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CONTROL OF OIL SLICKS IN FLOWING WATER USING AIR BUBBLE BARRIERS

by

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1. INTRODUCTION

In recent years air bubble barriers have been proposed for use in oil spill containment. Although a great deal of literature is available on air barriers, the majority of these dealt with their behaviour in still water and their use for keeping harbours free of ice or as breakwaters. Relatively little has been published concerning the behaviour of air barriers in the presence of a current and especially their ability to control oil spills in flowing water.

The Prairie Region Oil Spill Containment And Recovery Advisory Committee (P.R.O.S.C.A.R.A.C.) is interested in the possible use of air barriers for oil spill control in rivers. This study is carried out at the request of P.R.O.S.C.A.R.A.C. to investigate the effectiveness of air barriers for the containment or the diversion of oil slicks in open-channel flows. Because there is some urgency involved in obtaining results for use in the planning of a field exercise, this study is limited to an experimental investigation and no detailed theoretical analysis is included.

2. BACKGROUND REVIEW

A brief review of the dynamics of air barriers and their use for oil retention will be given here in order to focus attention on the items requiring investigation.

As air bubbles are released under water they rise to the surface, forming a plume of bubbles. This plume drags and entrains water along with it and produces an upward flow. As the upward flow of water hits the surface it is deflected and a surface current is generated. The flow pattern induced by the bubble plume is shown schematically in Figure 1.

Taylor (1955), by analogy with currents produced by a line source of heat, derived the following formula for the maximum vertical velocity in the plume:

$$V_{max} = k(gq)^{1/3} \tag{1}$$

where V_{max} is the maximum vertical velocity

g is the gravitational acceleration

q is the air flow rate per unit width

and k is a constant of proportionality

Assuming that no energy is lost as the vertical current is deflected into a horizontal current, the maximum surface velocity which is generated, U_{max}, will be equal to V_{max}.

The currents generated by air bubbles in still water have been measured by many workers and all have verified the fact that the maximum surface velocity is proportional to the air flow rate to the one-third power as given in equation (1). However, different values have been obtained for the dimensionless constant k, varying from 0.78 to the theoretical value of 1.90 given by Taylor. Basko (1971) found that k had a tendency to increase with depth. Grace and Sowyrda (1970) also found that the surface velocity increased with depth, although they did not compute values for k.

When an air barrier is deployed in flowing water, such as in a river, the bubble plume is deflected in the downstream direction and the actual upstream surface velocity which the barrier can generate is of course less than when it is in stagnant water. At some distance upstream of the plume, there is a stagnation point where the upstream current is stopped by the downstream flow. This configuration is shown schematically in Figure 2.

Basko (1971) assumed that the surface current generated in this case is equal to the linear superposition of the flow generated in stagnant water and the mean flow velocity, i.e.,

$$U_m' = U_{max} - U_{mean} \tag{2}$$

where U_m' is the maximum surface current

U_{mean} is the mean flow velocity

and U_{max} is the maximum surface current which would be generated in stagnant water

Measurements by Basko appeared to confirm this assumption. However, experiments by Jones (1972) showed that for small mean flows, the maximum surface velocity was about the same as the stagnant case except that the location of the maximum velocity was much closer to the bubble mound. For larger mean flows, the maximum surface current became much smaller than equation (2) would indicate. No other published data exist which can resolve this difference.

Tests of oil retention by air barriers in stagnant water were conducted by Basko (1971) in two channels with water depths of 2 feet and 7.7 feet respectively. He found that failure occurred when the densimetric Froude number based on oil slick thickness was greater than 1.2, i.e.

$$\frac{U_{max}}{\sqrt{gh\Delta}} \geq 1.2 \qquad (3)$$

where h is the thickness of the slick

and Δ = (1 - specific gravity of oil)

However, similar tests were carried out by Jones (1972) who found that the densimetric Froude number for failure was not a constant but varied with the densimetric Reynolds number $\frac{U_m h\Delta}{\nu_w}$, in which ν_w is the kinematic viscosity of water. The values for the critical densimetric Froude number varied from 0.72 to 0.91.

For oil retention in flowing water, Basko (1971) found that the critical densimetric Froude number of 1.2 was still valid when the velocity U_{max} was replaced by U_m'. Jones (1972) however found that the air barrier could not successfully contain oil in a current. For U_{max} equal to 1.25 ft/sec and U_{mean} equal to 0.75 ft/sec, Jones found that the oil slick went through the barrier on the surface. As the air flow was increased, the oil appeared to be held at the edge of the bubble mound but oil drops were torn off the bottom of the slick, went through the bubble plume and passed downstream. As the air flow rate was increased the slick was moved upstream but the amount of oil entrainment at the bottom of the slick appeared to increase. No measurement of this entrainment loss rate was made.

Since the primary objective of this study is to investigate the effectiveness of air barriers for oil spill control, the conflicting results of Basko (1971) and Jones (1972) must be resolved. Therefore, experiments were designed to study whether an air barrier placed at right angles to the flow can indeed retain an oil slick.

There is also interest in the ability of the air barriers to direct oil slicks to areas suitable for containment and clean-up. No material has been published so far dealing with oil slick diversion by air barriers. A successful case of diversion in the Chicago Barge and Sanitary Canal was cited by Jones (1972) but no details are available. Therefore the second part of this study was designed to investigate how well air barriers can divert oil slicks in different flow conditions.

Different types of oil were used in the study in order to investigate possible effects of oil properties on the effectiveness of the air barriers.

3. EXPERIMENTAL EQUIPMENT

The Flume

All tests were conducted in a flume rectangular in cross-section, one metre wide with glass walls 72 cm high and having an overall length of about 22 metres. Water was fed from a large constant-head tank through a 16 in.(41 cm) pipe which was terminated by a diffuser in the head box of the flume. In addition, baffles were placed in the head box to reduce surging of the flow and to provide a satisfactory velocity distribution throughout the cross-section of the flow at the entrance of the flume. Water discharge measurements were made to an accuracy of ±5% with a rectangular weir which received the discharge from the flume. Oil from the tests was largely retained downstream of the working section by means of a mechanical boom, which spanned the full width of the flume from where it was then manually removed and discarded.

For the first phase of the study (i.e. containment of oil by bubble barrier), the width of the flume was reduced to 60 cm, thus permitting faster flows within the discharge capacity of the measuring weir, Figure 3. A wooden partition was constructed, 40 feet long, built in four 72 cm x 250 cm sections end to end using 3/4" (19 mm) plywood which was thoroughly waterproofed and one similar section of 1/2" (12.5 mm) acrylic. The acrylic window was placed at the working section to allow lighting of the water from the far side for better viewing of the air-bubble-oil slick interaction.

For the second phase of the study (i.e. diversion of oil by bubble barrier), the partition was removed and the full one metre width of the flume was used, providing sufficient channel width for diversion of the oil slick.

The Air Bubbler Manifold

Air was introduced into the flow through a manifold fabricated from 1/2" (12.5 mm) diameter steel tubing with a row of 2 mm diameter holes drilled along the top, spaced 1 cm apart. The manifold was attached to the flume wall as shown in Figure 4. The vertical air supply pipe was fitted with a protractor and pointer to measure the angle of the bubbler manifold with respect to the flume wall during the slick diversion phase of the study, Figure 4.

For the containment phase of the study, a 60 cm manifold length was used to provide air bubbles over the full width of the channel. For the diversion study phase, a 45 cm length was used to provide the best balance between barrier length and channel width for effective diversion of the oil slick. The end of the manifold in each case was plugged and the intake connected to the laboratory air supply.

The air supply was controlled by passing it through a regulator and then through a needle point valve. This permitted the necessary fine adjustment of the air flow into the flume to obtain a suitable range of upstream velocities generated by the air bubble plume for a given set of flow conditions.

Types of Oil Used

Two synthetic oils, obtained from the Jetco Chemicals Co. in Corsicana, Texas, were used for this study. A third type was obtained by blending the two Jetco oils. The properties of the oils are summarized in Table 1. It can be seen that the oils used ranged from a light oil with low viscosity to a heavy oil with extremely high viscosity.

Two crude oils were also used in some of the preliminary experiments until their supply was exhausted. In general, the behaviour was much the same as the other oils.

4. EXPERIMENTAL PROCEDURE

Containment of Oil Slicks

Containment tests were conducted in the 60 cm wide channel with the manifold extending over the full width and perpendicular to the flow. The flow was set at a given depth and the discharge chosen to obtain a desirable average flow velocity. Once a steady, uniform flow was obtained, the surface velocity was measured with a Kent mini current meter. The air was then turned on to generate an upstream velocity, the maximum of which was located by trial and error and measured with the mini current meter. The upstream velocity was taken as the average of several measurements, but due to the highly turbulent flow conditions at the bubble plume, the variance of those measurements was found to be high. This was especially true when the air flow rate was low and the region with upstream flow occurred very close to the bubble mound.

Once the upstream velocity was established, oil was introduced by passing about 4000 ml of it into the flow at the upstream end of the channel. The slick was carried downstream where it was detained by a mechanical boom. This allowed the oil to collect into a slick which was then released to approach the bubble barrier. As soon as the slick reached the bubble barrier, its length was measured and the time noted. Observations of the slick were made to determine if it was being contained by the barrier or not. If oil loss by entrainment occurred, the loss rate was estimated by measuring the length of the slick with time.

After all the measurements had been made, the slick was allowed to pass downstream. Then the test was repeated with a different type of oil, with all other conditions unchanged. After all the oils had been tested, the air flow rate was increased to obtain a higher upstream surface velocity. The procedure was then repeated.

After a range of upstream velocities had been tested, the flow conditions were changed by changing the discharge while keeping the depth fixed. The experiments were then repeated. The test data are given in Table 2.

Diversion of Oil Slicks

The diversion tests were conducted with a 45 cm long manifold. At the beginning of a test the manifold was placed normal to the flow so that it extended from the window side 45 cm across the flume. After the flow in the flume was set up the air flow was switched on. A quantity of oil was released into the flow and observed to determine whether or not it was diverted by the barrier. If the barrier was not successful in completely diverting the oil, the manifold was rotated about a vertical axis at the wall so that it started to point downstream. The angle Θ between the manifold and the wall, i.e. the downstream flow direction, was measured, Figure 5a. Oil was again released for observation. The manifold was rotated until the oil was completely diverted around the bubble plume and none passed through. The angle Θ in that case was called Θ_{max} as it represented the maximum angle at which the manifold could be placed to the flow for complete diversion of oil, with the given air flow and ambient flow conditions.

The test was repeated using the other oils. The air flow rate was then increased and the procedure was repeated. After that the flume discharge was changed to obtain a different flow velocity or a different flow depth and the whole series of tests was repeated.

Table 3 summarizes the test data for the diversion experiments.

It would have been desirable to have measurements of air flow rates during these experiments. However, no flowmeter was available and therefore it was decided to use the induced upstream surface velocity as an indication of the air flow intensity. During preliminary testing, it was discovered that the air flow rates required for diversion were fairly small. This, plus the fact that the bubbler only extended less than half way across the flume, caused the bubble plume to be deflected at an angle as shown in Figure 5b, even though the manifold itself was normal to the flow. Measurements of the upstream surface velocity U_m' were very difficult and very unreliable in those cases. Instead, measurements were made of the angle of inclination of the bubble plume, α, and the surface velocity along that direction U_α, Figure 5b. The downstream component of U_α,($U_\alpha \cos\alpha$), was then assumed to be equal to the linear superposition of the surface velocity far upstream U_s, and the induced upstream velocity U_m'. Knowing U_α, α and U_s, U_m could be calculated. All the values for U_m' for the diversion test were obtained this way. The only exception was the one case in which the air flow rate was large enough that the bubble plume became almost normal to the flow and there was a large region with upstream surface flow where U_m' could be easily measured.

A number of these measurements of U_m' was checked by inserting a piece of plywood into the flume parallel to the flow to form a partition so that the 45 cm bubbler again occupied the full width of the flow. The upstream velocity was measured in the same manner as in the containment tests. The readings agreed to within about ten percent.

5. RESULTS AND DISCUSSION

Containment of Oil Slicks

The experiments usually started with the lowest air flow rates. When the air flow was too small the oil slicks simply passed right through the bubble plume on the surface. As the air flow rate and hence U_m' was increased, the slick was arrested just upstream of the bubble mound. However, it was observed that vortices were intermittently generated on the underside of the oil slick and oil was being torn off and carried through the bubble plume under water. These vortices looked like tornadoes on the underside of the slick. These 'tornadoes' would grow in size before eventually breaking up, scattering oil droplets into the flow. Some of the droplets remained in the stagnation region while others were carried through downstream. Figure 6 shows some typical pictures of this situation. When the air flow was increased, the slick was pushed further upstream but the rate at which the vortices were formed also seemed to increase. However, with the slick being farther away from the bubble plume, more of the entrained droplets returned to the slick. These observations are very similar to those made by Jones (1972). It was not possible to determine any kind of critical densimetric Froude number as was reported by Basko (1971) because there was always failure of some kind. The oil was either lost by passing through on the surface or by entrainment from the underside of the slick. Of course, in the latter case the rate of loss of oil was much smaller. Whether or not entrainment occurred was not governed by oil layer thickness at all.

For the very viscous oil, no. J-3, the vortices would tear the oil off in filaments rather than drops as shown in Figure 7. The tornadoes were not as pronounced probably because of the much greater viscosity of this oil. The overall behaviour was, however, very much the same as the other two oils.

To obtain a measurement of the rate of loss of oil by the entrainment from the underside of the slick, the length of the slick was measured at the time it first reached the bubble plume. The slick length was then measured as time progressed. It was noted that the slick thicknesses appeared to remain fairly constant with time. The change in slick length was therefore assumed to be directly proportional to the change in its volume. Since the initial volume which was released into the flume was known, the rate of loss of oil could be calculated. The entrainment loss rates E, in cm^3 of oil per second per cm of width, are given in Table 2.

Figure 8 shows a plot of E versus U_m' for the various tests with oil J-1. The results indicate that as the induced upstream velocity U_m' was increased, the entrainment rate E decreased. The decrease with U_m' was more pronounced when the surface velocity far upstream, U_s, was large. The results for the other two oils J-2 and J-3 are shown in Figure 9 and 10 respectively. The same trend is indicated in these two Figures. Comparison of the data shows that, for the same flow conditions and bubbling rates, the entrainment loss rates were not too different for the three oils even though their physical properties are quite different. The oil viscosity, for instance, varies from 8.5 cp to 4250 cp. The vortex action which pulls oil from the slick downwards into the flow is governed mainly by the turbulence generated by the bubble plume and the bursting of the bubbles at the surface and it appears that this action is not much affected by any viscous damping.

If one assumes that the oil properties do not govern the entrainment loss rate, then E should depend only on U_s, U'_m and g. Using dimensional analysis, one can write

$$\frac{Eg}{U'^3_m} = f\left(\frac{U'_m}{U_s}\right) \qquad (4)$$

The dimensionless loss rate $\frac{Eg}{U'^3_m}$ is plotted against $\frac{U'_m}{U_s}$ in Figure 11. It can be seen that all the data fall more or less on one curve. The agreement is quite good considering that the method of measuring E by measuring slick length was not an exact method and might have involved errors of up to fifteen percent. Figure 11 appears to confirm that the physical properties of the oils are not very significant as far as entrainment loss rate is concerned.

It should be noted that when $\frac{U'_m}{U_s}$ decreases to about 0.5, the loss rate increases very sharply. This seems to be the value of $\frac{U'_m}{U_s}$ when the oil begins to break through the bubble plume on the surface.

The flow depth was maintained constant at 64 cm in the containment tests. Because the observed behaviour of the entrainment loss was so similar to the observations made by Jones (1972) with water depth of 7 ft., it can be assumed that the depth had no effect on the behaviour of the slick. Of course, the air supply required to produce a given U'_m may change with the depth of the manifold.

Diversion of Oil Slicks

In these tests, the maximum angle at which the manifold could be placed to the flow, Θ_{max}, (Figure 5a) was measured for various combinations of U_s and air flow rate. It was discovered that at the larger air flow rates, the oil slicks were diverted around the bubble plume even when the manifold was placed normal to the flow, i.e. $\Theta = 90°$. Θ_{max}

was given a value of 90° for these cases and a number of these are shown in Figure 12. As the air flow rate was reduced, some of the oil began to pass through the bubble plume along the water surface but there was no entrainment from the underside. By rotating the manifold to point downstream, i.e. reducing Θ, complete diversion could again be achieved. Successful diversion was achieved in every case. Some typical pictures are shown in Figure 13. Values for Θ_{max} and other data are given in Table 3. The maximum surface flow velocity used was 50.2 cm/s (1.12 miles/hour) but there is no doubt that diversion can be achieved for higher velocities.

The results again seemed to show that the effect of using different oils was very insignificant and whether diversion was successful or not depended largely on U_s and U'_m. Therefore, Θ_{max} is plotted against $\frac{U'_m}{U_s}$ in Figure 14, which shows that data for all three oils are much the same. Some scatter can be expected because there is some degree of subjectiveness involved in deciding whether or not a slick was *completely* diverted. It can be seen from Figure 14 that for values of $\frac{U'_m}{U_s}$ larger than about 0.75, Θ_{max} has reached 90° and barriers placed normal to the flow can successfully divert an oil slick. Even at $\frac{U'_m}{U_s}$ equal to 0.4, a barrier can be placed at 50° to the flow and still divert oil. Θ_{max} appears to decrease linearly with $\frac{U'_m}{U_s}$ but it is not certain whether the extrapolation can be taken down to Θ_{max} equal to zero.

It should be noted that the bubbler cannot be used successfully as a diverter if it occupies too much of the width of the channel. When the 45 cm long manifold was used in a 60 cm wide channel the cross current which was generated would hit the opposite wall and part of it would deflect upstream, setting up an upstream current. The oil slick, rather than passing around the plume and going downstream, was contained upstream of the bubble plume very much like in the containment tests. Oil loss by entrainment from the underside then took place. This problem did not occur when the 45 cm manifold was used in the 1 metre wide channel.

6. SUMMARY AND CONCLUSIONS

Results of the laboratory experiments show that an air bubble barrier can never completely contain an oil slick in a river. If the air flow rate is not large enough, the slick simply flows through the bubble plume. If the air flow rate is increased so that the slick is held back, loss of oil by entrainment from the underside of the slick would occur. However, this does not mean that air barriers are completely useless for oil control because it can arrest the downstream movement of the slick and allow time for clean up action. If the air flow rate can be made large enough, the entrainment loss rate may be fairly small. For example if U_s is equal to one foot per second and $\frac{U'_m}{U_s}$ is equal to 2, Figure 11 shows that $\frac{Eg}{U'^3_m} \approx 0.02$. In this case the entrainment loss from a 30 foot wide slick would be about 0.4 barrels per minute.

Figure 11 shows that the dimensionless entrainment loss $\frac{Eg}{U'^3_m}$ depends only on $\frac{U'_m}{U_s}$ and effects of oil properties are insignificant.

Tests using the air barriers to divert oil show that the barriers are very effective for this purpose. For small currents or large air flow rates, the barrier can be placed normal to the flow and still divert oil around it. For larger mean flows or smaller air flow rates the barrier has to be placed at an angle. The maximum angle at which the barrier can be placed to the flow for complete diversion is a function of the ratio $\frac{U'_m}{U_s}$, as shown in Figure 12. Again, oil properties appear to have little effect.

An air barrier cannot divert oil successfully if the barrier occupies too much of the width of the channel. The upstream current which is set up impedes the movement of the oil downstream, resulting in a contained slick with entrainment losses along the whole width of the slick. A preliminary indication is that, for effective diversion, the bubble barrier should not extend more than three-quarters of the way across a channel.

The induced upstream velocity U_m' was rather difficult to measure, especially when the air flow rate was small. Hence there may be errors of up to ten percent in the absolute value of U_m' reported. For practical purposes, the air flow rates should be used since these can be measured much more easily. The air flow rates could be related to U_m' using the results of published studies.

This report gives a rough guide to the effectiveness of air barriers for oil-slick control. For practical situations, other factors such as cost, ease of deployment etc., have to be considered.

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8. ACKNOWLEDGEMENTS

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TABLE 1. OIL PROPERTIES

Oil Type	Density @ 20°C	Viscosity @ 22°C cP	Oil-Water interfacial tension @ 20°C dynes/cm
J-1	0.8738	8.49	38.7
J-2	0.8773	29.35	41.6
J-3	0.9590	4250.0	86.1

TABLE 2. DATA FOR CONTAINMENT TESTS

H cm	U_s cm/s	U'_m cm/s	U'_m/U_s	Entrainment Loss Rate E $\frac{cm^3}{sec\ cm}$ Oil J-1	Oil J-2	Oil J-3	Eg/U'^3_m Oil J-1	Oil J-2	Oil J-3
64	15.0	18.0	1.20	0.68	0.70	1.18	.114	.118	.199
64	15.0	24.8	1.65	0.60	0.70	-	.039	.045	-
64	15.0	32.5	2.17	0.45	0.67	1.07	.013	.019	.031
64	15.0	38.0	2.53	-	0.68	0.93	-	.012	.017
64	22.2	15.0	0.67	2.0	2.53	2.65	.581	.735	.770
64	22.2	22.5	1.01	1.77	2.08	2.92	.152	.179	.252
64	22.2	27.5	1.24	1.17	1.43	1.46	.055	.068	.069
64	28.0	13.5	0.48	4.48	5.96	-	1.79	2.35	-
64	28.0	15.8	0.56	3.43	3.88	-	.853	.965	-
64	28.0	21.5	0.77	2.91	3.63	5.83	.287	.358	.576
64	28.0	30.0	1.07	2.16	3.67	-	.079	.133	-

TABLE 3. DATA FOR OIL DIVERSION TESTS

H cm	U_s cm/s	U'_m cm/s	U'_m/U_s	Θ_{max} (degrees) Oil J-1	Oil J-2	Oil J-3
64	31.0	19.9	0.64	85	82.5	89
64	31.0	23.2	0.75	90	90	90
64	31.0	16.8	0.54	67.5	65	68
64	26.5	14.9	0.56	79	79	79
64	26.5	19.3	0.73	90	90	86
64	20.0	11.6	0.58	90	90	90
45	50.2	28.0	0.56	70	60	58
45	50.2	26.7	0.53	70	59	40
45	50.2	23.8	0.47	60	55	54
45	50.2	20.6	0.41	55	48	48
45	38.0	21.6	0.57	80	77.5	68
45	38.0	23.0	0.60	80	77	68
45	38.0	26.8	0.71	85	85	82
45	30.0	23.6	0.79	90	90	90
45	30.0	21.8	0.73	90	90	85
45	30.0	20.0	0.67	82	80	75
45	30.0	16.5	0.55	58	58	58
45	19.5	15.2	0.77	90	90	90
45	19.5	16.1	0.83	90	90	90
45	19.5	12.6	0.65	84	84	84
45	19.5	32.8	1.68	90	90	90

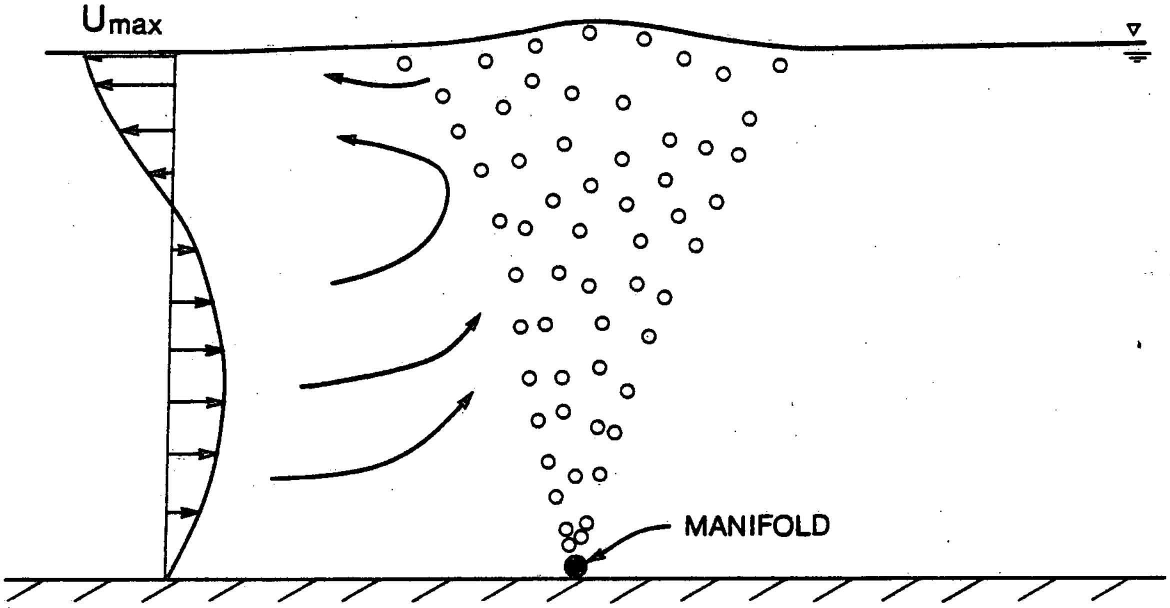


FIGURE 1. CURRENT PATTERN GENERATED BY A BUBBLE PLUME IN STILL WATER.

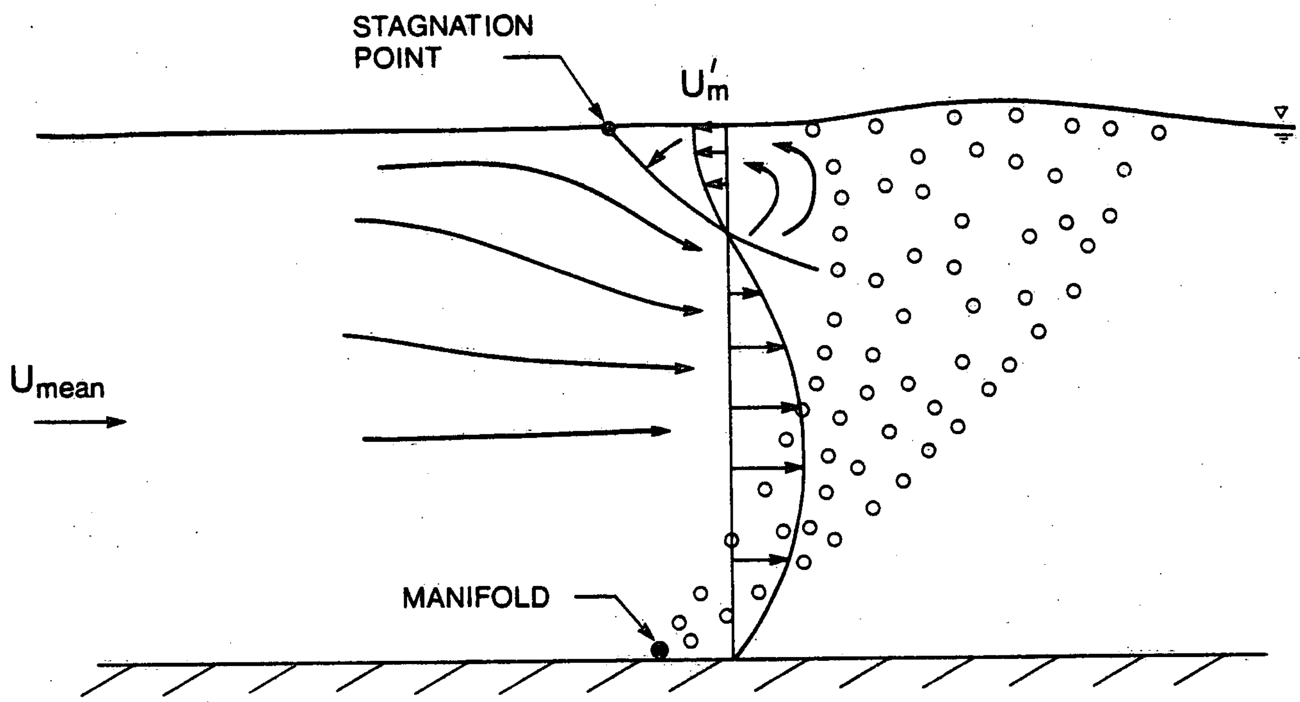


FIGURE 2. CURRENT PATTERN GENERATED BY A BUBBLE PLUME IN FLOWING WATER.

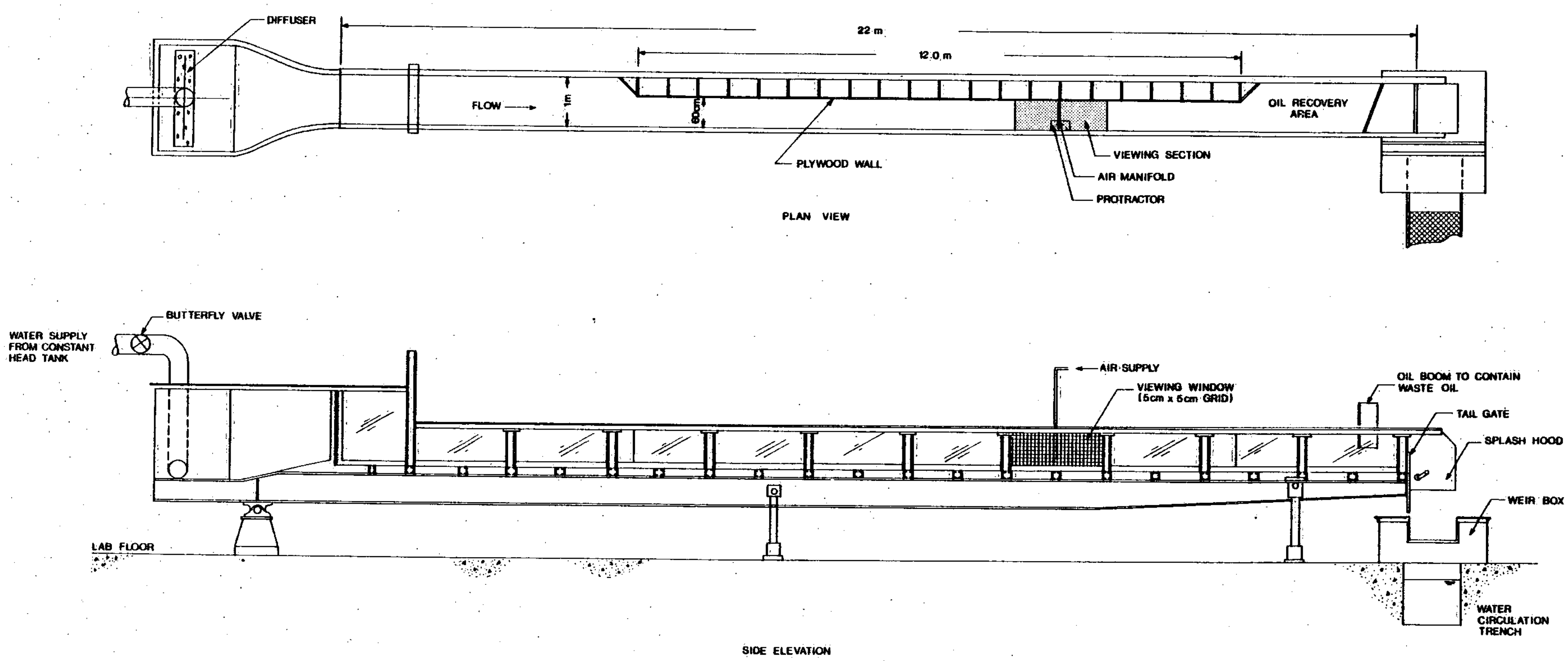
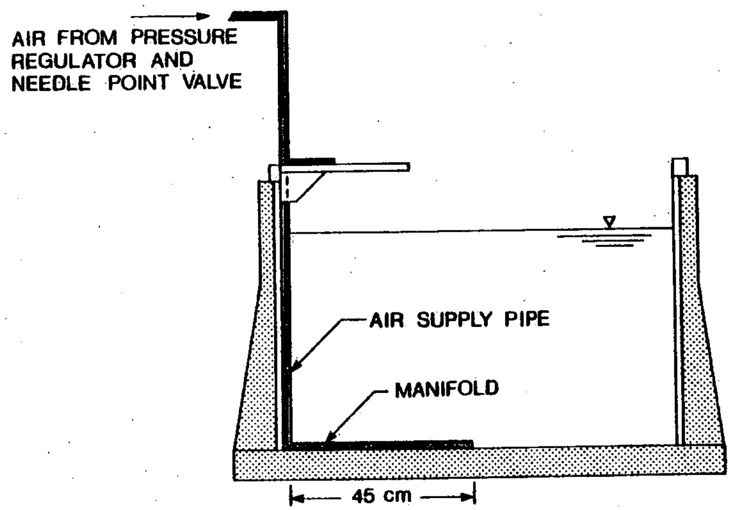
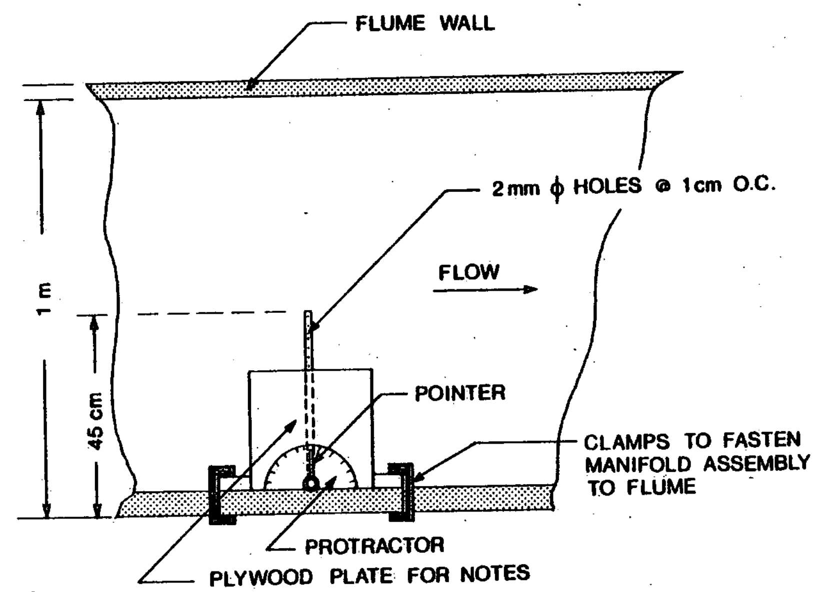


FIGURE 3. EXPERIMENTAL SET-UP IN 1m FLUME



CROSS - SECTION - UPSTREAM VIEW



PLAN VIEW

FIGURE 4. DETAILS OF AIR BUBBLE MANIFOLD

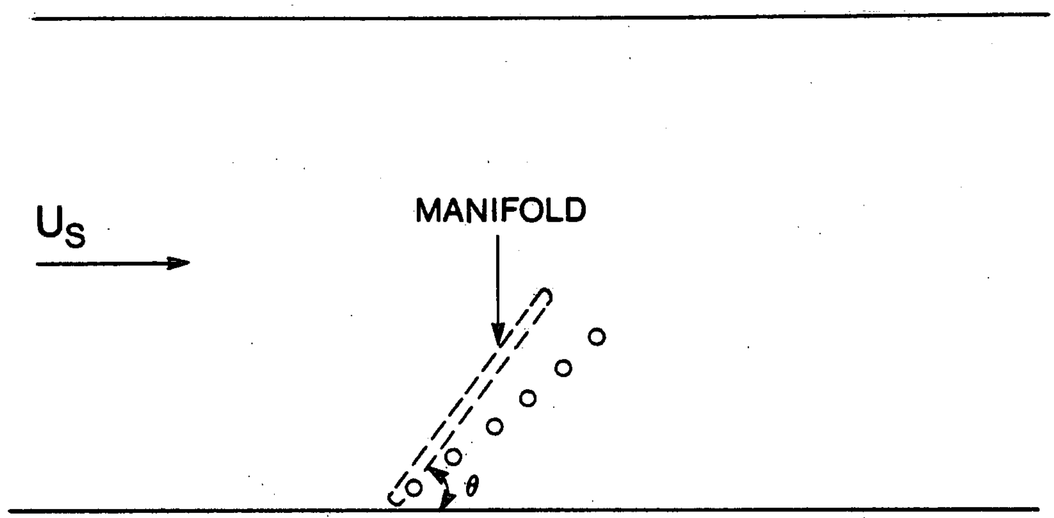


FIGURE 5a. PLAN VIEW OF MANIFOLD POSITIONED AT AN ANGLE TO THE FLOW.

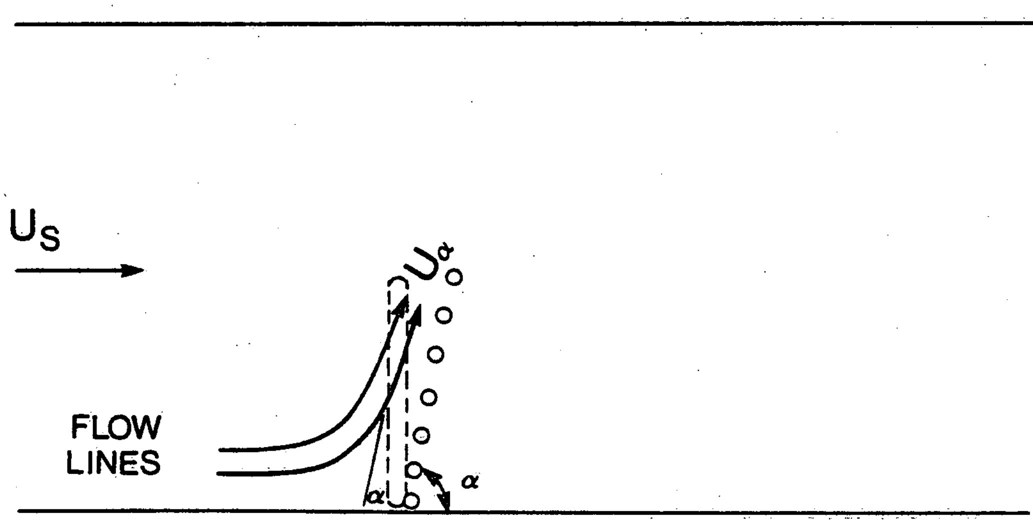
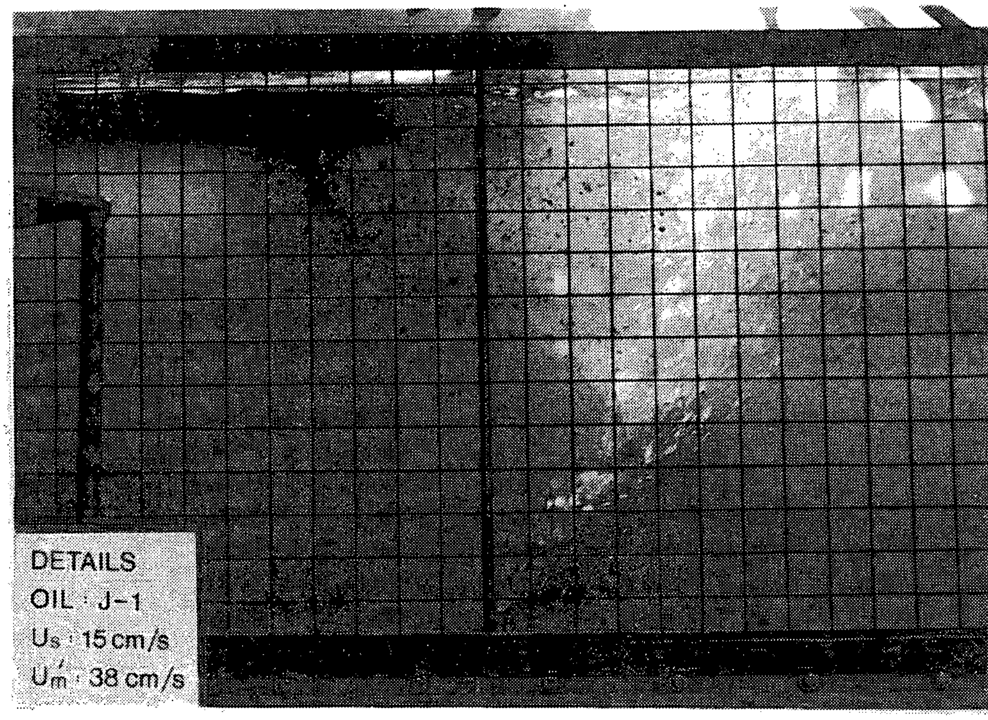
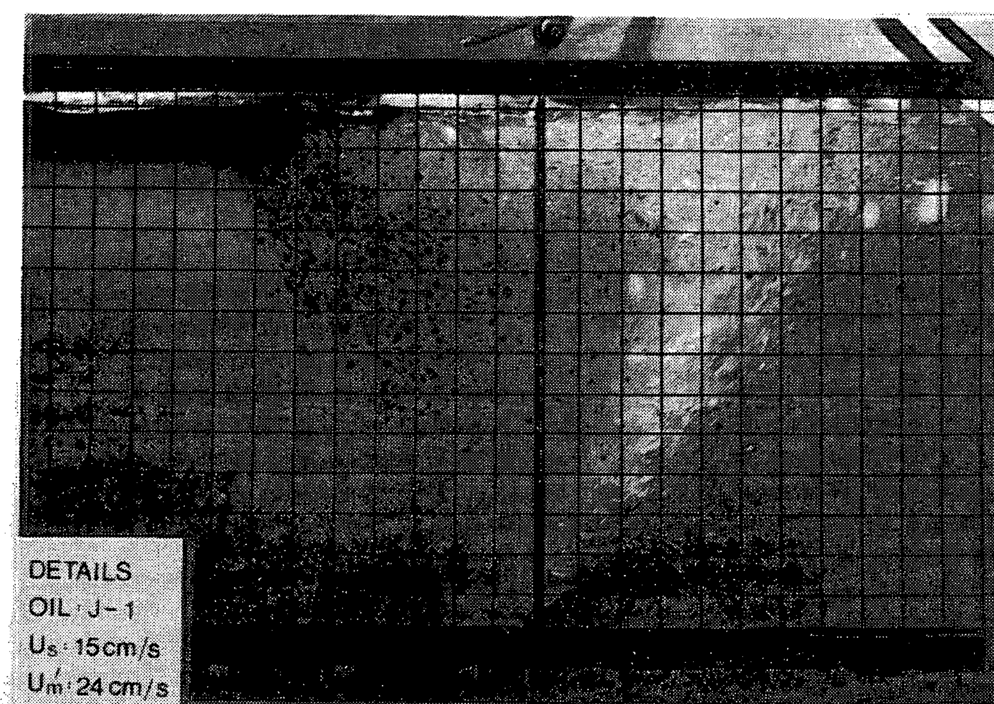


FIGURE 5b. DEFLECTED BUBBLE PLUME WITH MANIFOLD NORMAL TO THE FLOW.

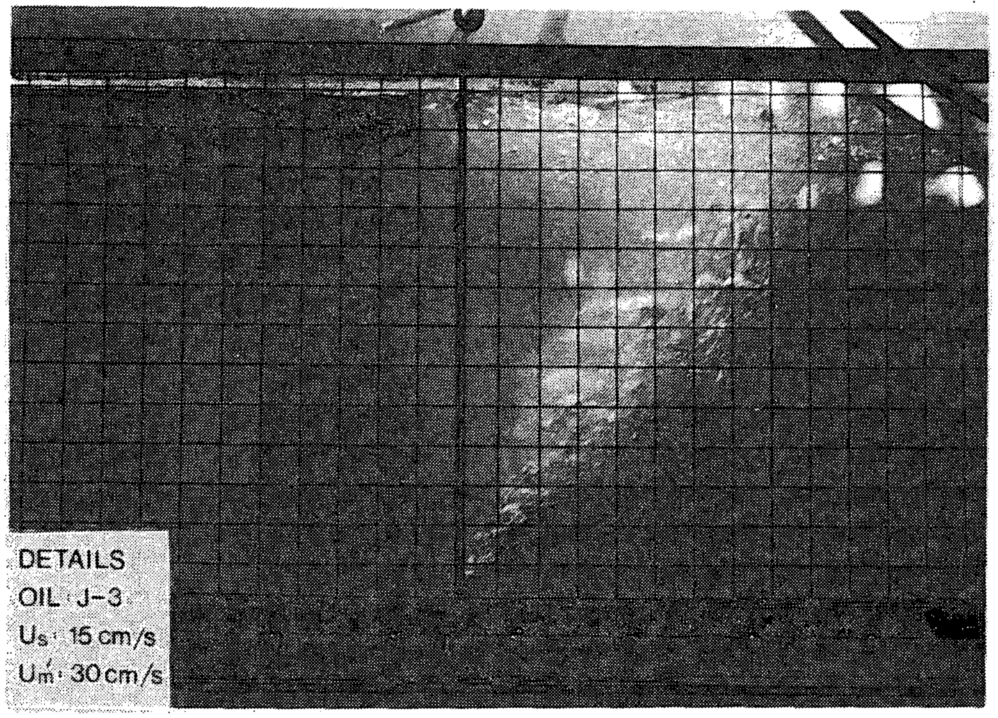


TYPICAL FORMATION OF A 'TORNADO' ON UNDERSIDE OF SLICK

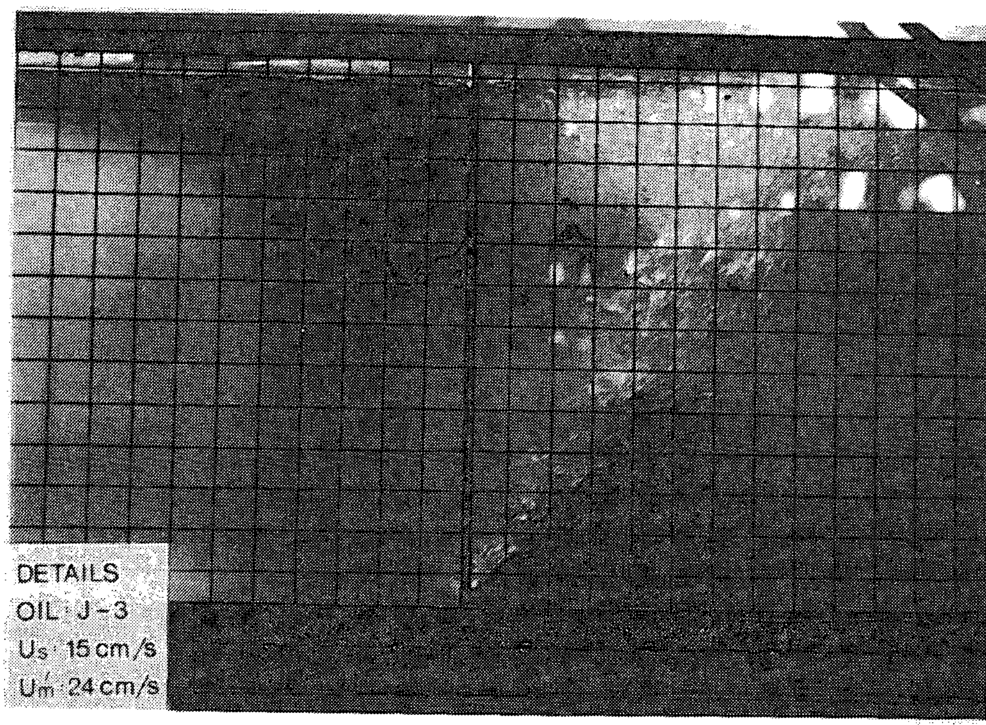


TYPICAL BREAK-UP OF A 'TORNADO' AND INCREASED ENTRAINMENT

FIGURE 6. TYPICAL SLICK - BARRIER INTERACTION FOR J-1 OIL.



BEGINNING OF OIL DETACHMENT



VIOLENT, INTERMITTENT OIL DETACHMENT

FIGURE 7. TYPICAL SLICK-BARRIER INTERACTION FOR J-3 OIL.

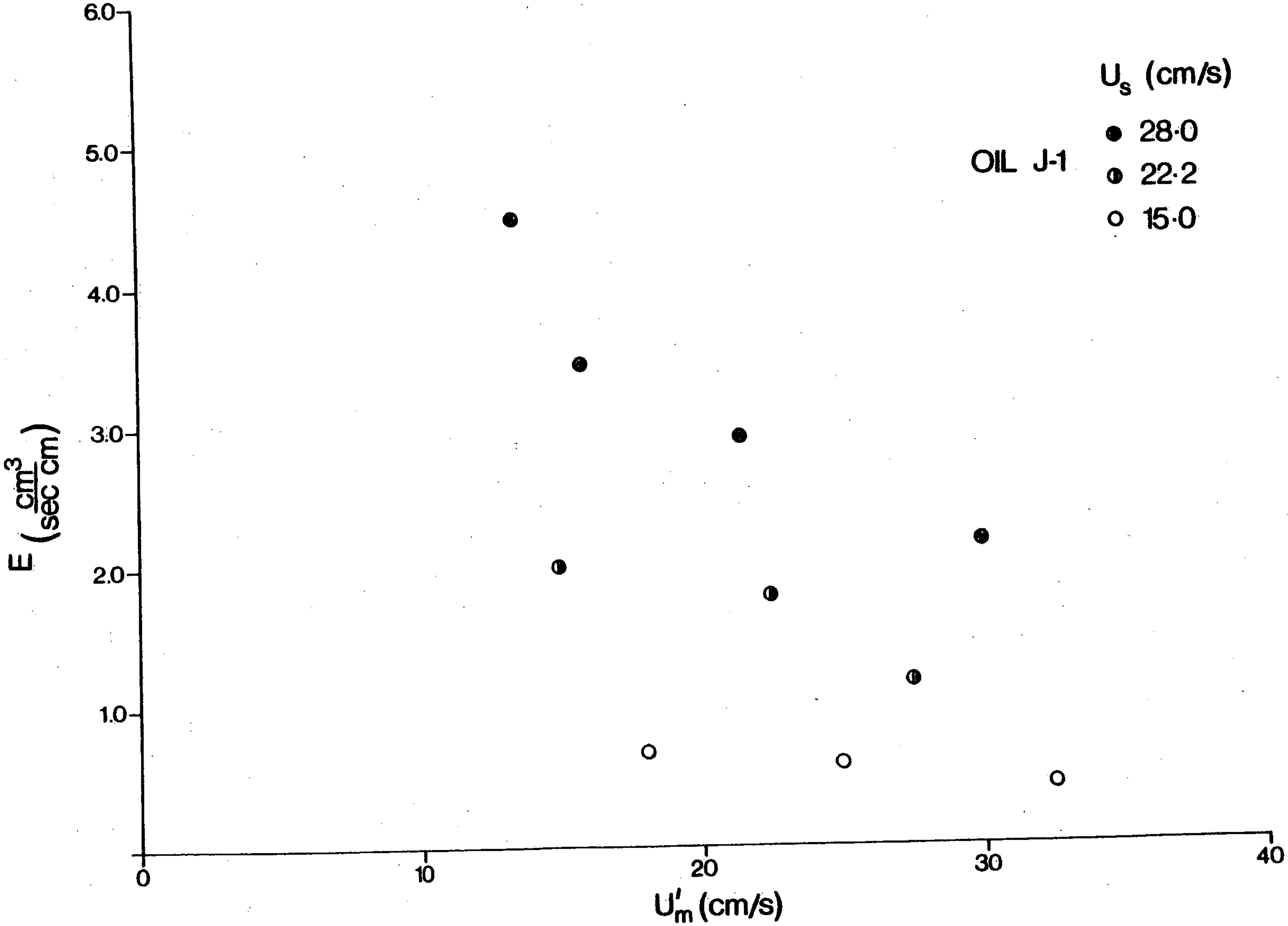


FIGURE 8. ENTRAINMENT LOSS RATE VERSUS INDUCED UPSTREAM VELOCITY FOR OIL J-1.

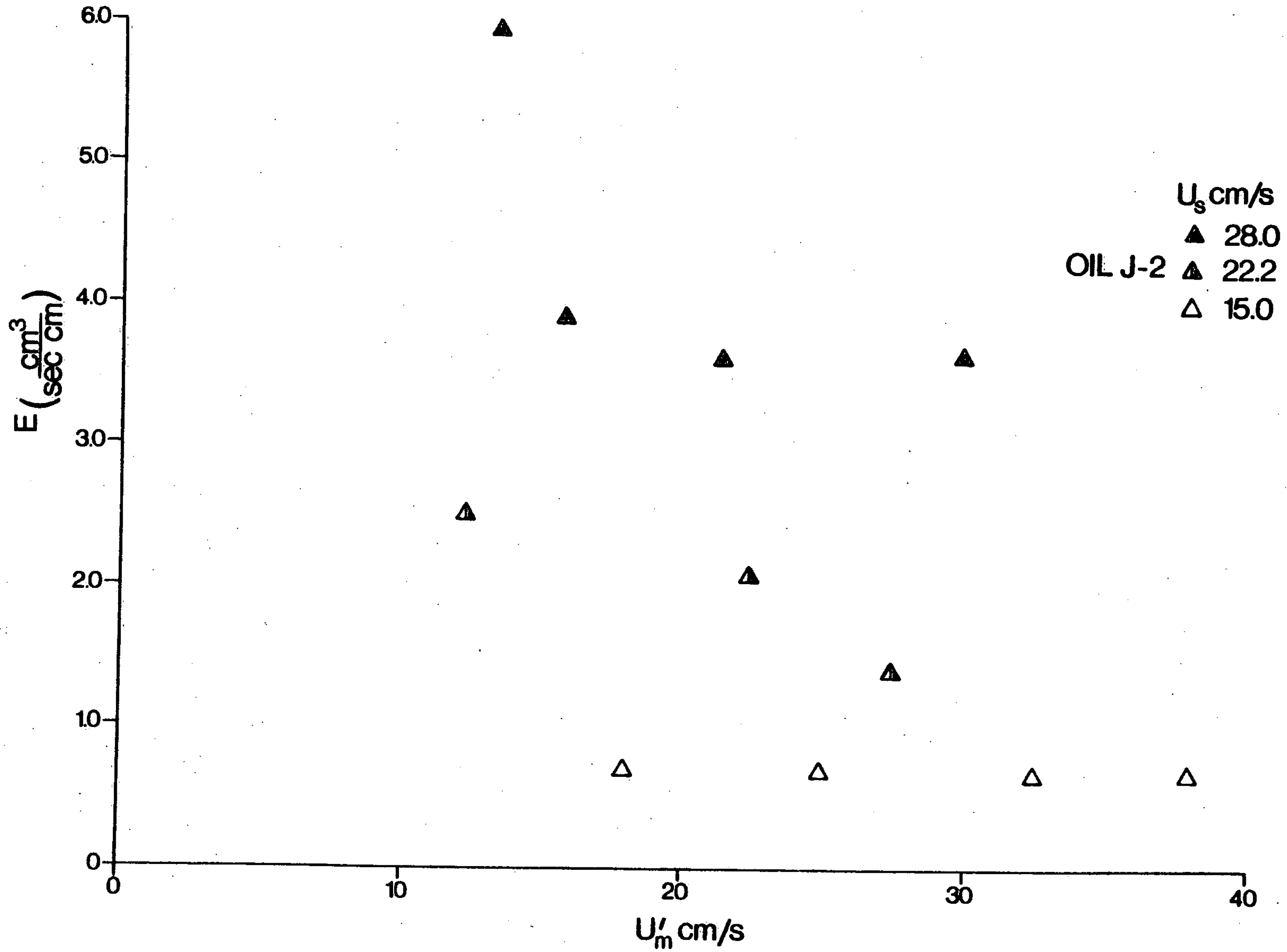


FIGURE 9. ENTRAINMENT LOSS RATE VERSUS INDUCED UPSTREAM VELOCITY FOR OIL J-2.

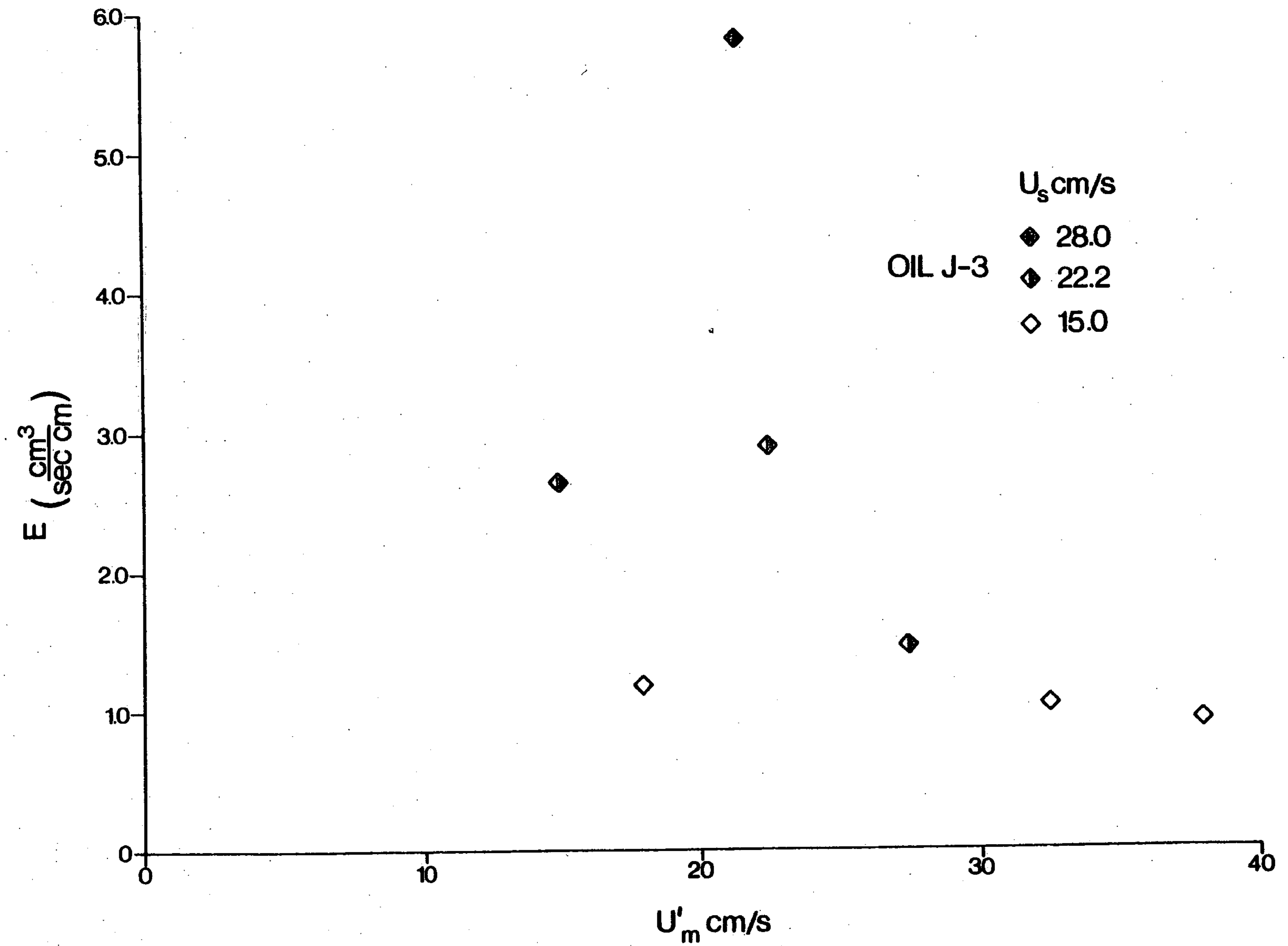


FIGURE 10. ENTRAINMENT LOSS RATE VERSUS INDUCED UPSTREAM VELOCITY FOR OIL J-3.

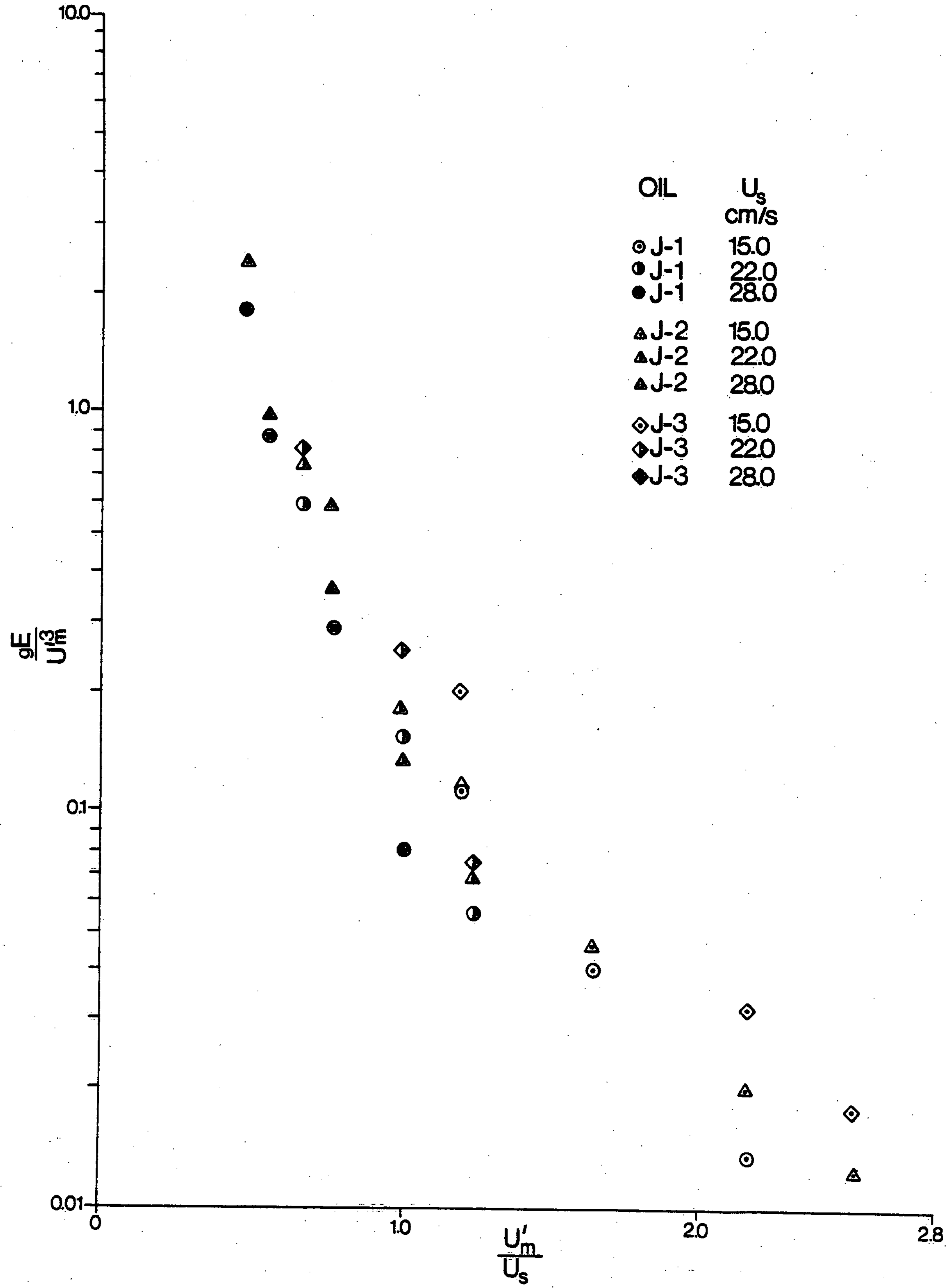
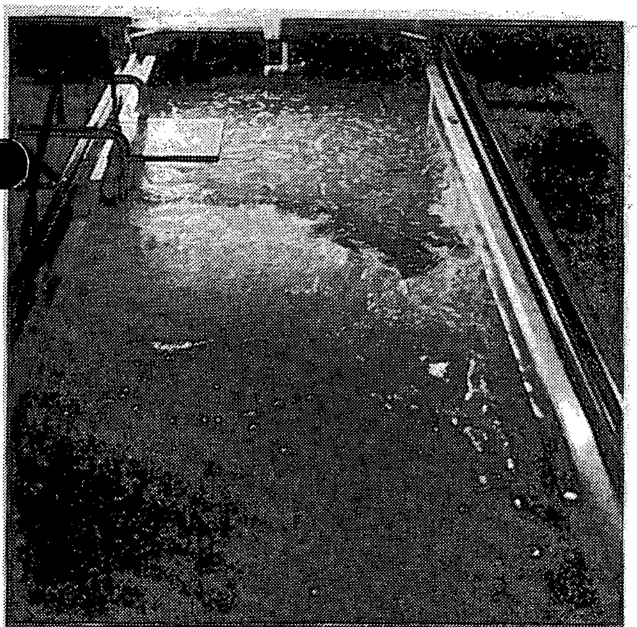


FIGURE 11. DIMENSIONLESS LOSS RATE VERSUS DIMENSIONLESS VELOCITY - ALL THREE OILS.



SLICK JUST AFTER ARRIVING AT BARRIER

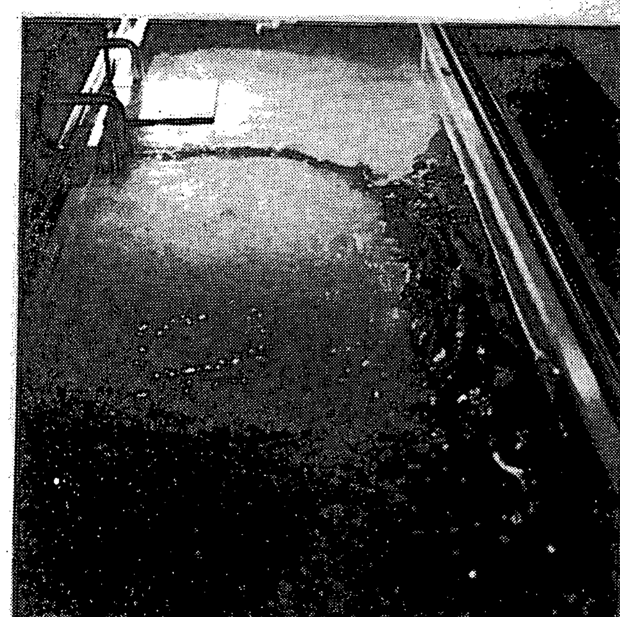
1

SLICK BEING DIVERTED

2

END OF SLICK APPROACHING BARRIER

3



END OF SLICK BEING DIVERTED

4

FIGURE 12. DIVERSION OF A LONG OIL SLICK WITH BUBBLE BARRIER NORMAL TO THE FLOW. (OIL = J-1, U_S = 20.0 cm/s. U'_m = 16.1 cm/s)

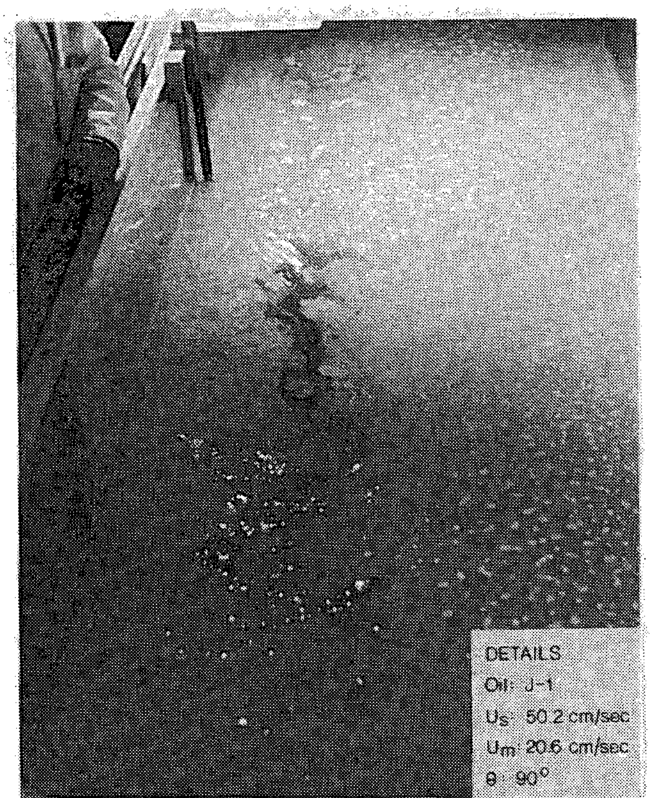


FIGURE 13(a) BARRIER PLACED NORMAL TO THE FLOW. SLICK PASSED THROUGH ON SURFACE.

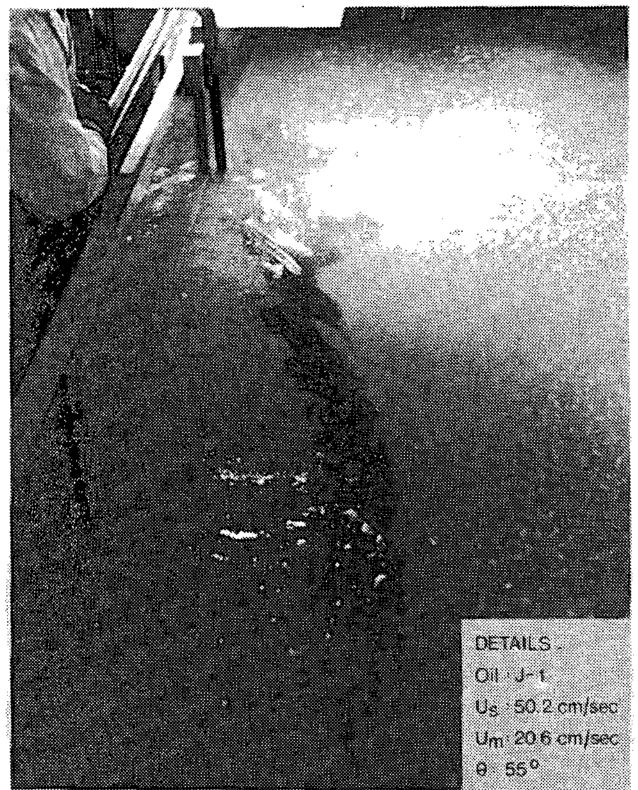


FIGURE 13(b) BARRIER ROTATED TO $\theta_{max} = 55^{\circ}$. SLICK COMPLETELY DIVERTED.

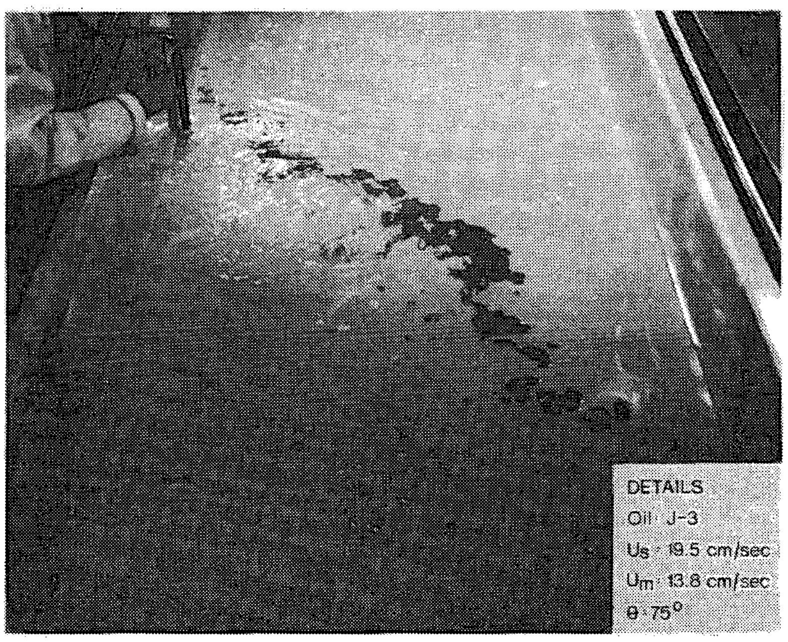


FIGURE 13(c) BARRIER ROTATED TO $\theta = 75^{\circ}$. SOME OIL STILL PASSING THROUGH ON SURFACE.

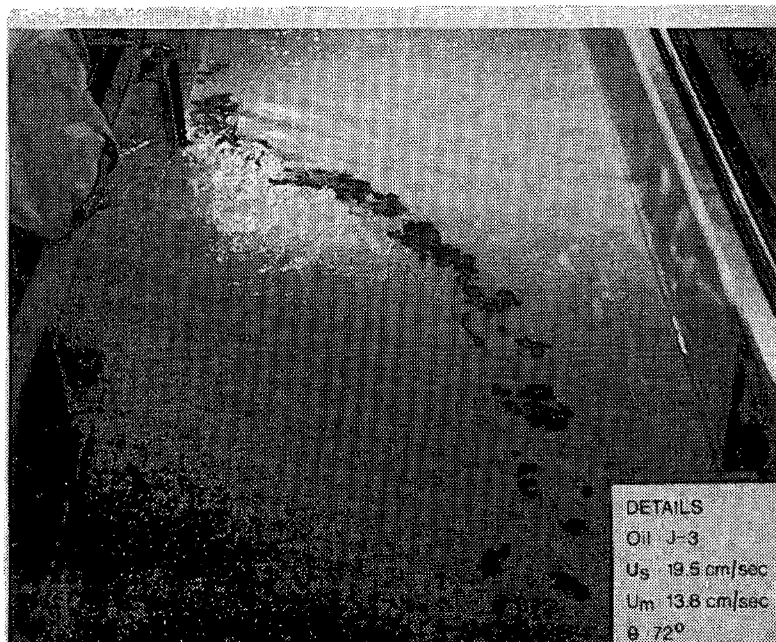


FIGURE 13(d) BARRIER ROTATED TO $\theta_{max} = 72^{\circ}$. SLICK COMPLETELY DIVERTED.

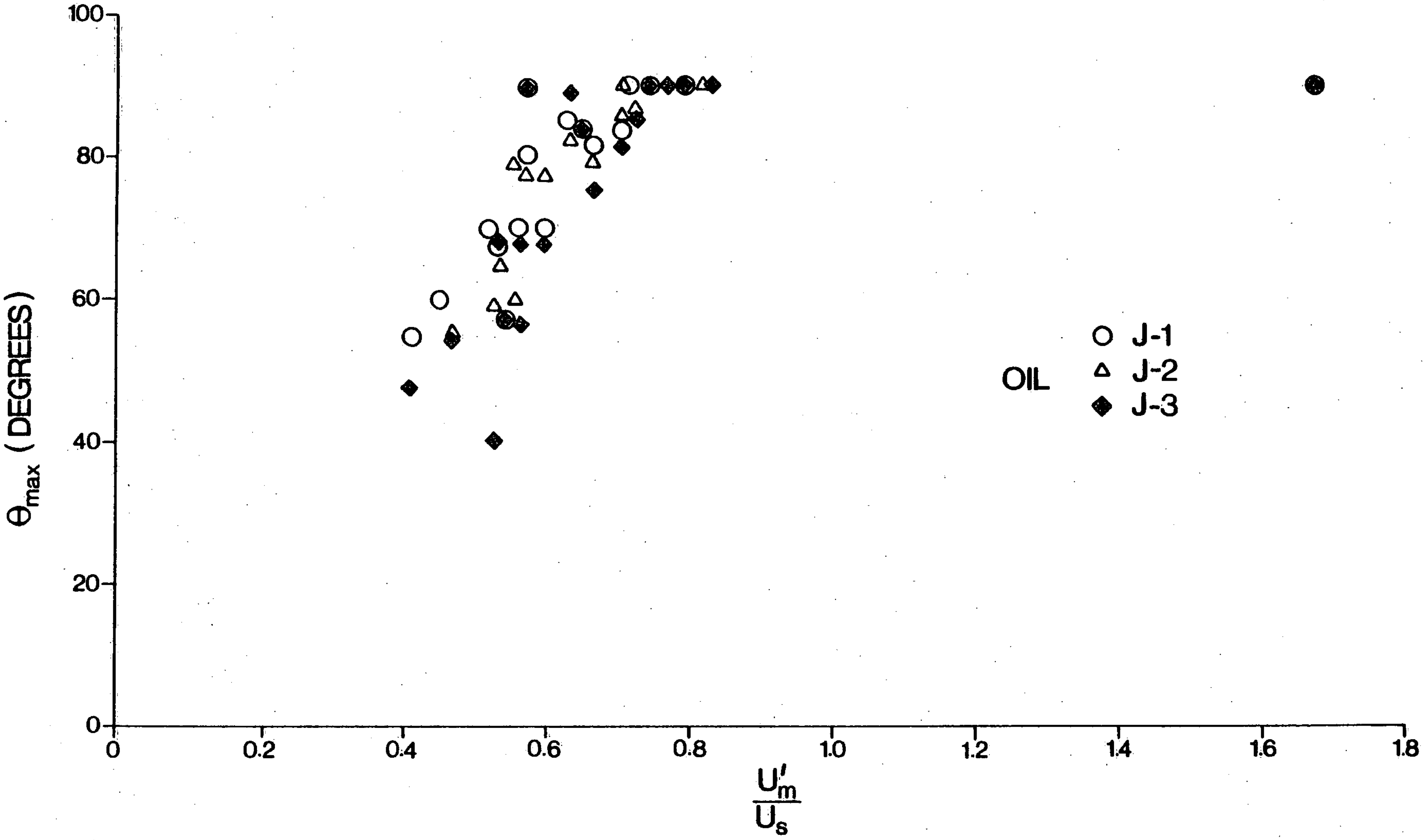


FIGURE 14. PLOT OF Θ_{max} VERSUS $\frac{U'_m}{U_s}$ – ALL THREE OILS.