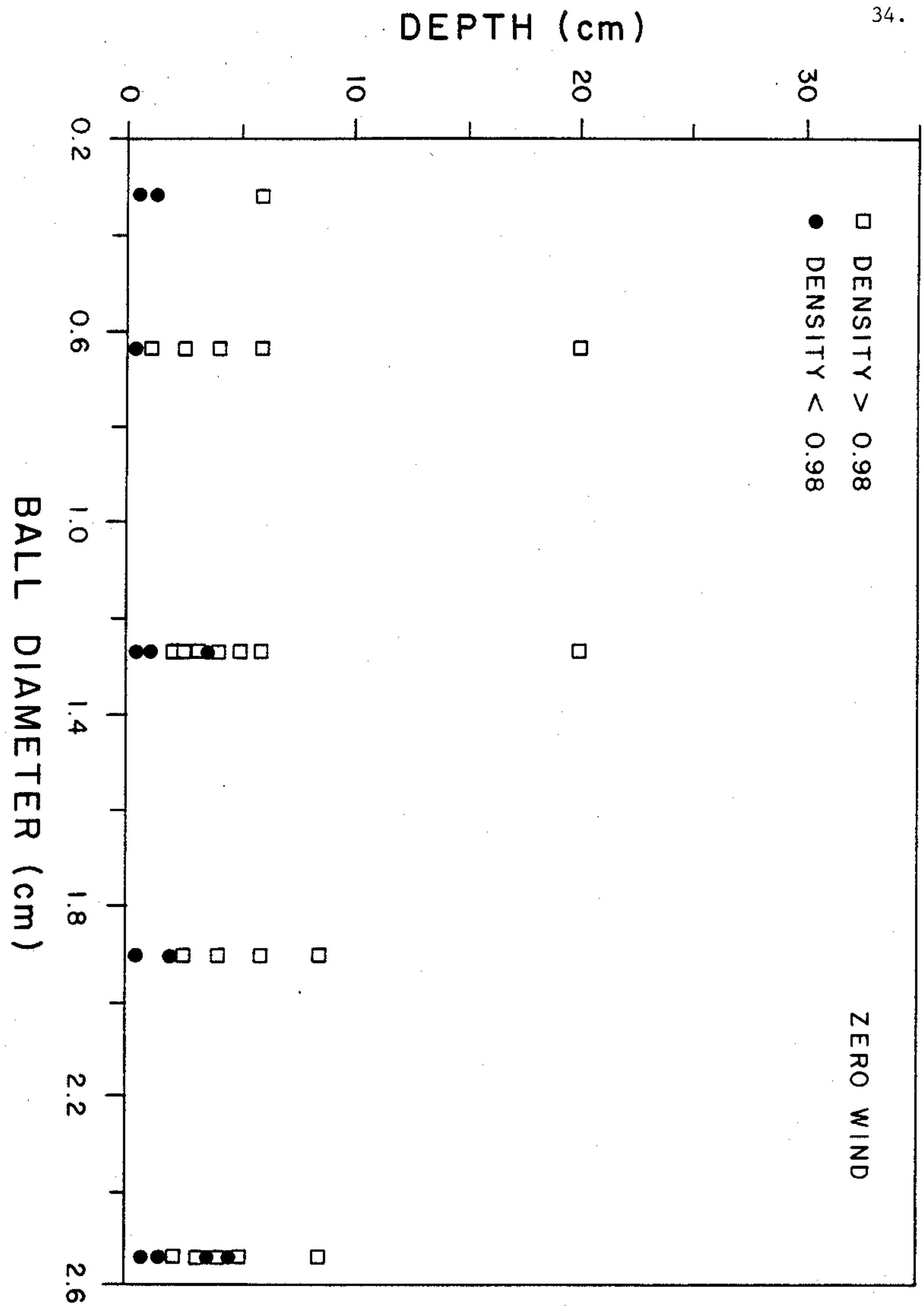


Figure 3.2: Plot of Maximum Submergence Depth as a Function of Ball Diameter, for Low and High Density Balls, zero wind.

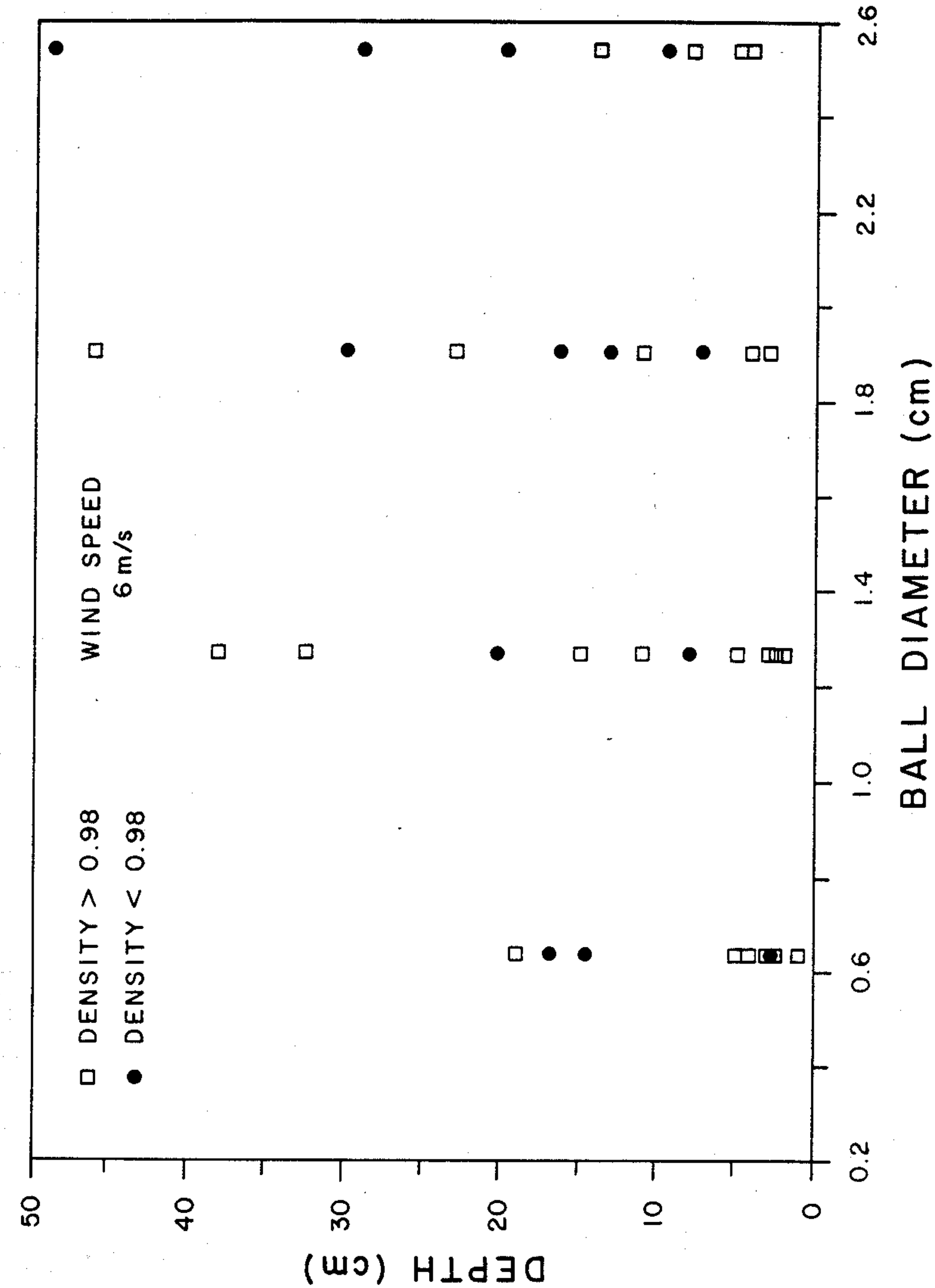


Figure 3.3: Wind speed 6 m/s.

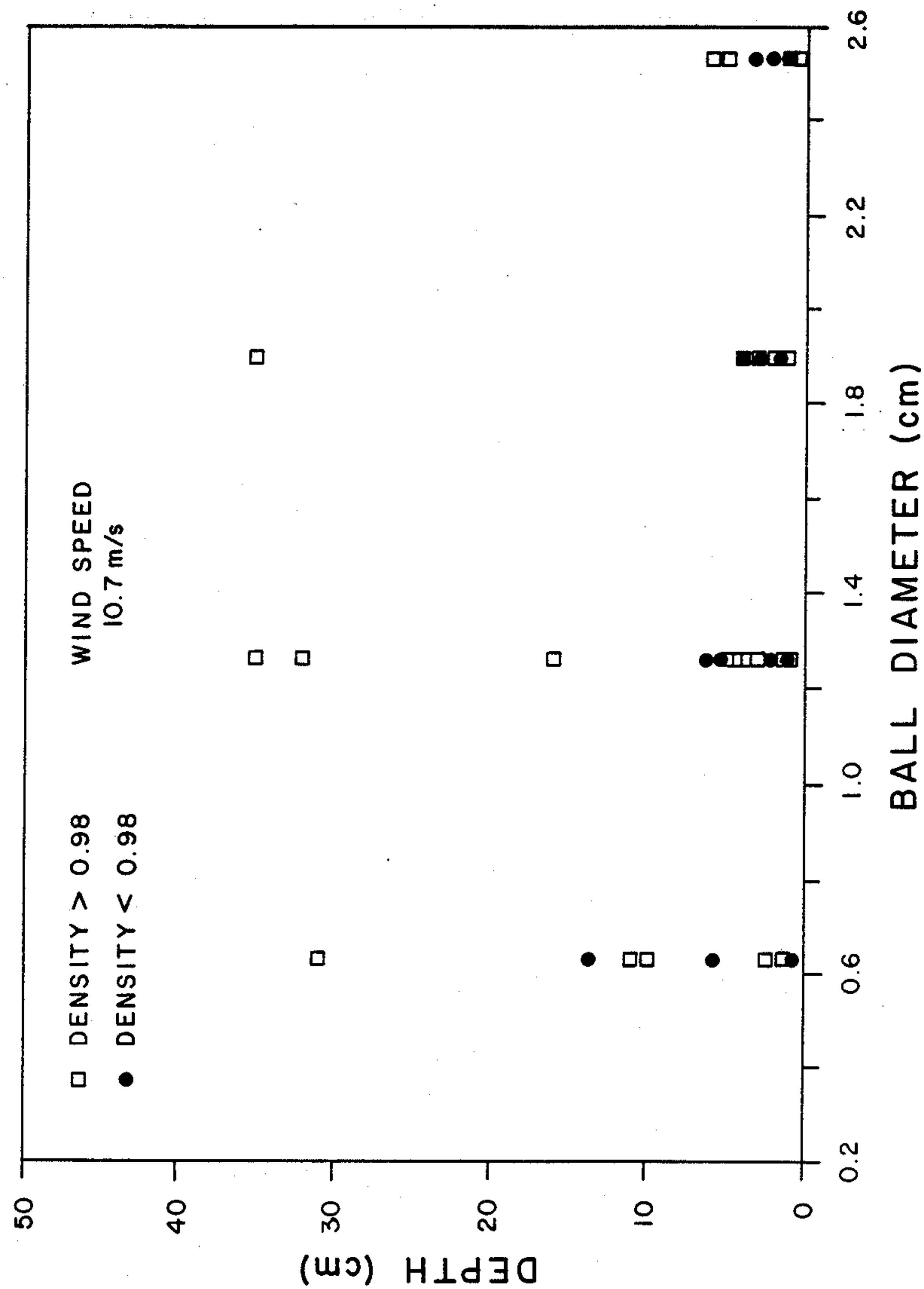


Figure 3.4: Wind speed 10-7 m/s.

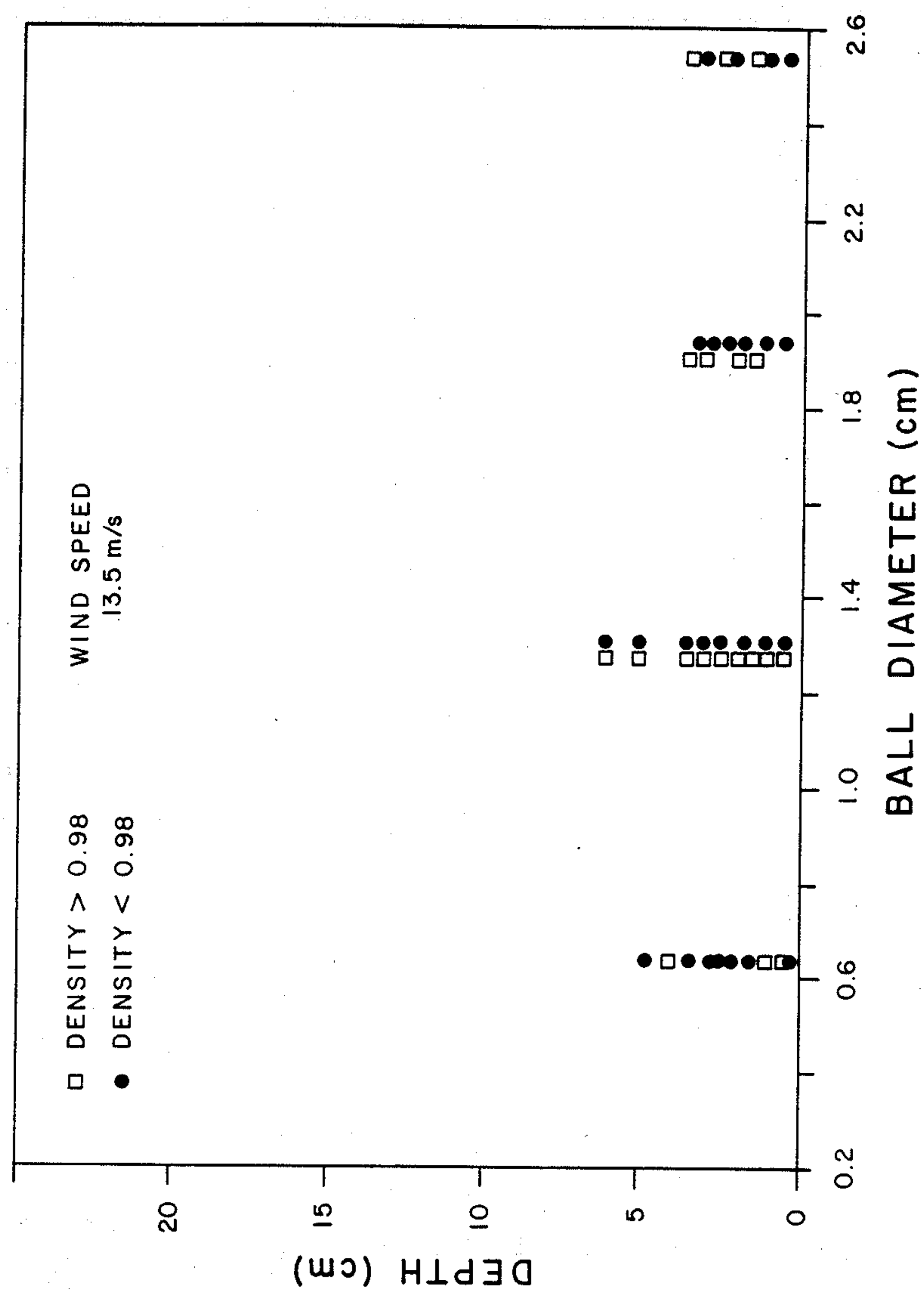


Figure 3.5: Wind speed 13 m/s.

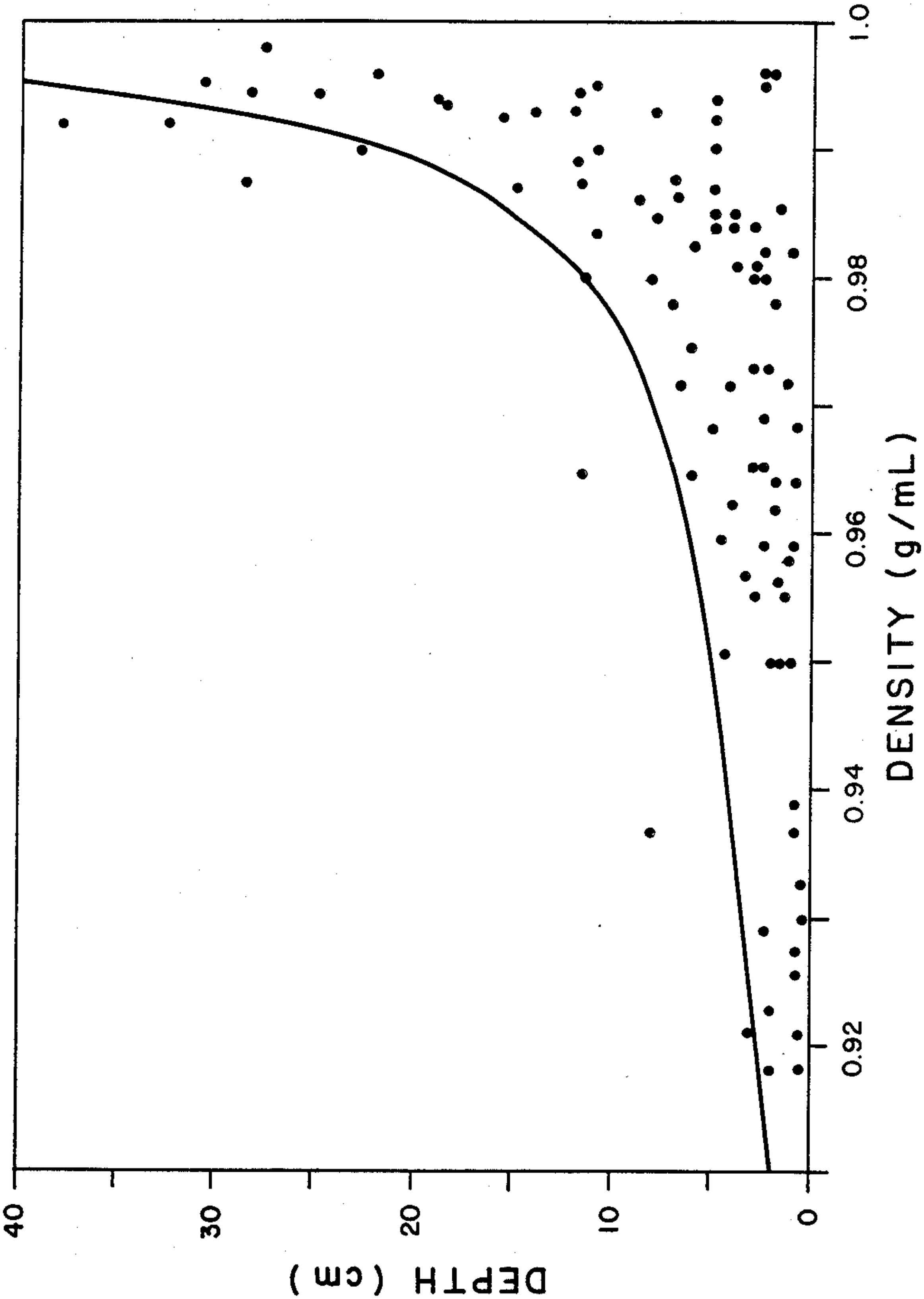


Figure 3.6: Plot of Average Depth Versus Ball Density for all Conditions.

Ball diameter does not therefore appear to have a significant effect in this range, density being the more important variable. This effect is included later in the submergence correlation.

Fig. 3.6 shows all the data plotted as a function of specific gravity. There is a region of increasing mean depth beyond 0.95. At 0.97 depths of up to 7 cm are common; at 0.98 this has increased to 10 cm, and at 0.99 it is 20 cm. The balls are thus found mainly in a zone of depth D which is approximately

0.2/SGD cm deep

but they are occasionally propelled to greater depths especially under the action of breaking waves.

These results should be treated as giving only an approximtate characterization of very complex behaviour. Prolonged measurements would be required to obtain statistically significant results and there is no certainty that these results would be applicable to oceanic conditions.

3.5 PAN FORMATION TESTS

A total of ten experiments was conducted in the glass tank and five in beakers using various oils, under various exposure conditions. The general aim was to find out why certain oils form "pans" as distinct from remaining as a slick or being dispersed into the water. The "design" was to conduct an experiment, assess the results, design the next experiment, etc. rather than set up a factorial block of variables. This more subjective (and it is hoped more efficient) method was adopted because only a limited number of tests could be included in the program, each test taking almost one week.

Figures 3.7 to 3.11 are a series of photographs giving selected views of the pan formation process.

EXPERIMENT 1

Experiment 1 was primarily a test to gain some insight into the overall sequences of events which occur to the oil in water. During this experiment, an optimum photographic exposure was determined, and experience was gained with the oil analysis techniques. The oil used was EPS Standard, 10% weathered.

It was observed that as time progressed, the oil would make transitions from the "slick" phase to an oil "raft" phase of thicker oil of reduced horizontal area, and then to a "blob" phase of distinct oil drops within the first 24 hours. Later, the blobs turned lighter in colour as 'chocolate mousse' formed.

Oil coated water drops (i.e. oil "balloons" filled with water) and oil droplets were found to exist at varying heights in the water column. Initially, both types of droplets were observed in high concentrations, but as time passed, the concentrations dropped considerably, presumably because their formation rate was reduced.

EXPERIMENT 2

In a repeat of Experiment 1, a slick was formed immediately upon the addition of 50 mL at EPS 10% weathered oil. Within 5 minutes, oil coated water drops ranging in sizes from 1 to 6 mm in diameter were observed to a 30 m depth in the water column. After 45 minutes, the oil coated water drops were observed at depths up to 70 cm in the water column. Fine oil droplets, less than 1 mm in size, were also dispersed throughout the top 60 m of the water column.

After 2 hours of wave action, an oil raft began to form on the water surface. As the raft agglomerated and thickened, the slick grew smaller.

Within 5 hours, blobs of various sizes were observed where the raft had existed. As time progressed, more blobs were formed in various sizes approximately 2 to 4 cm in length by 1 cm width by 1 cm thick. These would be overwashed with approximately 1 mm of water, 60 to 70% of the time.

24 hours after the introduction of the oil, lighter coloured blobs, i.e. chocolate mousse, were observed. There were very few oil coated water drops in the water column. However, fine oil droplets were dispersed throughout the column, with the larger droplets being closer to the surface.

Very little change had occurred when the experiment was concluded 98 hours after the introduction of the oil.

The oil was collected and analyzed. Its density was found to be approximately 0.85 g/cm^3, but this density could not be determined accurately due to insufficient sample size. The water content of the oil was found to be 65 to 70% by volume, thus it had emulsified appreciably.

EXPERIMENT 3

This experiment involved the use of a larger volume of the same oil which it was hoped would improve the quality of the results. Following addition of 100 mL of the 10% weathered EPS crude oil, a slick was formed having an approximate thickness of 1 mm. In areas where wave action was vigorous, oil coated water drops were produced by one of two methods. The first method involved the upward movement of a "jet" of water through the oil to form an oil coated water drop in air, which then sank through the oil slick

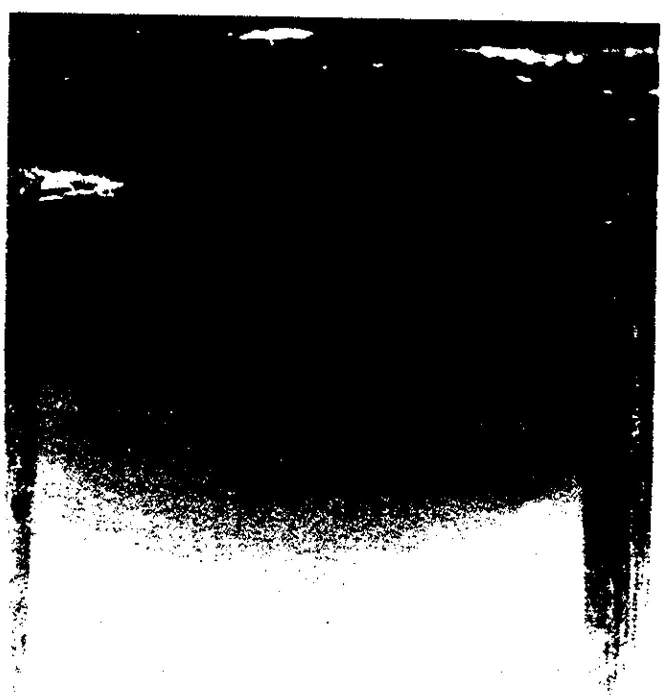


Figure 3.7: Above and below views of oil in initial condition showing spreading into sheen and thicker patches (Experiment 3)

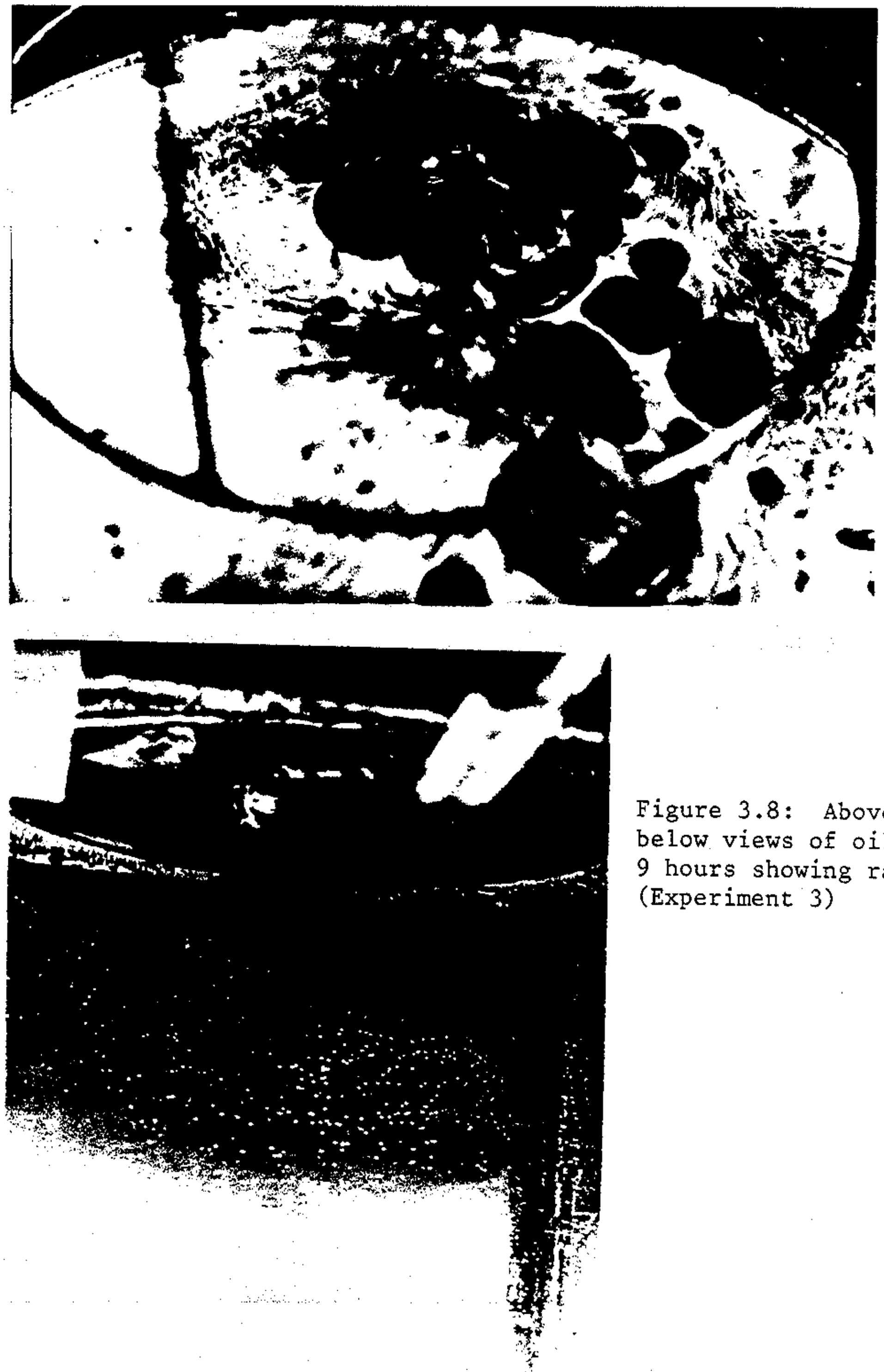


Figure 3.8: Above and below views of oil after 9 hours showing rafting (Experiment 3)

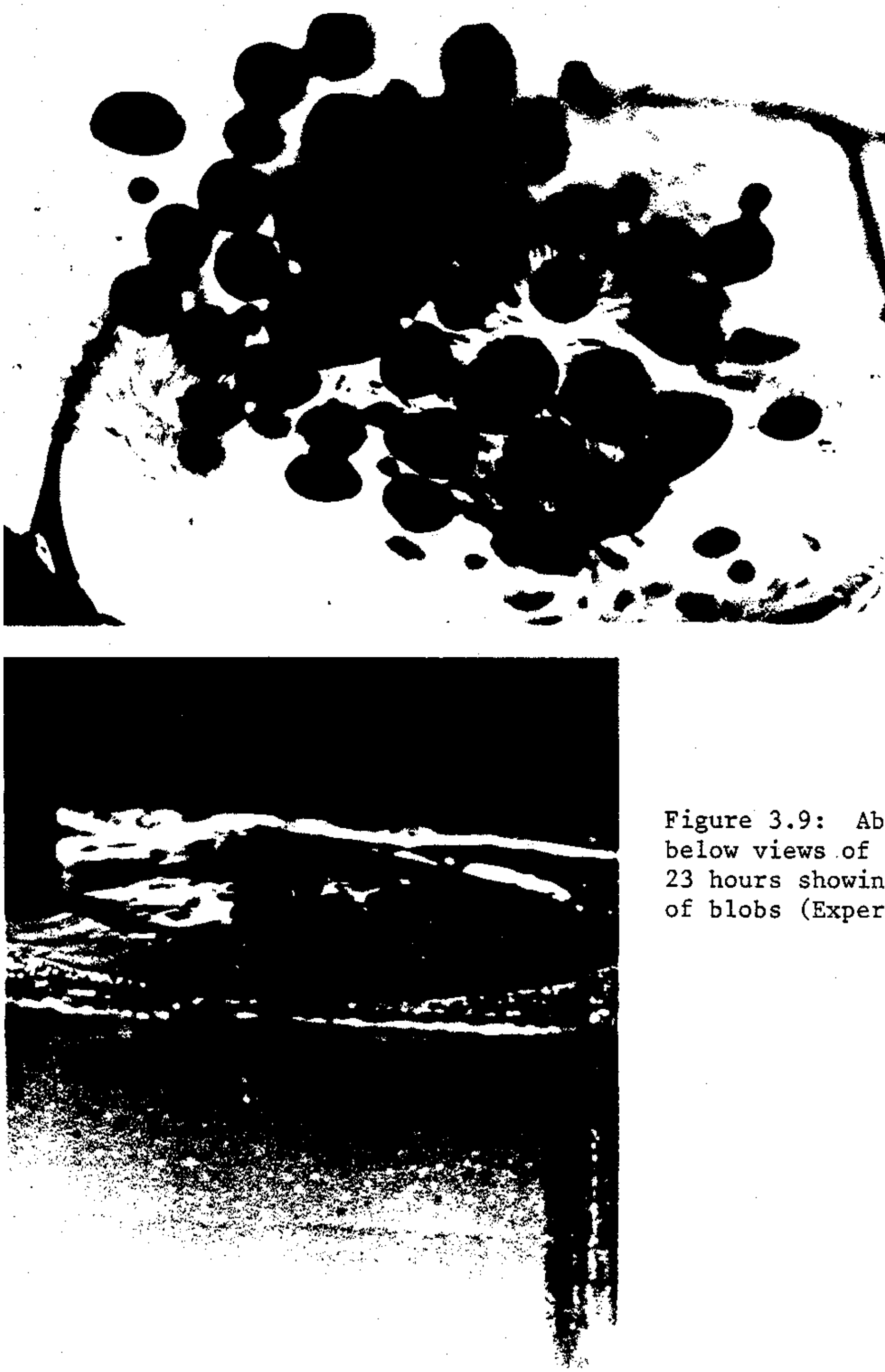


Figure 3.9: Above and below views of oil after 23 hours showing formation of blobs (Experiment 3)

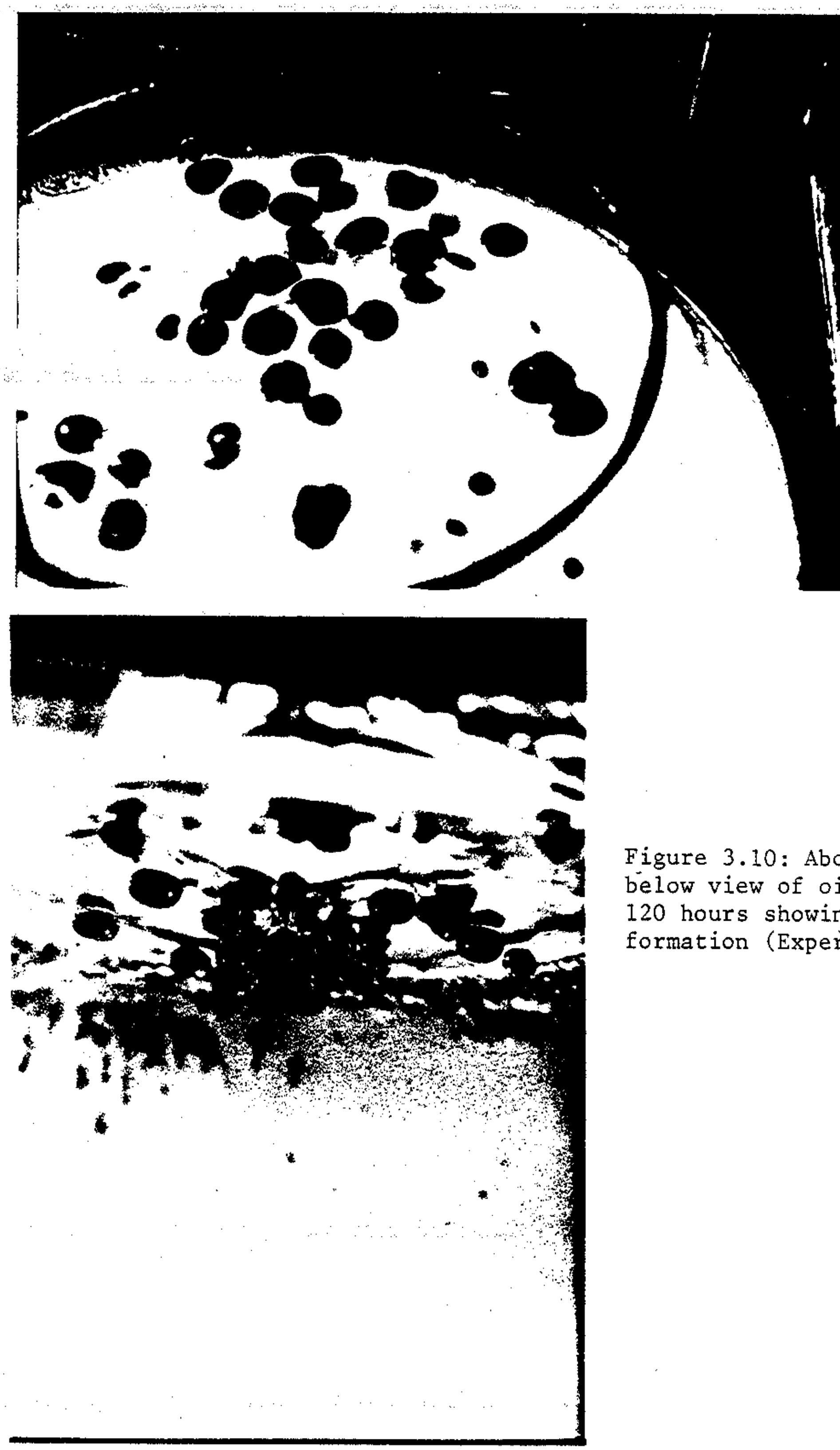


Figure 3.10: Above and below view of oil after 120 hours showing mousse formation (Experiment 3)

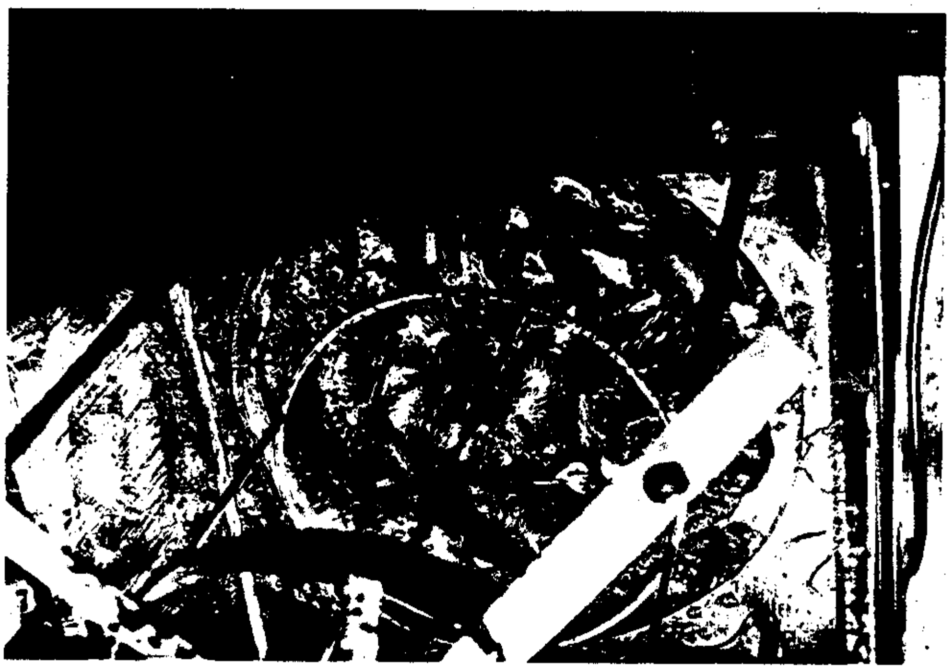


Figure 3.11: Above and below views of oil in Experiment 12 after 5 hours showing a cloud of dispersed oil drops in the water column. Many of the drops are water-in-oil-in-water drops

into the water column. These oil/water drops ranged from .1 to 5 mm in diameter and were conveyed distances of as much as 30 cm into the water column. They were nearly neutrally buoyant. They were also produced by the shearing of a water-in-oil 'pocket', or area of water covered only by a sheen of oil, but surrounded by raft. The pockets were formed usually in areas near large wave fronts where a wave would indent the oil slick surface. As the indentation moved along the edge of the slick, it would grow due to the addition of more water. After the pocket grew to an unstable size, the wave action would shear the pocket producing oil coated water drops. The drops formed by this method were 1 to 2 mm in diameter and would not drift deeper than 25 cm into the water column.

The presence of fine oil particles in the water column was also observed. These were formed immediately after the introduction of the oil, i.e. natural dispersion of the oil was occurring. However, it was observed that some of these drops were produced when the oil coated water drops ruptured in the water column.

Both the oil particles and the oil coated water drops were observed primarily during the time when the oil was in the slick phase.

After 1 to 2 hours of wave action, the oil began to coalesce near the wave centre. The resulting raft was approximately 10 to 12 cm in diameter. As time progressed, the raft became smaller, deeper and more viscous. Some oil particle and oil coated water drops were also formed, but at a lower rate than when the oil was present as a slick. As time progressed, both the oil and oil coated water drops had lower rising velocities. The raft phase continued in this manner for approximately 9 to 10 hours.

Eleven hours after the introduction of the oil, the oil formed several 'blobs' in sizes varying from 1 to 4 cm in diameter by 1 cm thick. Within an hour, more blobs were present, however, most were 1 to 2 cm in diameter and were overwashed approximately 50 to 60 percent of the time. It was observed that larger emulsion drops (≥ 2 cm) would break up by first elongating along a wave front, the splitting in the more turbulent areas.

With the passing of time, the blobs would be overwashed for a larger fraction of time. It was also observed that fewer oil or oil coated water drops were present in the water column.

Approximately 22 to 24 hours after the oil was introduced, lighter coloured blobs of "chocolate mousse" were formed.

The formation of the chocolate mousse continued throughout the length of the experiment (200 hrs). It was observed that there were differences between the blob phase and the mousse phase. Blobs were characteristically darker in colour and spread out when the wave generator was turned off. Chocolate mousse, on the other hand, was lighter in colour and would remain stable as an oil mass even when no waves were present.

At the conclusion of the experiment, the chocolate mousse was collected and analysed. The emulsion density was 0.996 g/cm^3 and was 67 to 75% by volume water.

EXPERIMENT 4

For this study, the EPS 10% weathered oil was doped with paraffin wax to 4.3% by mass. A volume of 212 mL of this mixture was added to the apparatus.

It was expected that the increase in wax content would accelerate the formation of pans.

Upon addition of this mixture, an oil "slush" formed, indicating that the oil was at or below its pour point. This phase continued for 45 minutes during which the slick edges became light brown in colour.

After 1 hour of wave action, the slush began to break up into smaller pieces approximately 2 to 3 cm in diameter. The process by which the main slick would segment itself was observed to be a physical breaking along a wave front. The resulting blobs would turn light brown in colour and be overwashed with 1 to 2 mm of water, approximately 50 to 70% of the time.

After 6 hours of wave action, the oil behaved as a viscous oil slick with no "slush" present. The slick had a surface area approximately 20% greater than when in the "slush" phase. Water pockets were observed to exist, however, they did not shear to produce oil coated water drops. It was observed that the pockets would either move within the slick or the collapse at the edge of the slick.

Within the slick, a raft 20 to 30% of the total slick diameter existed. However, it was very unstable and would expand or decrease in size with no apparent trend.

As time progressed, the slick/raft assumed a kidney shape in which the oil in each half of the kidney would spin towards the centre. This behaviour continued until the conclusion of the experiment (144 hours).

Towards the end of the test an oil raft definitely existed within the slick. Approximately 20 percent the size of the slick, it was located near the area of greatest turbulence. One oil blob was also formed, however, it would adhere to the main slick for 20 to 30 percent of the time.

The final oil density was found to be 0.989 g/cm³. The water content was between 55 to 75% by volume.

The expected result did not materialize. Addition of wax did not accelerate the formation of emulsion. It merely appeared to slow the processes.

EXPERIMENT 5

For this experiment, the asphaltene content of the EPS 10% volatilized oil was increased by 25% by mass by blending the oil with Alberta Cold Lake crude oil. It was expected that this would hasten emulsion formation.

Approximately 260 mL of the blend was added to the tank. Upon the addition of the oil, a slick was formed. Water pockets within the slick were observed to form oil coated water drops 1 to 5 mm in size.

It was also observed that the bottom of the slick contained a large number of oil spheres. They were formed during the addition of the oil to the tank and subsequently made their way to the surface.

After 30 minutes, the slick formed the kidney shape observed in experiment 4. The water pockets observed were the largest observed from any experiment, causing the slick to be 5 to 6 cm thick at times. The kidney shape was caused by the formation of two separate oil rafts.

Within 2 hours after the introduction of the oil, the oil was in the raft phase. The rafts were approximately 2 cm thick, and would have 40 to 70% of their surface area overwashed due to the presence of the waves.

This behaviour continued with little change for 19 hours. After 21 hours of wave aciton, the slicks broke down into smaller segments of various sizes, all being 1 cm thick. All the blobs formed were completely overwashed with 1 to 2 mm of water. The method of fragmenting was observed to be the same as in experiment 3. The oil would elongate along a wave front and break near the centre of turbulence.

Within the next 3 to 5 hours, the blobs agglomerated at times to form rafts, and the raft would fragment to form blobs. Generally, the trend was towards the blob state. The tendency continued until the conclusion of the experiment (266 hours). At the end of the experiment, it was observed that the blobs were generally 2 to 4 cm in diameter by 1 cm thick. They were completely overwashed with 1 to 2 mm of water.

The final density of the blobs was 0.982 g/mL. The water content was found to be 60 to 70 percent by volume.

EXPERIMENTS 6, 7, 8, 9, 10

These experiments were set up in continuously stirred 1 L beakers containing 20 mL of EPS 10% weathered crude and 500 mL water. It was hoped that the oil-in-water behaviour could be simulated using this method instead of the more time consuming water column apparatus.

It was found that the oil always remained in the slick phase with the exception of a conical shaped emulsion which formed in the slick centre.

Thus, this method did not effectively simulate oil-in-water behaviour.

EXPERIMENT 11

This experiment was another replicate using undoped oil. Upon the addition of 120 mL of EPS (10% weathered) crude, a slick formed fairly rapidly. After approximately 15 minutes, it could be seen that the water column contained a large concentration of oil drops (less than 1 mm in diameter) and oil coated water drops ranging from 1 to 3 mm in diameter.

After two hours had elapsed, the slick shrank to produce an oil raft near the wave centre continuing wave action resulted in the break-up of this raft within two hours (i.e. 4 hours after time zero). Unlike the previous experiments using this oil, the formation was observed of oil blobs below a fairly substantial oil slick. The slick persisted for two days. It was noticed that as the slick became smaller and more dispersed, the number of oil blobs increased. It was also observed that the oil blobs rarely exceeded a diameter of 1 cm.

After 2 days from addition of the oil the first formation of light brown oil blobs (chocolate mousse) was observed. After an additional 24 hours in the tank, the chocolate mousse was present in blobs ranging from 1 to 3 cm in diameter. They were all completely overwashed with 1 to 2 cm of water. The chocolate mousse was observed until the conclusion of the experiment, 125 hours after the introduction of the oil.

EXPERIMENT 12

This experiment was similar to experiments, 1,2,3 and 11 in that EPS 10% weathered crude oil was used. However, for the first five hours of the experiment, a UV light, was placed over the slick to determine its effect on the fate of the oil. The UV light was obtained using a CGE 275 watt sunlamp

(RSK-6C) having a major emission between 310 and 360 nm. The reason for this test was that it had become apparent that the oil's interfacial properties played a strong role in the behaviour and that these properties would be affected by the formation of surface active photo-products. This has been noted by others, as reviewed by Mackay (1984).

Within 2 hours, several oil blobs were observed. These blobs were always less than 1 cm in dimateter and appeared to be completely overwashed. At times, it was seen that these blobs were injected into the water column as much as 10 cm.

After 4 hours, very little of the oil slick was seen. In its place were several hundred oil globs ranging from 1 to 10 mm in diameter.

It was also noted that there was a relatively high concentration of oil and oil coated water drops within the water column.

Within 40 hours after the introduction of the oil, a light coloured chocolate mousse was formed. The mousse blobs were less than 1 cm in diameter and were completely overwashed 100% of the time. This state did not alter until the conclusion of the experiment, 112 hours after the oil was introduced.

Clearly the presence of UV light has a profound effect on the behaviour of the oil.

EXPERIMENT 13

Experiment 13 was a repeat of experiment 12 to check the reproducibility of the effects of the UV lighting. Unfortunately, there was a power failure.

By the time that the power was restored, the oil had pooled on the surface, thus conditions were not quite identical.

As the experiment proceeded, it was observed that the oil-in-water behaviour was different from that observed in experiment 12, since a definite raft phase was observed which remained stable until the experiment was concluded after 48 hours. The raft was approximately 1 cm thick and surrounded by small blobs less than 1 cm in diameter, however, there were relatively fewer blobs than observed in experiment 12.

EXPERIMENT 14

Experiment 14 was a repeat of experiments 12 and 13 to reproduce the oil-in-water behaviour. It was observed that the oil-in-water behaved similarly to that observed in experiment 12.

After 100 mL of oil was introduced into the tank, a slick was observed to form on the surface. Within 5 minutes, oil blobs less than 1 cm in diameter were present. Also, there was a relatively high concentration of oil and oil coated water drops in the water column.

As time progressed, more oil blobs formed. Within 1.5 hours, there was virtually no slick present, since the oil was present in the form of blobs less than 1 cm in diameter.

Little change was observed until 4 to 6 hours after the experiment started, at which time chocolate mousse blobs had formed. This state continued until the UV lamp was shut off after 8 hours of continual use.

Unfortunately, when the apparatus was checked 24 hours after the introduction of the oil, it was observed that the oil-in-water emulsion crept under the hoop apparatus and was deposited on the side of the tank wall. The experiment was thus concluded.

In general the hoop apparatus performed well, but it is believed that the configuration could be improved. There was a tendency for oil to reach the tank walls outside the hoops. This can probably be eliminated by improved design. A major advantage of the system is that the oil can be viewed from above and below and the changes in the regime readily identified.

4 DISCUSSION

4.1 GENERAL COMMENTS

This study has provided some insights into the process by which an oil slick becomes "broken up" into drops and pans and how these pans tend to become submerged. The basic phenomena have been elucidated to some extent but a number of questions remain. In this discussion we first address the issue of oil slick behaviour leading to pan formation, follow with a consolidation of the submergence/overwashing studies, develop mathematical correlations or models to the extent that this is possible, and outline future research needs including the conduct of "at sea" tests.

4.2 PAN FORMATION

It was observed that the oil slick went through a series of fairly distinct stages as depicted in Figure 4.1. Initially it was present as a slick of variable thickness with areas of sheen and thicker areas. As the slick aged the oil tended to gather into "rafts" of fairly thick oil surrounded by water. This seemed to be due to a reduced spreading tendency and a higher oil density and viscosity. Later the oil tended to break up into "blobs" of oil which were several mm to several cm in diameter and showed a reduced tendency to coalesce with each other and with the raft. The blobs were almost always awash with water or fully submerged thus they could not easily be seen from above the water surface. They later turned lighter in colour to a light brown "mousse" containing some 60% water. Also formed, especially initially, were oil-in-

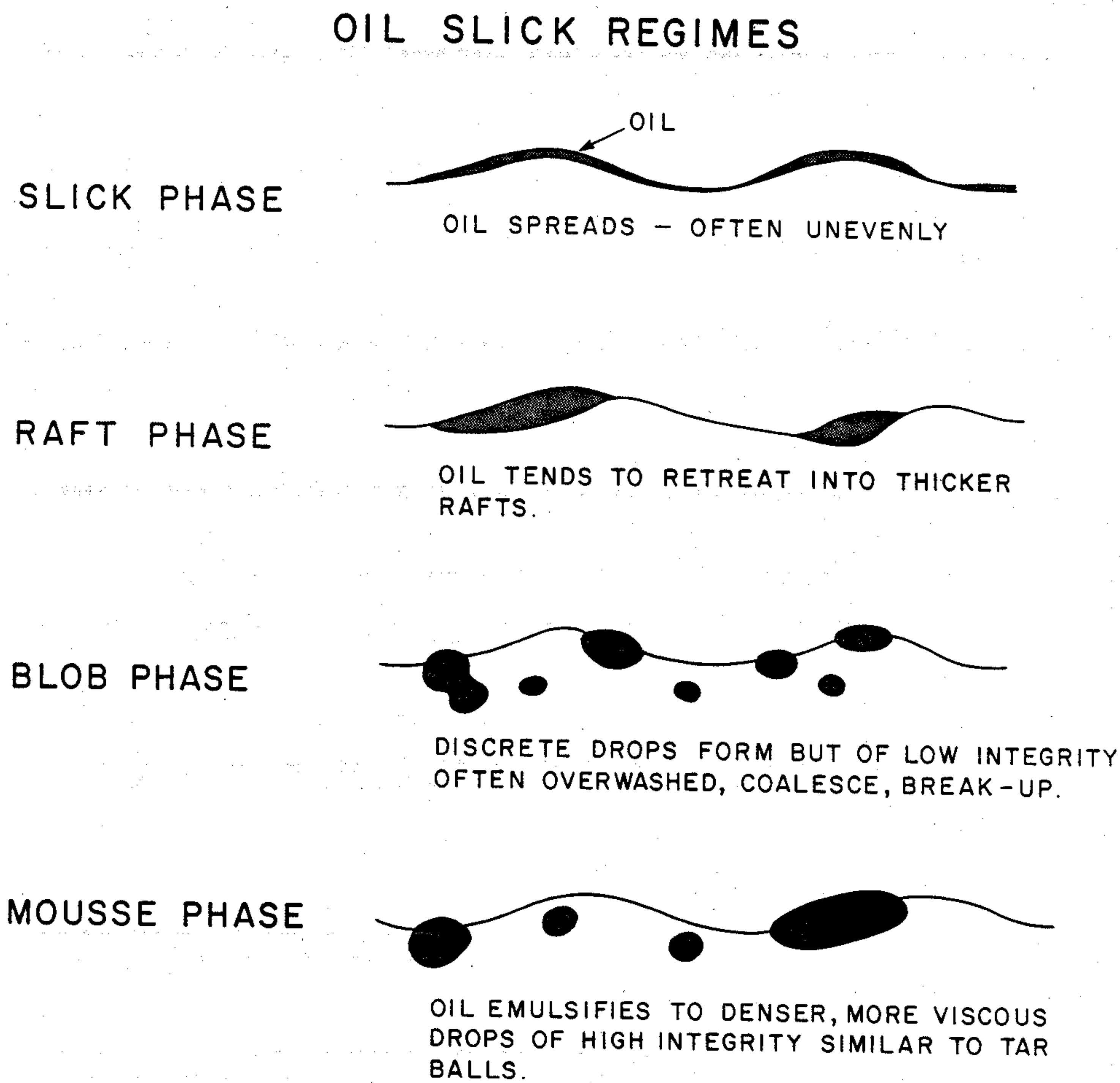


Figure 4.1: Oil Slick Stages

water emulsion particles and oil coated water drops, i.e. water in oil in water drops or "balloons" of oil in water.

The oil blobs retained their near spherical shape as long as conditions were turbulent, but if they were allowed to rest on a stagnant water surface they tended to spread out. The emulsified blobs on the other hand retained their shape.

Tests were conducted with an oil doped with wax and with asphaltenes because it was believed that waxes and asphaltenes contribute to more rapid emulsion formation. Surprisingly this had relatively little effect apart from increasing the oil's viscosity and generally slowing down the overall process of change from slick to raft to blob. Previous studies have shown that asphaltenes and was contribute to emulsion stability, but they also cause a viscosity increase and this may reduce the rate of formation towards an ultimately more stable emulsion. When the slick was subjected to UV light there was more rapid formation of emulsion indicating that surface-active photo-products were formed and played a role in the changing interfacial properties of the oil.

It appears from these results that as an oil weathers on a turbulent water surface it passes through several regimes which are controlled by oil density, viscosity, interfacial characteristics and the possible formation of a "skin" of relatively viscous material which resists deformation and coalescence. This "skin" formation may be enhanced by photolysis. What remains unclear is how the water in oil emulsion forms. It may result from the coalescence of blobs with only a partial "skin", insufficient to prevent coalescence, but sufficient to stabilize the small water drops which are formed from the imperfectly drained water film which exists at the coalescing surface.

What is clearly needed is a comprehensive analysis of the oil's physical and chemical properties as it progresses through the various regimes, supplemented by carefully designed experiments to test the emerging hypotheses.

One attractive hypothesis which we present here for consideration is that the oil's spreading-retreating characteristics are controlled by a balance of interfacial and hydrostatic forces. The conventional spreading theory is that oil on a water surface experiences three forces corresponding to interfacial energies. These are the energies of air-oil E_{AO}; oil-water E_{OW} and water-air E_{AW}. The units are J/m² or N/m, or traditionally dyne/cm.

If E_{AW} exceeds $(E_{AO} + E_{OW})$ the oil can reduce its energy by spreading. In some cases a sheen or solution forms which results in a reduced effective value of E_{AW} which then falls below $(E_{AO} + E_{OW})$ and the spreading retreats. It is observed that E_{AO} and E_{OW} change with time, tending to fall, probably as a result of accumulation of surface active or hydrophilic material at the interfaces. Thus if retreating occurs it is most likely to be due to a decrease in E_{AW}. This could result from dissolution of hydrocarbons, polar material and especially photo-oxidation products. We thus hypothesize that the retreating is not due to a change in oil properties, but to a change in its surrounding air-water environment.

Now the retreating force (corresponding to the energy difference) must be balanced at steady state. The balancing force is hydrostatic and can be expressed as $\Delta\rho\ g\ h^2/2$ where $\Delta\rho$ is the oil water density difference (kg/m³), g is the gravitational constant (m/s^2) and h is the oil slick thickness (m). This group thus has dimensions of kg/s^2 or J/m^2 or N/m. Justification for this form comes from equating the energy change as the oil mass incrementally spreads to increase its area by dA, thus increasing the interfacial energy by EdA. The loss of gravitational energy is $Vg\Delta\rho dh/2$ where V the oil volume (which is constant) is Ah, thus dA is d(V/h) or $(-V/h^2)dh$, thus

$$E = \Delta\rho g h^2/2 \text{ or } h = (2E/\Delta\rho g)^{1/2}$$

Interestingly, as $\Delta\rho$ becomes small as a result of weathering and emulsion formation, h increases rapidly. For example if E is 10 dyne/cm or 0.01 N/m, $\Delta\rho$ is 50 kg/m^3 (i.e., 0.05 g/cm^3) and g is 9.81, h becomes 6.4 mm. A decrease of $\Delta\rho$ to 12.5 kg/m^3 results in h increasing by a factor of two to 12.8 mm. It appears that as E increases and $\Delta\rho$ decreases, the slick increases in thickness to become a raft which is then susceptible to rupture into blobs under the action of turbulence. When a blob is formed it is likely to become overwashed with water, resulting in the disappearance of the E_{AO} term since there is now no oil-air contact. The drop of oil will then seek to minimize its oil-water area by becoming spherical or near spherical. If it reaches the surface and drains of water, it may spread back to its equilibrium thickness but it remains susceptible to submergence. The drop is thus in a continuing state of deformation under the action of variable interfacial and hydrostatic forces.

We further hypothesize that during this process photoproducts tend to accumulate at the oil-water interface and act to stabilize a "skin" of asphaltenes, resins and waxes which tends to resist oil-oil coalescence. Some coalescence does occur but during the water drainage period as the oil coalesces some water is trapped as a film which eventually becomes small emulsified drops of water. This water retains the stabilizing skin and thus becomes stable water-in-oil emulsion or mousse. If the stabilizing agents are absent the emulsion is unstable.

The test of this hypothesis is to obtain data on the various energy terms, densities and thicknesses as the oil weathers and emulsifies. It would also be interesting to attempt to analyse the "skin".

In terms of oil slick behaviour it appears that oils which are slow to disperse or emulsify to form oil in water emulsions or fine droplets may survive long enough to lose their ability to disperse, thus passing at least in part into a sequence of regimes in which they form "rafts", "blobs", mousse and eventually tar balls. Just what combination of properties corresponds to this loss of natural dispersing ability is not yet known but it seems to be a combination of viscosity and interfacial or skin stability properties. It is clear that when an oil forms blobs it will be substantially submerged and not necessarily readily visible from the surface. The blobs may remain a few cm in size or they may coalesce to form larger masses or pans which continue to weather and retain their integrity, eventually weathering into tar balls.

4.3 OVERWASHING AND SUBMERGENCE

It is desirable to "consolidate" all the submergence information for all the systems studied. The following general principles of behaviour are believed to apply.

When oil pans float on a water surface with wind and wave action they are generally awash, with at least 1 mm of water, and often several cm of water. Waves are the primary cause of overwashing. There is a difference in velocity between the pan and the surface water which tends to enhance overwashing. As the oil density increases towards that of water the overwashing becomes more pronounced and the submergence depth greater with the oil spending most of the time in the top 10 cm. There appears to be a spectrum of surface eddies which can drive the oil deeper into the water such that small drops (i.e. ≦ 1 cm) are almost continually being propelled downwards, but larger drops are less frequently propelled, the "cut off" at a wind speed of 5 m/s being about a 5 to 10 cm pan which may be subjected to submergence at a frequency of the order of once per minute. Much lower frequencies apply as the pans or rafts become larger.

4.4 MATHEMATICAL MODEL

Inspection of the empirical correlation equations and the probability distribution discussed earlier leads to a suggested overall correlation for submergence.

$$P = \exp\left(-(d/D^{x})\right)$$

where $D = KU^2/\left(SGD^{0.8} \cdot (L+L_o)\right)$

and x, K and L_o are constants, d is depth of submergence of the top of the oil pan below its equilibrium (still water) elevation, U is wind speed (m/s), SGD is specific gravity difference between water and oil, and L is the mean horizontal diameter of the pan or oil drop. The mean submergence or overwash occurs approximately when P is 0.5 or $(d/D)^{x}$ is 0.693. The power on U cannot be determined accurately but a square relationship seems intuitively reasonable since this is an energy-driven process.

A computer program was written and parameters tested to select those which gave a reasonable "best" fit to the experimental data. Most reliance was placed on the lard pan data. The tentative values selected were

L_o	5 cm
x	2.0
K	0.1

The simple program to calculate submergence characteristics is given in Table 4.1 and output for various combinations are given in Figures 4.2 to 4.10 for combinations of drops of size 1, 10 and 30 cm and wind speeds of 3, 8 and 13 m/s representing three sea states. It must be emphasized that this empirical equation is extremely simple, applies only to relatively large oil masses and yields only an approximate picture of the behaviour. No guarantee can be made that these results will apply to oceanic conditions, although the magnitude of the terms seems intuitively reasonable. Field (oceanic) verification or recalibration is essential.

The equation does quantify the effect that oil does tend to be appreciably submerged at high wind speeds when the density approaches that of seawater. It should be regarded as only a first step towards mathematically modelling this complex process.

4.5 DISCUSSION OF FUTURE RESEARCH DIRECTIONS

This work has raised a number of issues which should be addressed in future research programs.

1) In connection with oil behaviour on the ocean surface, it would be useful to compile a complete inventory of physical and chemical properties of the oil slick as weathering occurs and the oil passes

from slick to raft to blob to mousse regimes. This may elucidate the causes of the regime change.

2) It would be useful to measure the air-oil-water interfacial tensions of a sheen due to weathering and photolysis to determine the magnitude of the net interfacial tension reduction. If this energy is low, it may act as a herding mechanism to promote raft formation.

3) The nature of the "skin formation" phenomenon should be investigated since it may play a controlling role in determining the rate of mousse formation and of oil blob formation.

4) An aspect of this issue which was brought to the authors' attention at the 1986 AMOP meeting is that oil densities are much more temperature sensitive than water densities. For example, when cooled from 15°C to 0°C, a typical crude oil will increase in density by approximately 50 kg/m^3 or 0.05 g/cm^3. Fresh water will increase in density by about 10 kg/m^3 and 35 parts per thousand salt water by 20 kg/m^3 in this temperature range. The net effect is that as the oil-water system cools, the oil becomes denser faster than the water and the oil-water density difference becomes smaller. The magnitude of this effect is significant and could result in oil sinking or submergence on cooling.

The effect is complicated by the lower albedo of oil resulting in the oil becoming warmer than the water when subject to solar radiation. Sunlight thus increases oil temperature more and increases the oil-water density difference.

It is thus conceivable that a slick which is fairly buoyant under warm, sunny conditions will become substantially submerged when the temperature drops and radiation is reduced.

5) Some elementary hydrodynamic calculations indicate that when an oil mass is present on a water surface and subject to waves which are of a sufficient amplitude to overwash the oil, the oil mass may adopt a lower position in the water than that dictated by "static" or "no-wave" hydrostatic calculations because (i) part of it is exposed to the wave trough and is thus out of the water and (ii) the weight of the overwash water will tend to depress the mass. Some simple wave tank experiments would be useful to elucidate this phenomenon.

6) Consideration should be given to conducting oceanic tests with lard pans, possibly using lard coated with crude oil or carbon black. If a number of these pans were made of various densities and sizes and deployed from a boat it would be possible to determine their qualitative visibility from the boat and from remote sensing systems. These tests, which could be quite simple and inexpensive in nature, could yield interesting results in terms of the density "cut-off" at which appreciable submergence occurs and at which overwashing is significant.

7) Consideration should also be given to conducting oceanic and laboratory submergence tests with real oil. This will require "synthesis" of oil pan, probably by blending waxes with a heavy fuel oil. Sand could be added for ballasting.

Table 4.1: Computer Program

```
10 REM submerge
20 Z=1
30 X=2
40 K=.1
50 INPUT "oil mass diameter  ",L
60 D=0
70 INPUT "wind speed  ",U
90 LPRINT "Submergence conditions;"
100 LPRINT "Wind velocity in m/s",U
110 LPRINT "Oil pan or drop diameter cm",L
120 LPRINT " "
130 LPRINT "Probability that the oil is below the stated depth (cm)"
140 LPRINT "expressed as a rounded-off percentage"
150 LPRINT " "
160 LPRINT "                Oil-water specific gravity differences"
170 LPRINT "Depth (cm)      0.1            0.05            0.02            0.01
   0.005"
180 FOR J=1 TO 2
190 FOR I=1 TO 20
200 S=.1
210 P1=INT(100*EXP(-(D*S^.8*(L+5)/(K*U*U))^X))
220 S=.05
230 P2=INT(100*EXP(-(D*S^.8*(L+5)/(K*U*U))^X))
240 S=.02
250 P3=INT(100*EXP(-(D*S^.8*(L+5)/(K*U*U))^X))
260 S=.01
270 P4=INT(100*EXP(-(D*S^.8*(L+5)/(K*U*U))^X))
280 S=.005
290 P5=INT(100*EXP(-(D*S^.8*(L+5)/(K*U*U))^X))
300 LPRINT D,P1,P2,P3,P4,P5
310 D=D+Z
320 NEXT I
330 Z=5
340 NEXT J
```

Figure 4.2

Submergence conditions:
Wind velocity in m/s 3
Oil pan or drop diameter cm 1

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.00
0	100	100	100	100	100
1	32	69	91	97	99
2	1	22	71	89	96
3	0	3	46	77	92
4	0	0	25	63	86
5	0	0	11	49	79
6	0	0	4	36	71
7	0	0	1	25	63
8	0	0	0	16	55
9	0	0	0	10	47
10	0	0	0	6	39
11	0	0	0	3	32
12	0	0	0	1	26
13	0	0	0	0	20
14	0	0	0	0	16
15	0	0	0	0	12
16	0	0	0	0	9
17	0	0	0	0	6
18	0	0	0	0	4
19	0	0	0	0	3
20	0	0	0	0	2
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	0	0	0	0	0
45	0	0	0	0	0
50	0	0	0	0	0
55	0	0	0	0	0
60	0	0	0	0	0
65	0	0	0	0	0
70	0	0	0	0	0
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

Figure 4.3
Submergence conditions;
Wind velocity in m/s 8
Oil pan or drop diameter cm 1

Probability that the oil is below the stated depth (cm)
expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	97	99	99	99	99
2	91	97	99	99	99
3	81	93	98	99	99
4	70	89	97	99	99
5	57	83	95	98	99
6	45	76	94	98	99
7	33	69	92	97	99
8	24	62	89	96	98
9	16	55	87	95	98
10	10	48	84	94	98
11	6	41	81	93	97
12	4	35	78	92	97
13	2	29	75	91	96
14	1	23	71	89	96
15	0	19	68	88	95
16	0	15	65	86	95
17	0	12	61	85	94
18	0	9	58	83	94
19	0	7	54	81	93
20	0	5	51	80	92
25	0	1	34	70	89
30	0	0	22	60	84
35	0	0	12	50	79
40	0	0	6	41	74
45	0	0	3	32	69
50	0	0	1	24	63
55	0	0	0	18	57
60	0	0	0	13	51
65	0	0	0	9	46
70	0	0	0	6	40
75	0	0	0	4	35
80	0	0	0	2	31
85	0	0	0	1	26
90	0	0	0	1	22
95	0	0	0	0	19
100	0	0	0	0	16
105	0	0	0	0	13
110	0	0	0	0	10
115	0	0	0	0	8

Figure 4.4

Submergence conditions:
Wind velocity in m/s 13
Oil pan or drop diameter cm 1

Probability that the oil is below the stated depth (cm)
expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.00
0	100	100	100	100	100
1	99	99	99	99	99
2	98	99	99	99	99
3	97	99	99	99	99
4	95	98	99	99	99
5	92	97	99	99	99
6	89	96	99	99	99
7	85	95	98	99	99
8	81	93	98	99	99
9	77	91	98	99	99
10	72	90	97	99	99
11	68	88	97	99	99
12	63	86	96	98	99
13	58	83	96	98	99
14	53	81	95	98	99
15	49	79	94	98	99
16	44	76	94	97	99
17	40	73	93	97	99
18	35	71	92	97	99
19	31	68	91	97	99
20	28	65	90	96	98
25	13	52	86	95	98
30	5	39	80	93	97
35	2	27	74	90	96
40	0	18	67	88	95
45	0	12	61	85	94
50	0	7	54	81	93
55	0	4	48	78	92
60	0	2	41	75	90
65	0	1	36	71	89
70	0	0	30	67	87
75	0	0	25	63	86
80	0	0	21	60	84
85	0	0	17	56	82
90	0	0	14	52	80
95	0	0	11	48	78
100	0	0	8	45	76
105	0	0	7	41	74
110	0	0	5	38	72
115	0	0	4	34	70

Figure 4.5

Submergence conditions;
Wind velocity in m/s 3
Oil pan or drop diameter cm 10

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	0	10	58	83	94
2	0	0	11	49	79
3	0	0	0	20	59
4	0	0	0	6	39
5	0	0	0	1	23
6	0	0	0	0	12
7	0	0	0	0	5
8	0	0	0	0	2
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	0	0	0	0	0
45	0	0	0	0	0
50	0	0	0	0	0
55	0	0	0	0	0
60	0	0	0	0	0
65	0	0	0	0	0
70	0	0	0	0	0
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

Figure 4.6

Submergence conditions;
Wind velocity in m/s 8
Oil pan or drop diameter cm 10

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

Depth (cm)	Oil-water specific gravity differences 0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	87	95	98	99	99
2	57	83	95	98	99
3	28	66	90	96	98
4	10	48	84	94	98
5	3	32	76	91	97
6	0	19	68	88	95
7	0	10	59	84	94
8	0	5	51	80	92
9	0	2	42	75	91
10	0	1	34	70	89
11	0	0	28	65	87
12	0	0	22	60	84
13	0	0	16	55	82
14	0	0	12	50	79
15	0	0	9	45	77
16	0	0	6	41	74
17	0	0	4	36	71
18	0	0	3	32	69
19	0	0	2	28	66
20	0	0	1	24	63
25	0	0	0	11	48
30	0	0	0	4	35
35	0	0	0	1	24
40	0	0	0	0	16
45	0	0	0	0	9
50	0	0	0	0	5
55	0	0	0	0	3
60	0	0	0	0	1
65	0	0	0	0	0
70	0	0	0	0	0
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

Figure 4.7

Submergence conditions;
Wind velocity in m/s 13
Oil pan or drop diameter cm 10

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	98	99	99	99	99
2	92	97	99	99	99
3	83	94	98	99	99
4	72	90	97	99	99
5	60	84	96	98	99
6	49	79	94	98	99
7	37	72	92	97	99
8	28	65	90	96	98
9	20	58	88	96	98
10	13	52	86	95	98
11	9	45	83	94	98
12	5	39	80	93	97
13	3	33	77	91	97
14	2	27	74	90	96
15	1	23	71	89	96
16	0	18	67	88	95
17	0	15	64	86	95
18	0	12	61	85	94
19	0	9	58	83	94
20	0	7	54	81	93
25	0	1	38	73	90
30	0	0	25	63	86
35	0	0	15	54	81
40	0	0	8	45	76
45	0	0	4	36	71
50	0	0	2	28	66
55	0	0	1	22	60
60	0	0	0	16	55
65	0	0	0	12	50
70	0	0	0	8	44
75	0	0	0	6	39
80	0	0	0	4	35
85	0	0	0	2	30
90	0	0	0	1	26
95	0	0	0	1	22
100	0	0	0	0	19
105	0	0	0	0	16
110	0	0	0	0	13
115	0	0	0	0	11

Figure 4.8
Submergence conditions;
Wind velocity in m/s 3
Oil pan or drop diameter cm 30

Probability that the oil is below the stated depth (cm)
expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	0	0	5	38	72
2	0	0	0	2	28
3	0	0	0	0	5
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	0	0	0	0	0
45	0	0	0	0	0
50	0	0	0	0	0
55	0	0	0	0	0
60	0	0	0	0	0
65	0	0	0	0	0
70	0	0	0	0	0
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

Figure 4.9
Submergence conditions;
Wind velocity in m/s 8
Oil pan or drop diameter cm 30

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	47	78	94	98	99
2	4	37	79	92	97
3	0	10	59	84	94
4	0	1	40	73	90
5	0	0	23	62	85
6	0	0	12	50	79
7	0	0	6	39	73
8	0	0	2	29	67
9	0	0	0	21	60
10	0	0	0	15	53
11	0	0	0	10	47
12	0	0	0	6	40
13	0	0	0	4	34
14	0	0	0	2	29
15	0	0	0	1	24
16	0	0	0	0	20
17	0	0	0	0	16
18	0	0	0	0	13
19	0	0	0	0	10
20	0	0	0	0	8
25	0	0	0	0	2
30	0	0	0	0	0
35	0	0	0	0	0
40	0	0	0	0	0
45	0	0	0	0	0
50	0	0	0	0	0
55	0	0	0	0	0
60	0	0	0	0	0
65	0	0	0	0	0
70	0	0	0	0	0
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

Figure 4.10

Submergence conditions;
Wind velocity in m/s 13
Oil pan or drop diameter cm 30

Probability that the oil is below the stated depth (cm) expressed as a rounded-off percentage

	Oil-water specific gravity differences				
Depth (cm)	0.1	0.05	0.02	0.01	0.005
0	100	100	100	100	100
1	89	96	99	99	99
2	64	86	96	98	99
3	37	72	92	97	99
4	17	56	87	95	98
5	6	41	81	93	97
6	2	27	74	90	96
7	0	17	66	87	95
8	0	10	59	84	94
9	0	5	51	80	93
10	0	2	44	76	91
11	0	1	37	72	89
12	0	0	30	67	87
13	0	0	24	63	85
14	0	0	20	58	83
15	0	0	15	54	81
16	0	0	12	50	79
17	0	0	9	45	77
18	0	0	7	41	74
19	0	0	5	37	72
20	0	0	3	33	69
25	0	0	0	18	57
30	0	0	0	8	44
35	0	0	0	3	33
40	0	0	0	1	23
45	0	0	0	0	16
50	0	0	0	0	10
55	0	0	0	0	6
60	0	0	0	0	4
65	0	0	0	0	2
70	0	0	0	0	1
75	0	0	0	0	0
80	0	0	0	0	0
85	0	0	0	0	0
90	0	0	0	0	0
95	0	0	0	0	0
100	0	0	0	0	0
105	0	0	0	0	0
110	0	0	0	0	0
115	0	0	0	0	0

5. CONCLUSIONS

A series of laboratory experiments has been conducted, and have been reported which explore the oil submergence phenomena.

Oil can be simulated using ballasted wooden blocks, plastic balls or ballasted lard pans. The lard pans are preferred.

There are formidable experimental difficulties in quantifying the submergence phenomena. The best approach appears to be the postulation of a probability distribution function.

The depth of submergence is primarily influenced by oil density relative to water, by turbulence and by oil pan size. A tentative mathematical model is proposed which is structured to express the effect of these factors quantitatively. It requires oceanic calibration.

The spreading-retreating process of oil on a water surface has been examined. It is apparent that as oil weathers it tends to pass through various regimes of (i) a "slick" phase in which the oil spreads thinly, (ii) a "raft" phase in which the oil retreats into thicker patches, (iii) a "blob" phase in which discrete oil drops form, and which often submerge and finally (iv) a "mousse" phase in which the oil emulsifies to denser more viscous drops which may be frequently submerged. In the later stages on appreciable fraction of the oil may be submerged. The nature of these processes is worthly of investigation and may form oil drops which are susceptible to submergence. The nature of these processes is worthy of further investigation.

Finally, some recommendations have been made for future studies.

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