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082 Drop Size and Dispersant Effectiveness: Small-Scale Laboratory Testing

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DROP SIZE AND DISPERSANT EFFECTIVENESS: SMALL-SCALE LABORATORY TESTING

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SUMMARY

The objective of this study has been to evaluate the validity of a mathematical model developed by D. Mackay concerning the prediction of the effectiveness of oil spill dispersants. The model predicts the likely effectiveness of a dispersant using the mean dispersant drop size and the oil slick's thickness distribution based on two dispersion regimes; dispersant performance-limited and access-limited regimes.

A small-scale laboratory test was developed to test the theory. The important components of the test included a system for applying dispersant of ultra-uniform drop size, the ability to generate oil slicks of uniform thickness, and the establishment of the appropriate dispersant dosage and mixing energy. Tests were carried out with three dispersants (Corexit 9527, Enersperse 700, and Finasol OSR5) and four crude oils (Alberta Sweet Mixed Blend, Uviluk, Norman Wells, and Redwater).

The test results did not support the simple "performance-access" theory of dispersant effectiveness. An "access"-limited dispersion regime was not clearly evident for oil slicks as thin as 200 microns with dispersant drops ranging from 300 to 1100 microns in diameter.

RESUME

Cette étude fut menée pour vérifier un modèle mathématique mis au point par D. Mackay pour prédire l'efficacité des dispersants de nappes d'huile. Il prédit l'efficacité probable d'un dispersant á partir de la grosseur moyenne de ses gouttelettes et de la variation d'épaisseur de la nappe d'huile, compte tenu de deux modes de dispersion possibles, l'une limitée par le pouvoir de dispersion du produit et l'autre par le contact.

La théorie fut éprouvée en laboratoire dans un dispositif à petite échelle spécialement conçu. Les éléments importants de ces essais comprenaient l'application de dispersant sous forme de gouttelettes extrêmement uniformes, la prodution de nappes d'huile d'épaisseur homogène, et la détermination d'un dosage de dispersant et d'une agitation appropriés. Trois dispersants (Corexit 9527, Enersperse 700 et Finasol OSR5) furent combinés à quatre pétroles bruts (Alberta Sweet Mixed Blend, Uviluk, Norman Wells et Redwater).

Les résultats n'ont pas soutenu la théorie basée simplement sur la dispersion limitée par le pouvoir de dispersion du produit. Une limitation par le contact n'était pas évidente non plus pour des nappes aussi minces que 200 microns arrosées de gouttelettes de dispersant variant entre 300 et 1100 microns de diamètre.

INTRODUCTION

An interesting mathematical model has been developed by D. Mackay of the University of Toronto concerning the prediction of the effectiveness of oil-spill dispersants when applied to oil spills under field conditions (Mackay et al. 1986). The model recognizes the importance of dispersant-oil interaction and predicts the likely effectiveness of a dispersant based primarily on the mean dispersant drop size and the oil slick's thickness distribution. The model defines two dispersion regimes that are controlled by these parameters (Figure 1).

The performance-limited regime describes the situation in which the dispersant is used to its maximum potential. This occurs when dispersant is applied to thick oil slicks (relative to dispersant-drop diameter) and is able to disperse "X" volumes of oil per volume of dispersant. The performance factor "X" has been estimated to be about 40 for good dispersants on readily dispersible oils.

The access-limited regime occurs when dispersant is applied to thin slicks or sheens, in which case the dispersant is unable to contact "X" times its volume of oil. Mackay postulates that these drops of dispersant can "access" a circle of the oil slick only "M" times the drop diameter. This less-efficient use of dispersants has been described by Mackay as a first-order process with an exponential decrease in oil remaining as a function of increasing dispersant dosage. Although theoretical values of "M" based on maximum, potential, drop spreading can exceed 20, a typical value of 5 has been estimated by Mackay for field application of dispersants where herding effects are present.

The primary objective of this study was to evaluate the validity of this model by conducting a series of controlled laboratory-scale tests. The experiments were intended to determine the performance factors "M" and "X" and the transition oil thickness between the two dispersion regimes (see Figure 1) for a range of dispersants and oils.

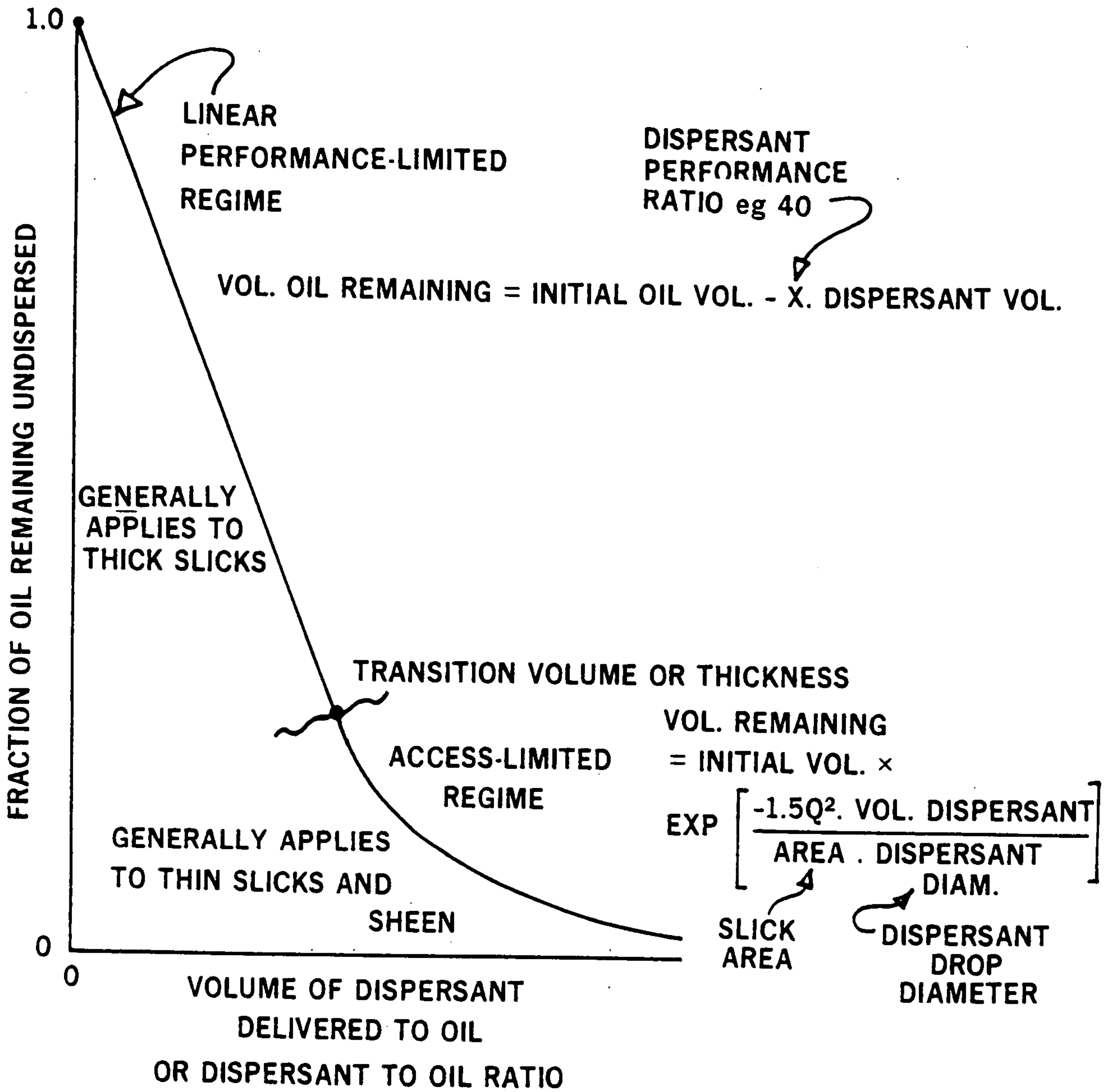

Figure 1. Schematic diagram showing the two regimes of dispersion, initial linear regime and later, less-efficient, access-limited regime (Mackay 1985).

EXPERIMENTAL DESIGN, APPARATUS, AND PROCEDURE

DESIGN

In developing the test procedure to meet the experimental objectives, certain criteria had to be met:

i) Very uniform dispersant drop-size distributions and oil-slick thicknesses would be needed if the final data were to be useful in estimating the performance factors "X" and "M" and the transition between performance- and access-limited dispersion regimes.

ii) The test would have to be conducted at a mixing level sufficiently low to avoid masking the effects of the dispersant and sufficiently high to enable the dispersants to function at reasonable dosage rates.

iii) The dispersant dosage would have to be set such that an excess of dispersant was not present to mask the effects of dispersant drop size.

iv) A reliable method of measuring the overall effectiveness of the dispersant would have to be developed.

We were able to satisfy these criteria with varying degrees of difficulty. By far the hardest task was the design of a uniform drop generator for the dispersant application; this design took several months to perfect. We feel that the effort was justified because the end product was a unique system capable of delivering the applied dispersant in a spray composed of virtually identical-sized droplets.

Uniform oil slick thicknesses were achieved by placing the oil in a containing ring and mechanically spreading the oil to achieve a "uniform" thickness. The slick was considered uniform when a light shining through the slick resulted in a consistent colouring throughout the slick.

The mixing level was set such that the fresh, untreated oils would not disperse (i.e., <5% dispersion) during the 10-min test. The mixing level was varied in a series of tests to establish this upper bound on mixing energy.

The dispersant dosages used in the study were established by conducting a series of tests on pre-mixed dispersant in oil at the mixing energy selected for the oil. The dispersant-to-oil ratio was increased from 1:100 up to as high as 1:5 while measuring the dispersant's effectiveness during the 10-min test. The concentration of pre-mixed dispersant that resulted in 75 to 90% dispersion was selected for use in the final test program. This concentration assured that an excess of dispersant was not added.

The dispersion efficiency was measured by taking water samples from the centre of the test tank, extracting the oil with a colourless solvent, and determining the oil concentration colorimetrically. Preliminary tests, in which oil concentrations were measured 3, 6, and 10 min after the application of dispersant, indicated that the main effect of the dispersant was finished within 6 min. This result allowed the sampling program to be reduced to only one sample at the 10-min mark. To improve the reproducibility of the test, all the oil remaining on the surface of the tank at 10 min was removed with a sorbent pad, and the contents of the test vessel was completely mixed with a paddle to ensure that the one sample was indeed representative of the average oil concentration in the tank.

Although this method for determining the dispersed oil concentration and dispersant efficiency seems quite simple, it evolved as a result of much testing and analysis and several failed techniques.

APPARATUS

The major apparati used in the testing program were the hoop tank, used to hold the test water and oil and to provide the mixing energy to the system, and the dispersant application apparatus.

The hoop tank (Figure 2) was filled with 125 L of salt water for each test. Mixing energy was applied via the cantilevered hoop supported above the tank by an off-centre cam. The cam can be adjusted to increase the stroke length of the mixing hoop and the stroke frequency can be varied by the D.C. motor powering the cam. Water samples are taken from the centre of the vessel via a sampling tube that passes through the tank bottom. A light is shone through the clear tank bottom to assist in the viewing of the dispersion and surface slick characteristics.

A schematic drawing of the dispersant application apparatus is presented in Figure 3. The major components of the system are a supply of pressurized air with a stable pressure regulator, a pressure vessel to hold the dispersant supply, a filter to clean the dispersant to prevent orifice clogging, a pressure gauge to monitor the fluid pressure being delivered to the nozzle, a nozzle body, precision orifices, and a method of vibrating the liquid in the nozzle body at a specific frequency. The quantity of dispersant reaching the oil slick is controlled by a mechanical shutter placed in the path of the dispersant spray. A high-quality stroboscope is also needed to view the spray being generated to ensure that the equipment is operating properly.

The strobe is triggered by the signal generator (which also controls the liquid oscillation), via a variable-frequency divider to enable stop-action viewing of the drop-stream generated at each orifice. To prevent coalescence of the drops downstream of the orifice a high-voltage charging ring is placed around the spray pattern close to the nozzle head to charge the particles exiting the orifices. Not only does this prevent coalescence because of particle repulsion, but also it provides a method of adjusting the spray pattern reaching the oil slick. By altering the charging voltage, and thus the charge on the drops, the divergence of the spray pattern can be controlled.

This basic technique for mono-disperse (i.e., uniform drop) drop generation was brought to our attention by researchers at the National Research Council's National Aeronautics Establishment in Ottawa. Several

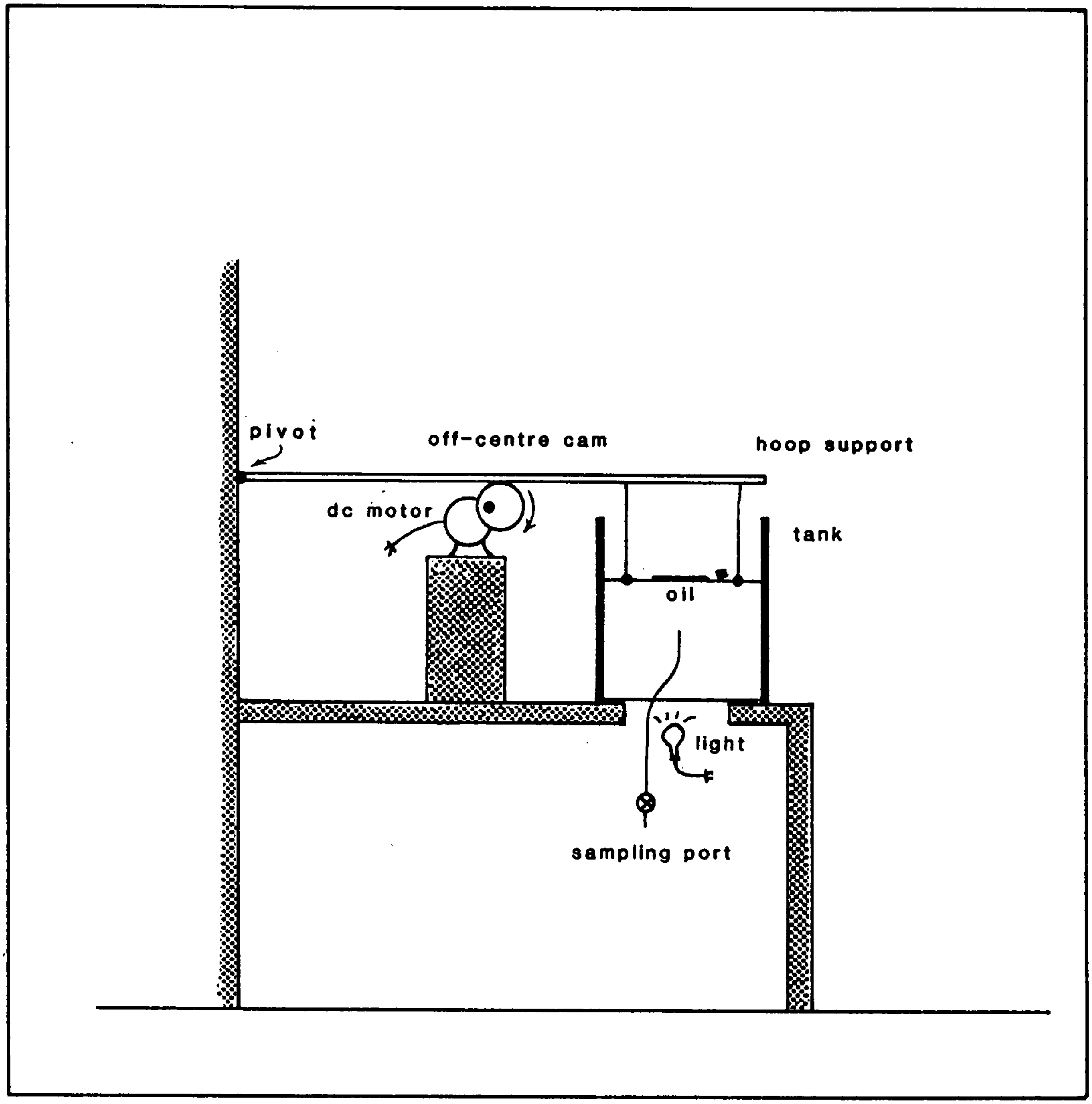

Figure 2. Hoop tank (side view)

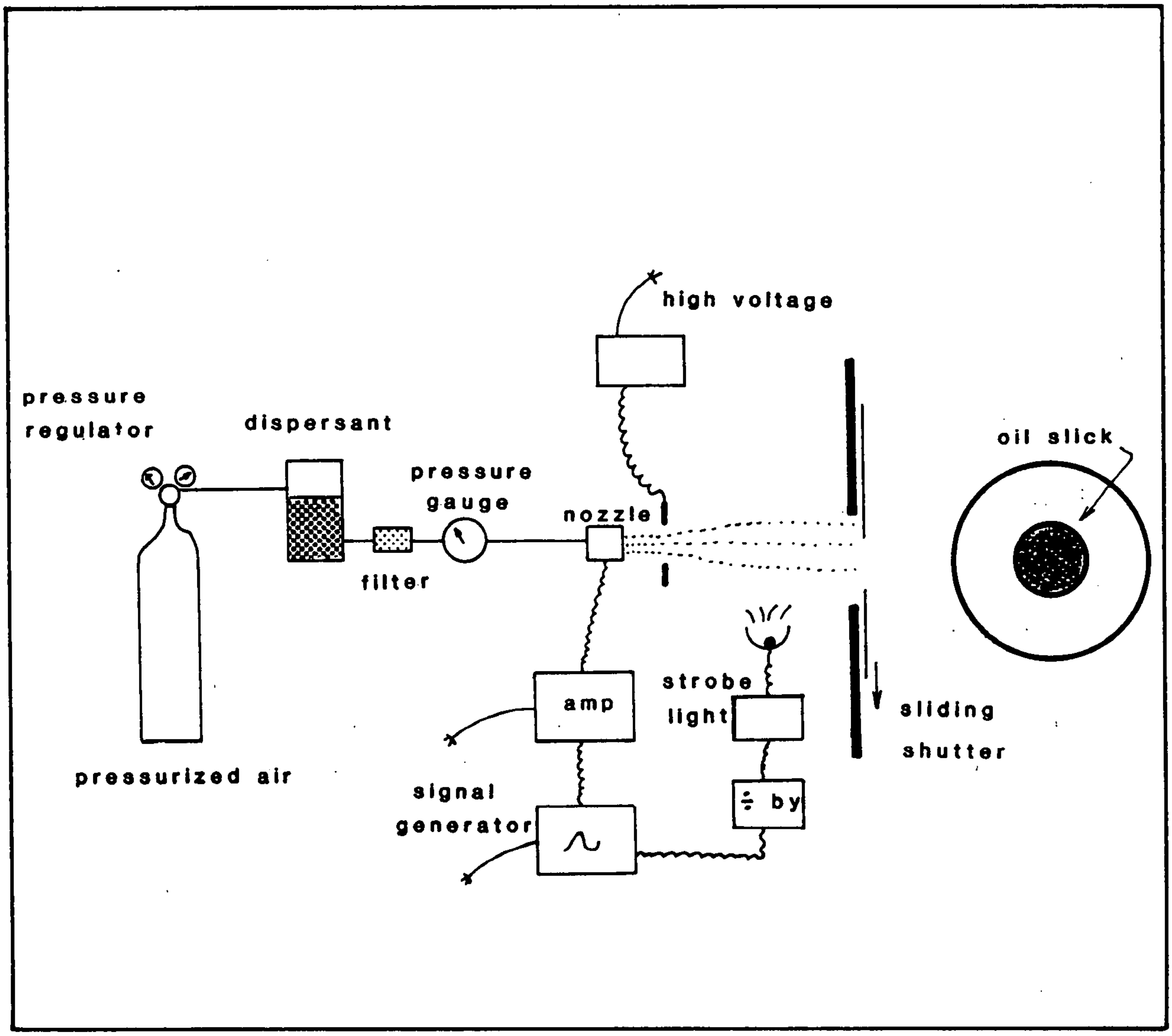

Figure 3. Layout of mono-disperse drop generator.

papers by other researchers were also consulted during the development of our system (Threadgill et al. 1974, Lindbland and Schneider 1965, Sakai et al. 1982, Goedde and Yuen 1970). The system works as follows: Normally, if a liquid is forced through a nozzle orifice the resulting stream disintegrates into a series of droplets having a relatively wide size distribution. If, however, the liquid is vibrated or oscillated at a regular, given frequency, the liquid stream exiting the orifice will "neck" uniformly and break into a series of equal-sized droplets. In this application, the fluid in the nozzle body is kept at a constant pressure (thus providing a steady exit velocity from the nozzle orifice) and is oscillated at a particular frequency to achieve the desired uniform size of droplets after the liquid exits the orifice.

The system developed for this study uses a piezoelectric transducer powered by a frequency generator and amplifier to generate the desired liquid vibration.

The following equations were used to approximate the liquid pressure and transducer frequency needed to generate the proper liquid necking and drop formation for a given orifice diameter. These equations are simplified versions of those presented in the various papers cited earlier and therefore provide only an approximation of the pressure-frequency combination necessary for proper operation. These values were used as a guide during the operation of the system. The strobe light was essential in fine-tuning these settings to establish proper operation of the system.

$$\phi j = 0.86 \times \phi d \qquad (1)$$

where: ϕj = diameter of the liquid stream
ϕd = diameter of orifice

$$\lambda = 4.5 \times \phi j \qquad (2)$$

where: λ = wave length of necking fluid

$$V = \lambda f \qquad (3)$$

where: V = velocity of existing liquid

f = frequency of oscillations in liquid

$$h = \frac{V^2}{2g} \qquad (4)$$

where: h = velocity head

g = gravitational constant.

Equation 1 is used to estimate the diameter of the liquid stream based on the orifice diameter. Then the wavelength needed for proper necking of the fluid is calculated from equation 2. A frequency is selected and used in equation 3 to calculate a liquid velocity, which is then used in equation 4 to determine the velocity head or pressure needed to generate the appropriate wavelength in the fluid at the selected frequency. A number of pressure-frequency combinations can thus be used to generate the appropriate conditions for proper droplet formation. The final drop sizes are primarily a function of the orifice diameter and vary only slightly with different pairs of pressure and frequency.

The three orifice diameters used in this study, resulted in the estimates of operating pressures shown in Table 1 based on equations 1 through 4.

TABLE 1

Approximate operating pressures and frequencies for proper drop formation

Orifice diameter (mm)	Jet diameter (mm)	Operating pressures kPa (psi) at each frequency		
		5,000 Hz	15,000 Hz	30,000 Hz
0.127	0.109	2.55 (.37)	23 (3.3)	90 (13)
0.381	0.328	23.0 (3.3)	205 (29.8)	820 (119)
0.635	0.546	63.0 (9.2)	571 (82.9)	2289 (332)

Dispersant drop diameters of 0.30, 0.65, and 1.10 mm were generated for this study. Figure 4 is a photograph of a multiple-orifice nozzle generating 300-µm drops. Virtually all of the liquid volume exiting the nozzle is discharged in drops of equal diameter. Coalescence of the drops is then prevented by the electrostatic charging of the drop stream.

The speed of the shutter used to control the amount of dispersant reaching the oil slick (see Figure 3) was controlled by varying the weight used to pull the shutter across the spray opening. The size of the shutter opening was also adjusted to vary the quantity of dispersant passing through to the slick.

The orifices used were purchased from a manufacturer of precision jewel bearings. The high-voltage charging system was built by us based on a system developed for insecticide spraying in confined areas. Suitable high speed strobe lights and frequency dividers are commercially available but because of their high cost these were also designed and constructed by us.

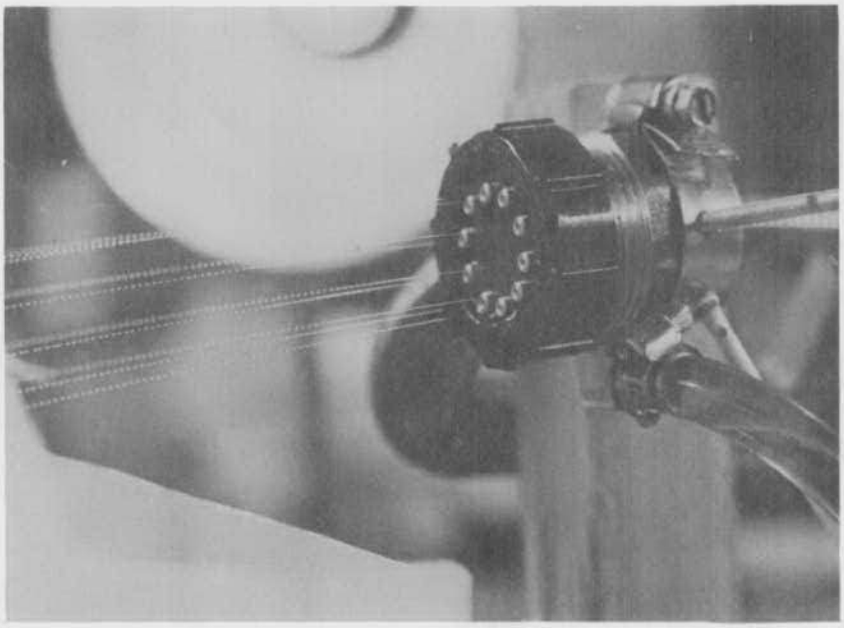

Figure 4. Multiple-orifice nozzle generating 300-μm drops of dispersant.

Most of the remaining components of the drop generator were off-the-shelf items. These include the pressurized air supply and regulator, pressure gauge, pressure vessel, filters, signal generator, and amplifier. The nozzle body was fabricated from brass plumbing fittings to eliminate machining costs.

PROCEDURE

The final test procedure used for the testing program is summarized briefly.

1) The hoop tank was filled with approximately 125 L of 32 ppt salt water. The water was brought up to the level of the hoop when resting in its central position on the off-centre cam.

2) The oil slick thickness for the test was chosen and the volume of oil needed to create a slick of a certain diameter was calculated. The quantity of dispersant needed for the test was then calculated.

3) The dispersant spray nozzle, high-voltage charging circuit, and shutter were set such that the dispersant spray pattern would hit only the oil slick and the quantity of dispersant passing through the shutter was the amount necessary for the test.

4) The quantity of dispersant passing through the shutter was verified by operating the spray system prior to the final test and catching the dispersant on a pre-weighed sorbent. The quantity of dispersant passing by the shutter was determined by weighing the dispersant-soaked sorbent.

5) The oil was then placed carefully in a containing ring of appropriate diameter and spread to fill the ring evenly.

6) The spray nozzle was started by pressurizing the fluid line to the nozzle, the piezoelectric transducer was turned on at the appropriate

frequency and voltage, the droplet-charging circuit was energized at the pre-set voltage, and the entire set-up was allowed to equilibrate for a few seconds with the dispersant being caught by the closed shutter.

7) The oil retaining ring was lifted.

8) The shutter was activated to allow passage of the pre-determined quantity of dispersant.

9) The agitating hoop was started.

10) The dispersant spray equipment was turned off.

11) Observations of the behaviour of the oil slick were recorded periodically throughout the test.

12) After 10 min of agitation any remaining surface oil was removed by an oil sorbent.

13) The tank's contents were mixed completely by a large hand-paddle to ensure that any dispersed oil was evenly distributed.

14) A 250-ml sample was then taken from the centre of the tank for oil extraction and colorimetric analysis.

15) The hoop agitation was stopped and the tank was cleaned in preparation for the next test.

RESULTS

Tests were conducted with three dispersants (Corexit 9527, Enersperse 700 (EN700) and Finasol OSR5) and four crude oils (Alberta Sweet Mixed Blend (ASMB), Uviluk, Norman Wells, and Redwater). Some of the basic physical and chemical properties of these oils are provided in Table 2. Some preliminary testing was also conducted using Corexit 9550 but, because of its low effectiveness on most of the oils and the difficulty of forcing this viscous product through the small orifice of the drop generator, the dispersant was not studied in the final test matrix. Table 3 summarizes the main tests that were carried out in the study. The dispersant effectiveness measurements are summarized in Figures 5 to 12. Estimates of the "X" and "M" factors (as previously defined) for each of the tests are provided in Table 4.

TABLE 2

Physical and chemical properties of test oils+

Oil	Density [g/ml]	Viscosity [sCt]	Oil-Water Interfacial Tension
Alberta Sweet Mixed Blend	0.84	11	21.5
Uviluk	0.90	15	21.4
Norman Wells	0.83	6.1	16.4
Redwater	0.92	89	--

+ Note: these data were taken from Bobra and Chung 1986.

Discussion

Figures 5, 6, and 7 strongly suggest that the simple "performance-access" theory of dispersant effectiveness put forth by Mackay cannot be applied in a general manner to all oils. For example, in the case of Enersperse 700 applied to Norman Wells crude oil (see Figure 5) an "access-limited" regime did not seem to materialize (at least not for oil slicks as thin as 200 µm with dispersant drops as large as 1100 µm in diameter). Instead, the dispersant performed similarly at all oil thicknesses. Although this does not directly contradict Mackay's theory, one would have expected the transition between the "access and performance" regimes to occur within the range of oil slick thicknesses tested, at least for the largest, dispersant drop size.

The results for the ASMB oil are even less encouraging with respect to the support of the proposed dispersion theory. For both Finasol OSR5 and Corexit 9527 a reverse trend to that proposed by Mackay was noted in the testing (see Figures 6 and 7). As the oil slick thickness increased the dispersant efficiency dropped. The reason for this charge is not known.

The ASMB, EN700 results (see Figure 8) are also difficult to interpret. There was no significant variation in dispersant effectiveness for the 650-µm dispersant drop size over a wide range of oil thicknesses; however, for both the 300- and 1100- µm drop sizes, a sharp reduction in effectiveness was noted for the thin oil slick tests. We attribute this drop in measured efficiency to wall effects. In these tests involving thin slicks, only small quantities of oil were used; therefore, any oil that adhered to the tank wall resulted in in-water oil concentration estimates of dispersion far less than 100% even when no slick was observed at the end of the test period. Unfortunately, we had no way to quantify accurately the small volumes of oil attached to the side wall at the end of each test. Although we have plotted in this report the measured efficiencies on all of the curves, we feel that the low efficiencies measured for most of the thin slick cases are not accurate and that the 100% dispersion, based on the visual observations, is likely a more correct indication of the dispersant's

TABLE 3

Summary of test conditions

Oil Type	Dispersant	Dispersant drop size (microns)	Oil thickness (microns)
ASMB	Corexit	300	200*, 400, 1300
	9527	650	200, 1000, 2000, 3000
	C1:50	1100	500, 1000, 2000, 3000
	Enersperse	300	200, 400, 1200
	700	650	200, 700, 2200
	C1:40	1100	200, 1000, 2500
	Finasol OSR5	650	200, 700, 2200
	C1:25	1100	200, 1000, 2000
Uviluk	Corexit	300	200, 400, 1300
	9527	650	200, 500, 1000, 2000
	C1:50	1100	500, 1000, 2000, 3000
	Enersperse	650	200, 700, 2200
	700	1100	200, 1000, 2500, 3000
	C1:40		
	Finasol	650	200, 700, 2200
	OSR5	1100	200, 1000, 3000
	C1:50		
Norman Wells	Enersperse	300	200, 400, 1500
	700	650	200, 700, 3000
	C1:75	1100	200, 1000, 2000
Redwater	Enersperse	300	200,400, 1000
	700	650	200, 700, 1500
	C1:15	1100	200, 1100

* Note: This was the thinnest slick which could be generated in this test tank

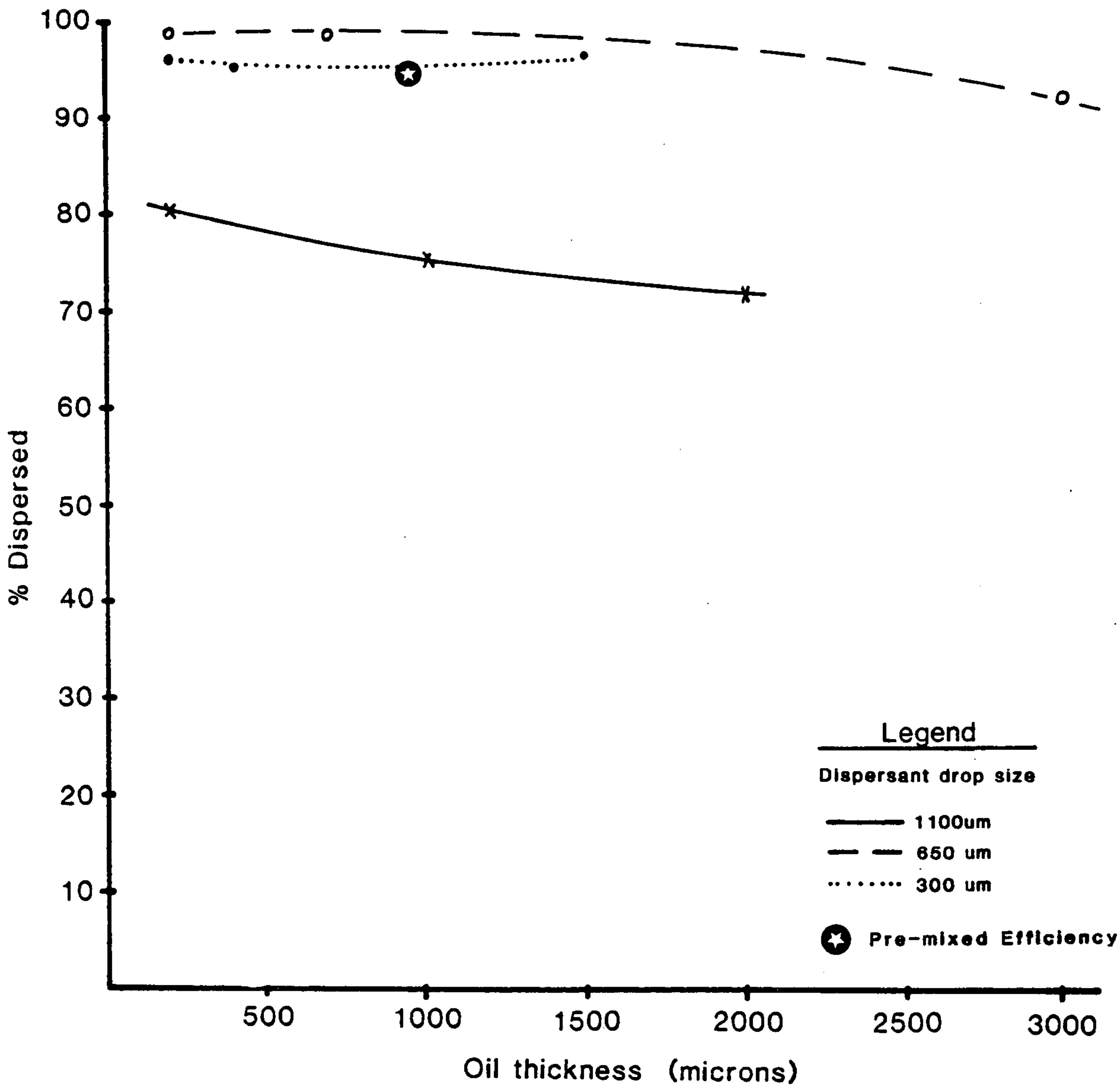

Figure 5. Dispersion efficiency vs oil thickness and dispersant drop size : EN700 at 1:75 on Norman Wells

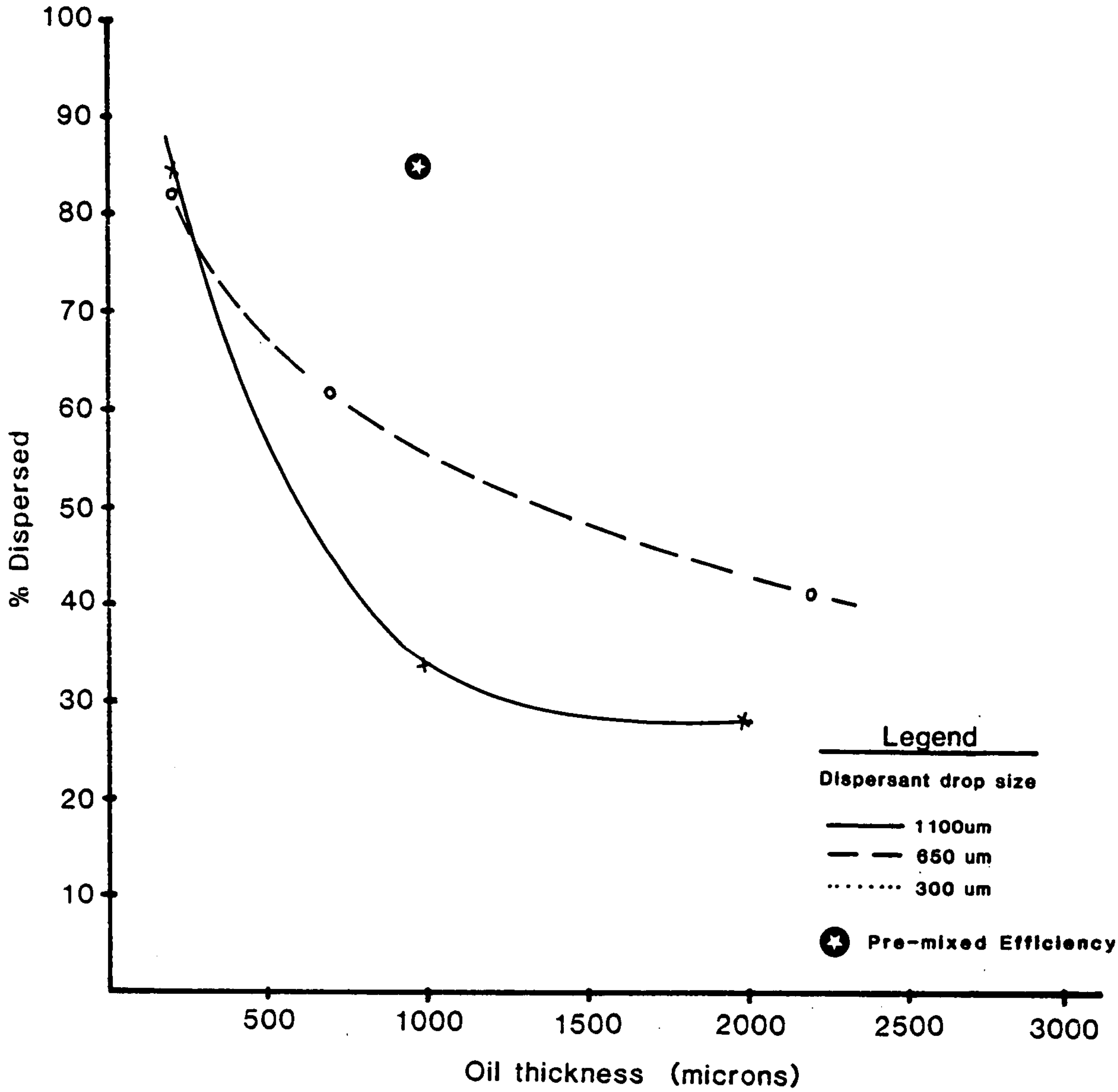

Figure 6. Dispersion efficiency vs oil thickness and dispersant drop size : Finasol at 1:25 on ASMB

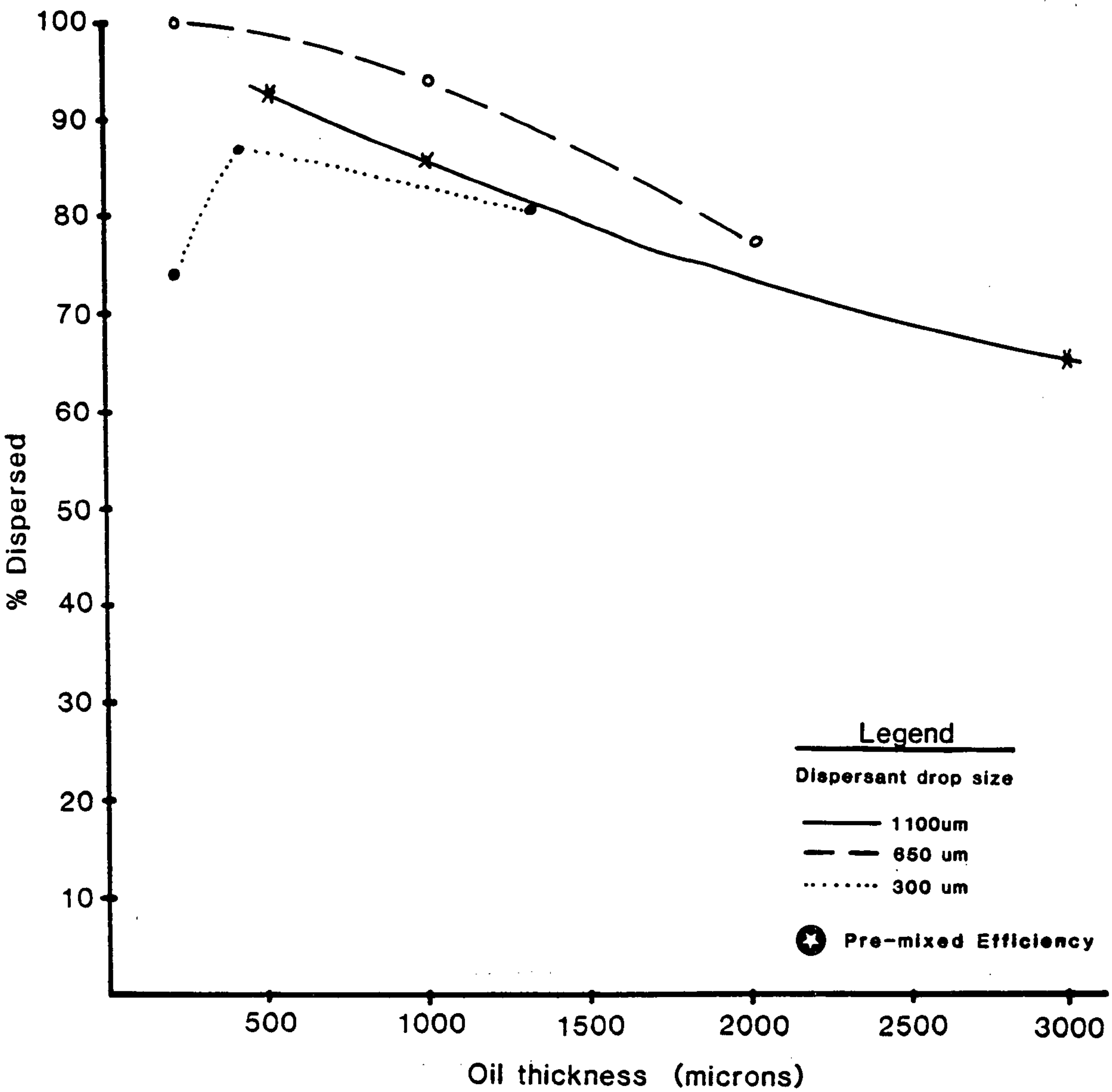

Figure 7. Dispersion efficiency vs oil thickness and dispersant drop size : Corexit 9527 at 1:50 on ASMB

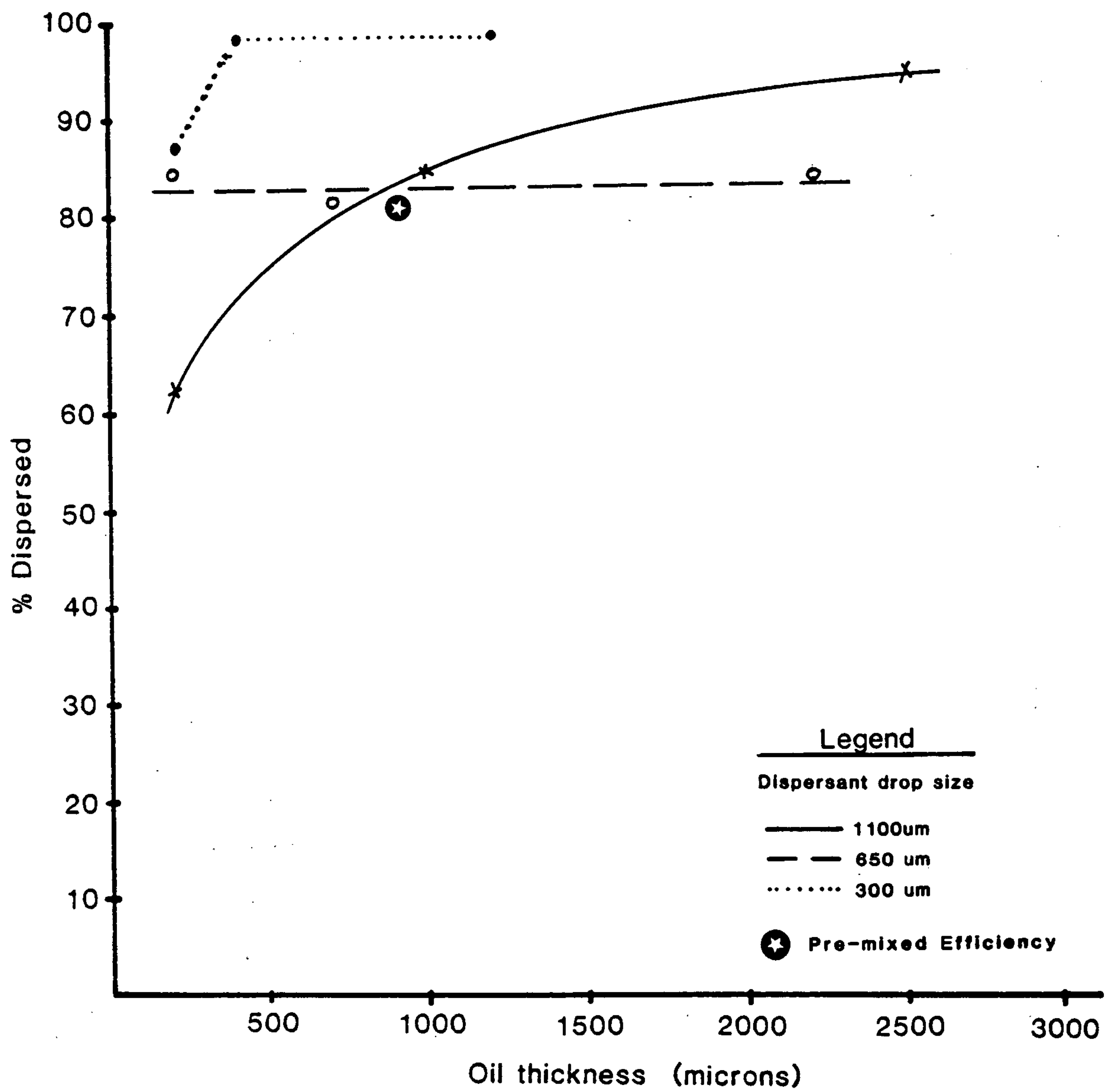

Figure 8. Dispersion efficiency vs oil thickness and dispersant drop size : EN700 at 1:40 on ASMB

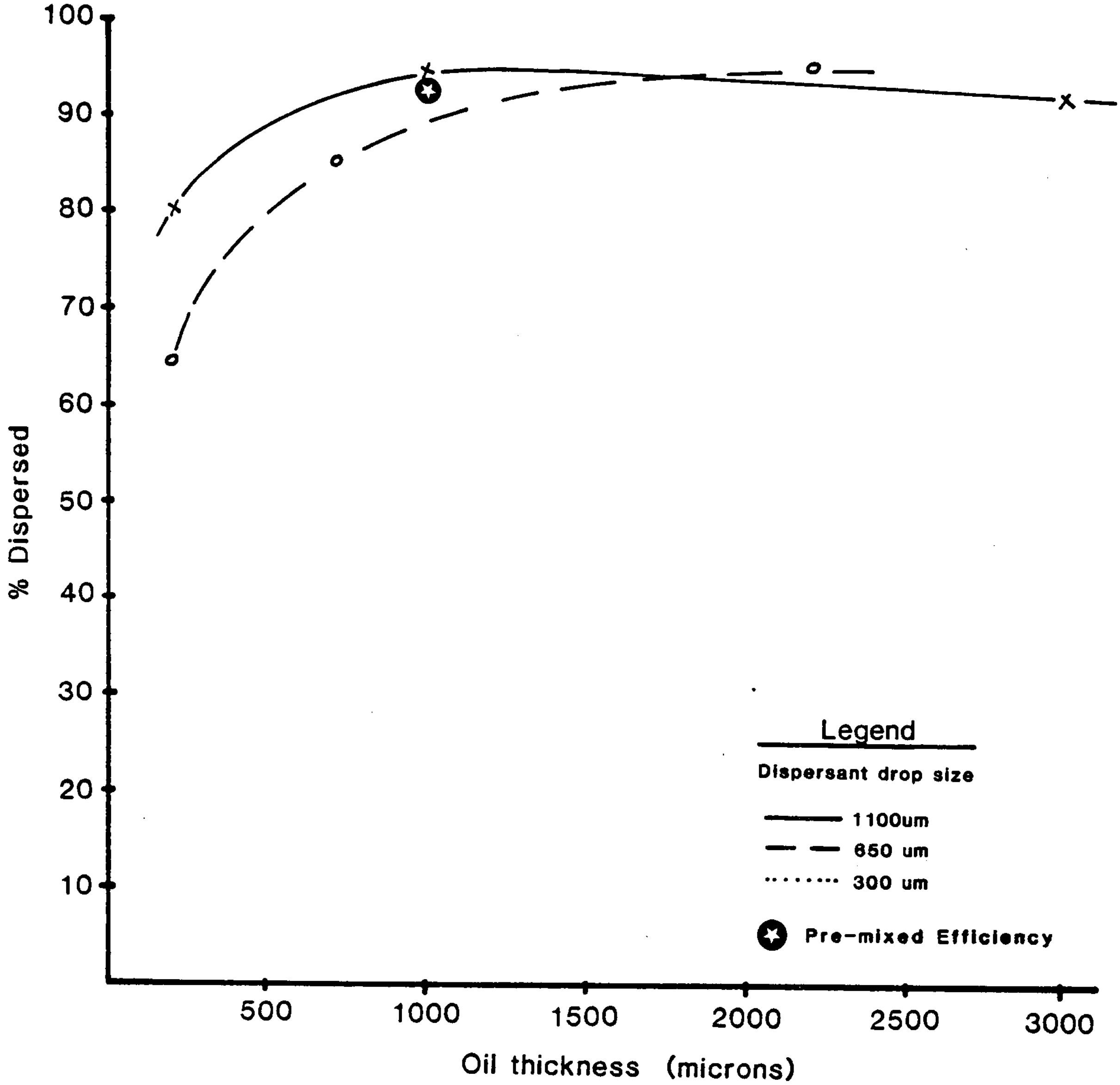

Figure 9. Dispersion efficiency vs oil thickness and dispersant drop size : Finasol at 1:50 on Uviluk

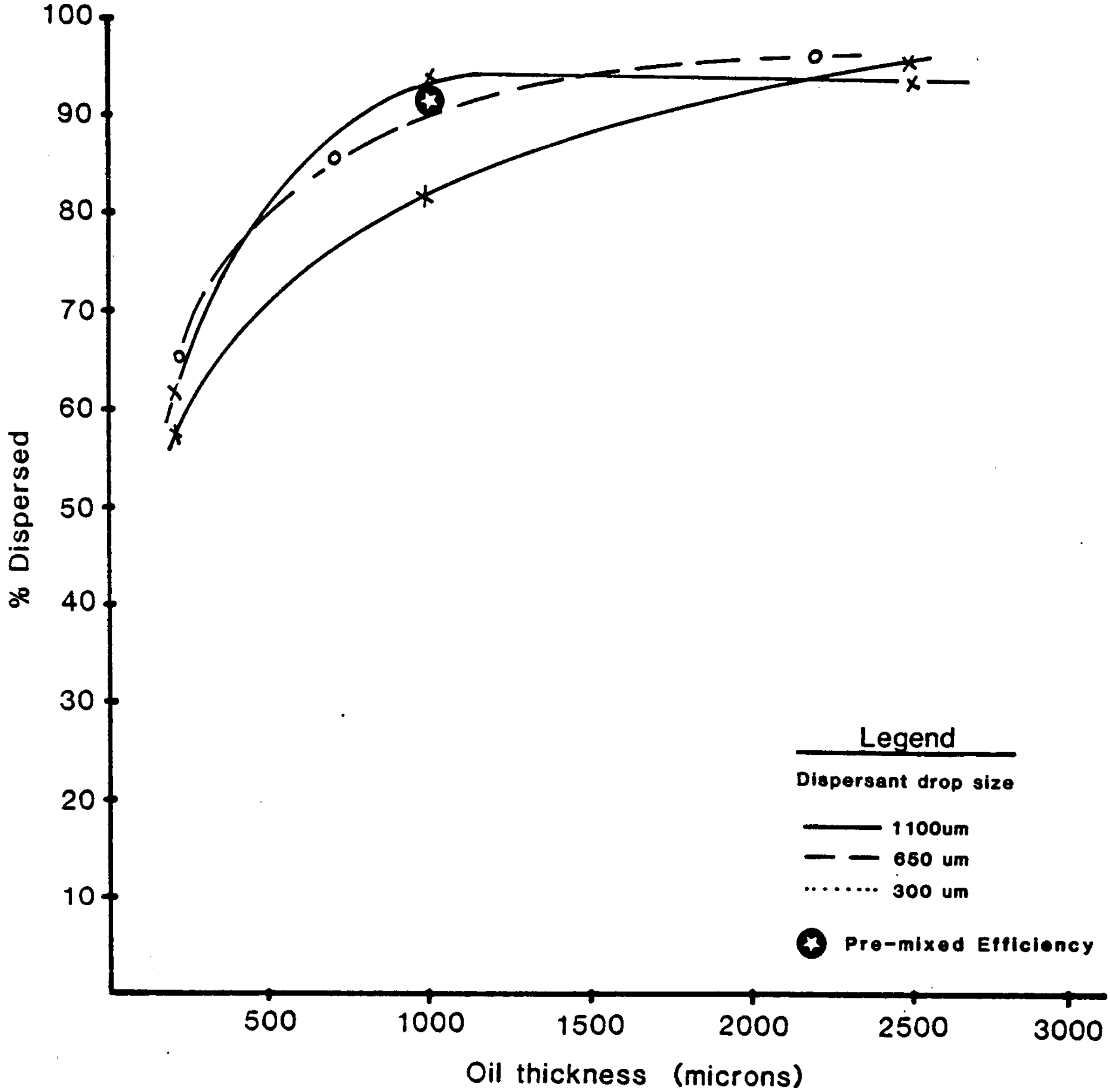

Figure 10. Dispersion efficiency vs oil thickness and dispersant drop size : EN700 at 1:40 on Uviluk

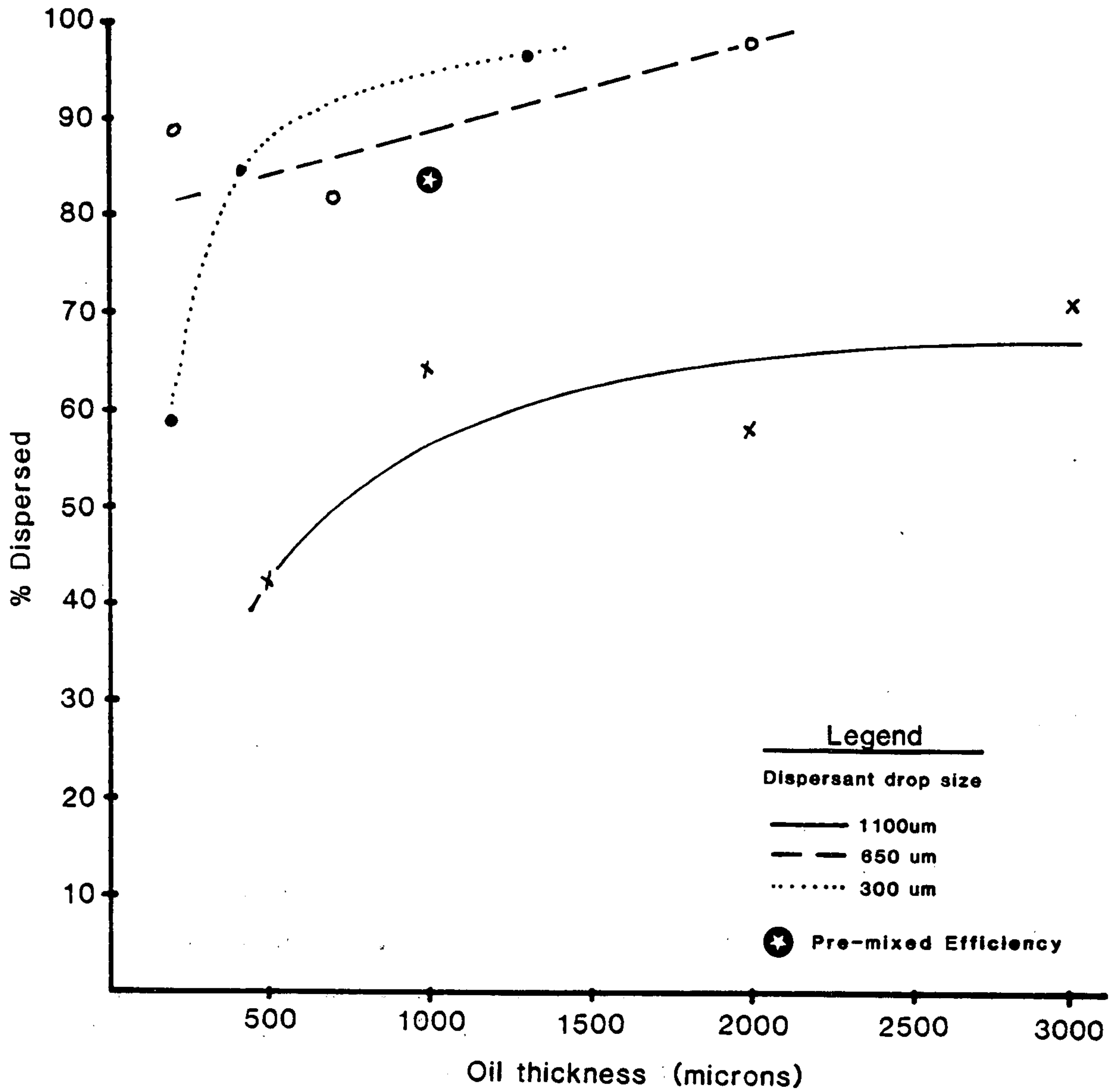

Figure 11. Dispersion efficiency vs oil thickness and dispersant drop size : Corexit 9527 at 1:50 on Uviluk

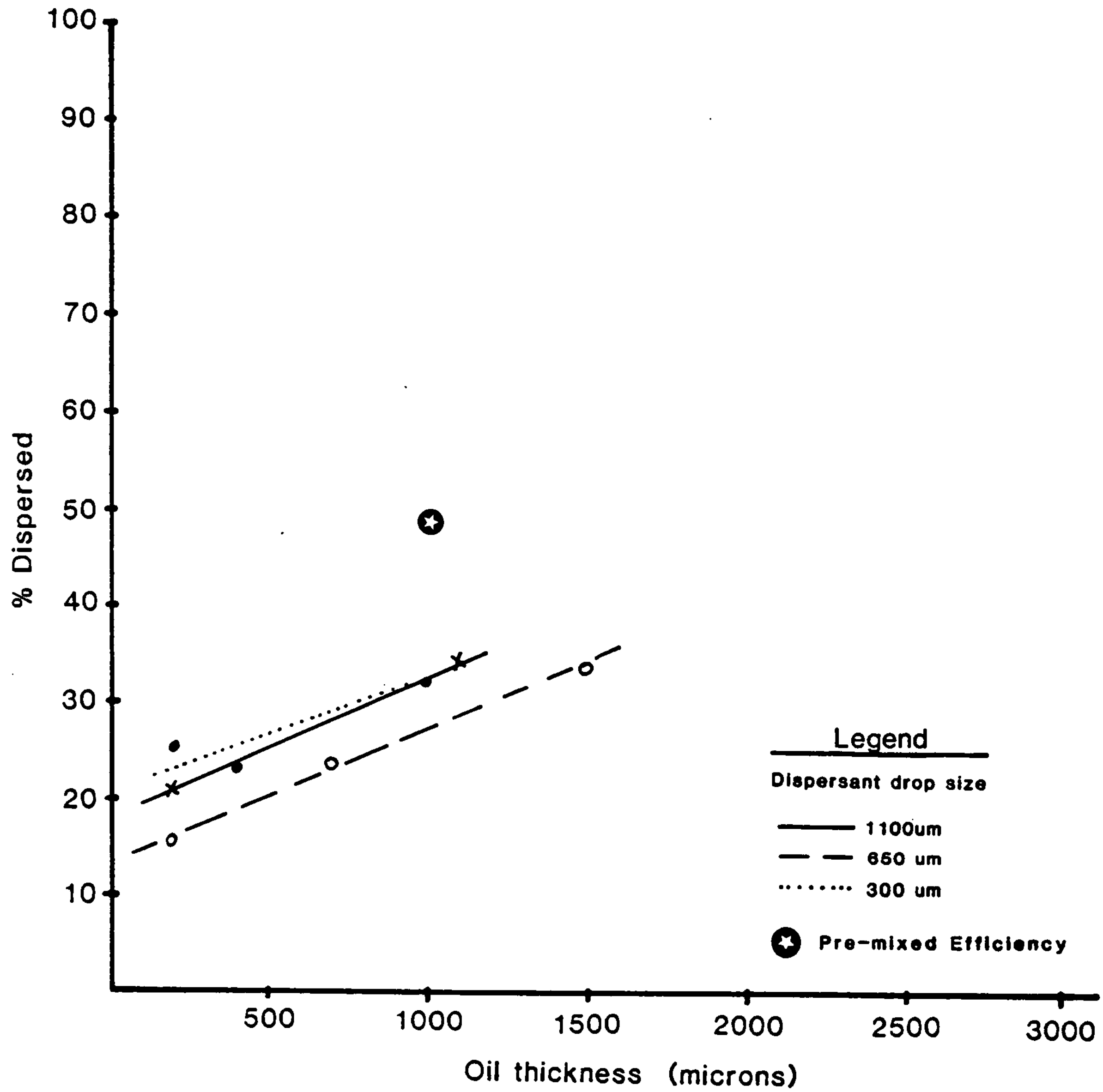

Figure 12. Dispersion efficiency vs oil thickness and dispersant drop size : EN700 at 1:15 on Redwater

Table 4

Summary of Calculated Performance and Access Factors "X" and "M"

Oil Type	Oil Thickness	Dispersant Type	Dispersant Drop Size	Percent Dispersed	D:O Ratio	"X"	"M"
ASMB	200	C 9527	300	87.0	50	43.4	6.7
ASMB	200	C 9527	650	55.4	50	27.6	7.7
ASMB	200	C 9527	650	73.2	50	36.5	9.0
ASMB	400	C 9527	300	87.9	50	43.9	4.7
ASMB	500	C 9527	1100	91.6	50	45.8	8.2
ASMB	1000	C 9527	650	93.8	50	46.9	4.5
ASMB	1000	C 9527	1100	86.8	50	43.3	5.7
ASMB	1300	C 9527	300	80.2	50	40.1	2.5
ASMB	2000	C 9527	650	76.1	50	38.0	3.0
ASMB	2000	C 9527	1100	83.7	50	41.8	4.0
ASMB	3000	C 9527	650	51.0	50	25.4	2.0
ASMB	3000	C 9527	1100	66.4	50	33.2	3.0
ASMB	3000	C 9527	1100	72.4	50	36.2	3.0
ASMB	200	EN 700	300	87.0	40	34.8	6.0
ASMB	200	EN 700	650	84.5	40	33.2	8.5
ASMB	200	EN 700	1100	63.0	40	25.2	9.7
ASMB	400	EN 700	300	98.5	40	39.4	4.5
ASMB	700	EN 700	650	80.9	40	32.3	4.5
ASMB	1000	EN 700	1100	84.2	40	33.6	5.0
ASMB	1200	EN 700	300	98.4	40	39.3	2.5
ASMB	2200	EN 700	650	84.2	40	33.6	2.7
ASMB	2500	EN 700	1100	94.6	40	37.8	3.5
ASMB	200	FINA OSR	650	82.1	25	20.6	6.7
ASMB	200	FINA OSR	1100	83.7	25	21.0	9.0
ASMB	700	FINA OSR	650	61.0	25	15.2	3.2
ASMB	1000	FINA OSR	1100	33.3	25	8.2	2.5
ASMB	2000	FINA OSR	1100	28.1	25	7.0	1.7
ASMB	2200	FINA OSR	650	40.5	25	10.1	1.5
NORMAN W	200	EN 700	300	97.1	75	72.8	8.5
NORMAN W	200	EN 700	650	98.9	75	74.1	12.7
NORMAN W	200	EN 700	1100	80.0	75	60.0	15.0
NORMAN W	400	EN 700	300	96.0	75	72.0	6.0
NORMAN W	700	EN 700	650	98.4	75	73.8	6.7
NORMAN W	1000	EN 700	1100	76.0	75	56.9	6.5
NORMAN W	1500	EN 700	300	98.2	75	73.6	3.0
NORMAN W	2000	EN 700	1100	73.3	75	54.9	4.5
NORMAN W	3000	EN 700	650	92.5	75	69.3	3.2

Table 4 (continued)

Oil Type	Oil Thickness	Dispersant Type	Dispersant Drop Size	Percent Dispersed	D:O Ratio	"X"	"M"
REDWATER	200	EN 700	300	25.0	15	3.7	1.7
REDWATER	200	EN 700	650	17.4	15	2.6	2.5
REDWATER	200	EN 700	1100	20.4	15	3.0	3.5
REDWATER	400	EN 700	300	22.2	15	3.3	1.2
REDWATER	700	EN 700	650	24.0	15	3.5	1.5
REDWATER	1000	EN 700	300	32.6	15	4.8	0.0
REDWATER	1100	EN 700	1100	34.8	15	5.2	2.0
REDWATER	1500	EN 700	650	32.9	15	4.9	1.2
UVILUK	200	C 9527	300	58.5	50	29.2	5.5
UVILUK	200	C 9527	650	27.3	50	13.6	5.5
UVILUK	200	C 9527	650	88.6	50	44.2	10.0
UVILUK	400	C 9527	300	85.3	50	42.6	4.7
UVILUK	500	C 9527	650	30.7	50	15.3	3.7
UVILUK	500	C 9527	1100	41.4	50	20.7	5.7
UVILUK	1000	C 9527	650	38.9	50	18.9	3.0
UVILUK	1000	C 9527	650	81.1	50	40.5	4.2
UVILUK	1000	C 9527	1100	64.0	50	32.0	5.0
UVILUK	1300	C 9527	300	96.9	50	48.4	2.7
UVILUK	2000	C 9527	650	89.9	50	44.9	3.2
UVILUK	2000	C 9527	650	98.6	50	49.2	3.2
UVILUK	2000	C 9527	1100	57.9	50	28.9	3.2
UVILUK	3000	C 9527	1100	71.5	50	35.7	3.0
UVILUK	200	EN 700	650	52.7	40	20.7	6.7
UVILUK	200	EN 700	650	64.5	40	25.3	7.5
UVILUK	200	EN 700	1100	60.6	40	23.8	9.5
UVILUK	200	EN 700	1100	57.2	40	22.8	9.2
UVILUK	700	EN 700	650	86.9	40	34.7	4.7
UVILUK	1000	EN 700	1100	61.6	40	24.6	4.2
UVILUK	1000	EN 700	1100	94.5	40	37.8	5.5
UVILUK	1000	EN 700	1100	81.3	40	32.5	5.0
UVILUK	2200	EN 700	650	93.9	40	37.5	2.7
UVILUK	2500	EN 700	1100	91.9	40	36.7	3.5
UVILUK	2500	EN 700	1100	95.8	40	38.3	3.5
UVILUK	3000	EN 700	1100	73.5	40	29.4	2.7
UVILUK	200	FINA OSR	650	64.3	50	32.1	8.5
UVILUK	200	FINA OSR	1100	80.2	50	38.8	12.0
UVILUK	700	FINA OSR	650	85.8	50	42.9	5.2
UVILUK	1000	FINA OSR	1100	94.0	50	46.8	6.0
UVILUK	2200	FINA OSR	650	96.1	50	48.0	3.2
UVILUK	3000	FINA OSR	1100	91.6	50	45.8	3.5

effectiveness. Therefore, we do not believe that the low dispersant efficiencies measured for the thin oil slicks (200 µm) represent an "access-limited" dispersion regime.

This same problem occurred during the tests on Uviluk crude oil with all three dispersants (see Figures 9, 10, and 11). Although the measured data plotted for these tests indicate a reduced efficiency at the 200-µm slick thickness, our observations again indicated that little or no surface oil was present at the end of all these tests except for the 1100-µm Corexit 9527 test in which an incomplete dispersion was noted. All the dispersants applied on Uviluk crude gave similar dispersion efficiencies close to the pre-mixed efficiency. The EN700 (1100-µm drop size) on Uviluk crude oil tests were duplicated to evaluate the repeatability of the test procedure (see Figure 10). The general trends identified by the two data sets are similar and the individual data points differed by only 3 to 12%.

The Redwater crude and EN700 dispersant results differ from all others in that a linear increase in dispersion efficiency occurred with an increasing slick thickness, even in the zone where the "performance" of all dispersants was constant for the other oils (see Figure 12). This increase may somehow result from the more viscous nature of the Redwater crude.

In summary, the results of this testing program generally do not support the "performance-access" theory of dispersant effectiveness. Tests conducted with ASMB using Corexit 9527 and Finasol OSR5 and Redwater using EN700 resulted in trends very different from those proposed in this theory. The remaining tests on Norman Wells, Uviluk, and ASMB did not identify a transition between a performance and access dispersion regime for oil slicks greater than 200 µm (the thinnest, uniform oil slick that we could generate in the test) and dispersant drops as large as 1100 µm in diameter.

The performance factors ("X") calculated for the tests approach the dispersant-to-oil ratio as would be expected for an efficient dispersant application. The calculated access factors ("M") ranged from about 2 to 15 with many tests exceeding the "typical" value of 5 estimated by Mackay. In these tests the access factor did not appear to be limited by herding effects as suggested by Mackay and values of "M" approached the theoretical value of 20 proposed by Mackay (see Table 3).

For the field cases used by Mackay to test his model the estimated thick slick thicknesses generally exceeded 200 µm, sheens were assumed to be 10 µm thick, dispersant drop sizes were 400 to 1000 µm and transition thicknesses ranged anywhere from 30 to 2000 µm. The tests conducted for this study bracket the input conditions used by Mackay to test his model but do not identify a transition between "access- and performance"-limited dispersion as his model suggests. If such a transition exists for these oils it must occur at even thinner oil thicknesses. If it applies only to very thin slicks or sheens (i.e., 50 µm or less) then the problem is academic because the oil volume is small in slicks of these thicknesses and natural dispersion is generally fairly rapid for thin slicks.

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