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034 Development of a High Pressure Water Mixing Concept for Use with Ship-based Dispersant Application

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DEVELOPMENT OF A HIGH PRESSURE WATER MIXING CONCEPT FOR USE WITH SHIP-BASED DISPERSANT APPLICATION

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SUMMARY

To develop an efficient, ship-based, oil-dispersing system using a high-pressure water jet mixing concept, a total of 65 large-scale laboratory tests simulating ship speeds from 1 to 3 m/s were conducted to study the effects of nozzle pressure, nozzle flow rate, and nozzle-to-water separation on the ability of high-pressure water jets to disperse oil slicks.

Dispersion efficiency at slow operating speeds (1 m/s) and small nozzle stand-off distances (0.6 m) was found to be very good. Nozzle pressure had little effect on dispersion efficiency at these conditions. Higher pressures were beneficial at higher operating speeds but pressures up to 80 000 kPa (12 000 psi) were needed to duplicate the low speed results.

Increased nozzle flow rates greatly improved the dispersion efficiency at the lower operating speeds for all pressures. Dispersion efficiencies up to 80% were measured with flow rates of 45 L/min. Data extrapolation indicates that 100% dispersion could be achieved in the laboratory with a nozzle flow rate of 50 - 60 L/min at even the lowest pressure tested.

Large nozzle stand-off distances were found to generate a reduced oil dispersion efficiency: a placement of 1.5 m was from two - seven times less effective than the smaller separation (0.6 m). Increased nozzle flow rates, or pressures, or both can overcome this reduced efficiency to some extent.

As it is difficult to translate the laboratory test results to those which would be achieved under typical offshore or nearshore conditions, for comparison purposes laboratory experiments were also conducted with the well-known Warren Spring Laboratory (WSL) breaker board system.

The high-pressure water system was found to be much more effective than the WSL breaker boards at the slow speeds. At operating speeds of 2.5 - 3.0 m/s, the water jet system becomes slightly less efficient than the breaker boards but neither system, in any case, appears to be efficient at these speeds.

Based on the test results, specifications for a practical high-pressure water jet system have been suggested. The system would operate with a nozzle pressure of 7000 kPa, a flow rate of 55 L/min per nozzle, and nozzles positioned about 0.6 m from the water surface.

Recommendations for further development of the mixing system include the construction of a near shore duty prototype system with the above-noted specifications, the testing of the system under typical near shore conditions to evaluate the system's durability, handling and efficiency, and finally the development of an offshore system if the results of the prototype testing are encouraging.

RESUME

Un total de 65 tests en laboratoire à grande échelle, simulant des vitesses de navire de 1 à 3 m/s furent effectués afin de développer un système de dispersion d'huile efficace à partir d'un navire. De plus, on cherchait à connaître les effets de la pression des lances, du taux d'écoulement des lances, et de l'apport lance-eau quant à l'efficacite des jets d'eau à haute pression sur la dispersion de nappes d'huile.

L'efficacité de dispersion à des vitesses opératoires reduites (1 m/s) à courte distance (0.6 m) se révéla très bonne. La pression de la lance avait peu d'effet sur l'efficacité de dispersion dans ces conditions. Des pressions plus élevés furent efficaces à des vitesses opératoires supérieures mais des pressions atteignant 80 000 kPa (12 000 psi) furent nécéssaires afin de reproduire les résultats obtenus à vitesse réduite.

Des taux d'écoulements accrus améliorèrent considérablement l'efficacité de dispersion aux vitesses opératoires réduites pour toutes les pressions. Des efficacités de dispersion allant jusqu'à 80% furent atteintes avec des taux d'écoulements de 45 L/min. L'extrapolation des données indique qu'une dispersion de 100% pourrait être atteinte en laboratoire avec un taux d'écoulement de 50-60 L/min et ce même à la pression testée la plus faible.

De grandes distances lance-nappe d'huile produisirent une efficacité de dispersion réduite: une distance de 1.5 m était de deux à sept fois moins efficace que la distance plus courte (0.6 m). Des taux d'écoulements et/ou de pression accrus peuvent jusqu'à un certain point contrecarrer cette efficacité réduite.

Puisqu'il est difficile de savoir si les résultats obtenus en laboratoire seront les mêmes que ceux obtenus sous des conditions typiques au large ou à

proximité des côtes, nous avons aussi effectues dés expériences en laboratoire avec le système de planches brise-lames bien connu de la "Warren Spring Laboratory" (WSL). Le système d'eau à haute pression s'avéra beaucoup plus efficace que le système de planches brise-lames WSL aux vitesses réduites. A des vitesses opératoires de 2.5 - 3.0 m/s, le système de jet d'eau devient quelque peu moins efficace que celui des planches brise-lames bien que ni l'un ni l'autre de ces systèmes n'apparaît efficaces à ces vitesses.

D'après nos résultats, nous suggérons les caractéristiques suivantes pour un système de jet d'eau à haute pression. La pression de la lance serait de 7000kPa, le taux d'écoulement serait de 55 L/min par lance avec les lances placées a environ 0.6 m de la surface de l'eau.

Pour le développement futur de système de mélange nous recommandons la construction d'un système prototype avec les caractéristiques ci-haut pour service à proximité des côtes, l'essai du systèm sous des conditions à proximité des côtes afin d'évaluer sa durabilité, sa manutention et son efficacité, et finalement le développement d'un système pour usage au large des côtes si les résultats du prototype sont prometteurs.

1.0 INTRODUCTION

The development of dispersant application systems for the treatment of large expanses of oil slicks from aircraft has overshadowed the potential benefits of ship-based systems. Ship-based dispersing operations are more suited to small, near shore operations or to the treatment of relatively small, continuous oil discharges from a damaged tanker or oil-well blowout. One advantage they hold over aerial systems is the ability to add additional mixing energy to the interface of oil and sea to improve the effectiveness of the chemical being applied. Work carried out in 1983 to develop better ship-based dispersing systems identified a simple, yet promising, mixing concept using high-pressure, relatively low-volume water jets to assist the dispersion process (S.L. Ross Environmental Research Ltd. 1983). This study considers this high-pressure water jet concept in more detail.

1.1 REVIEW OF PREVIOUS WORK

The most important conclusion of the previous work was that high-pressure water mixing can generate a better overall dispersion efficiency than towed mixing devices, especially at slower ship speeds. The high-pressure system tested in the previous study was four times as efficient as the WSL breaker board system at the 1.0-m/s operating speed (Figure 1). This greater efficiency results largely from the creation of much smaller oil droplets in the dispersion. An additional advantage of the water jet concept over towed systems is improved mobility because the mixing nozzles are placed above the water surface.

The high-pressure system evaluated in the previous study employed a single nozzle flow rate and pressure at all of the test speeds; also a single nozzle-to-water surface separation was used in all tests. Thus, as the speed

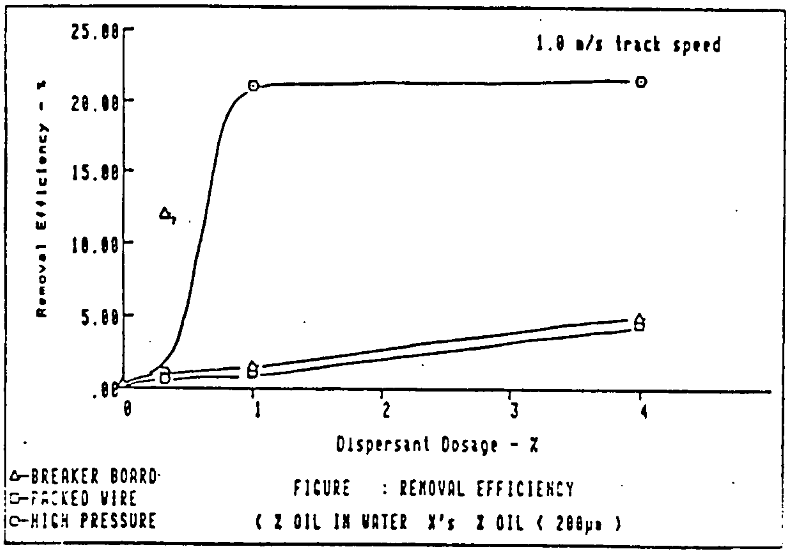

FIGURE : REMOVAL EFFICIENCY
(% OIL IN WATER X's % OIL < 200μm)

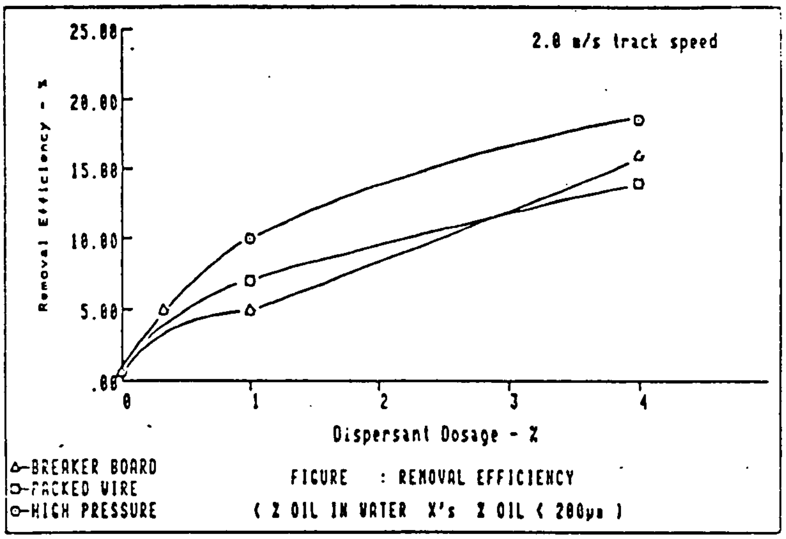

FIGURE : REMOVAL EFFICIENCY
(% OIL IN WATER X's % OIL < 200μm)

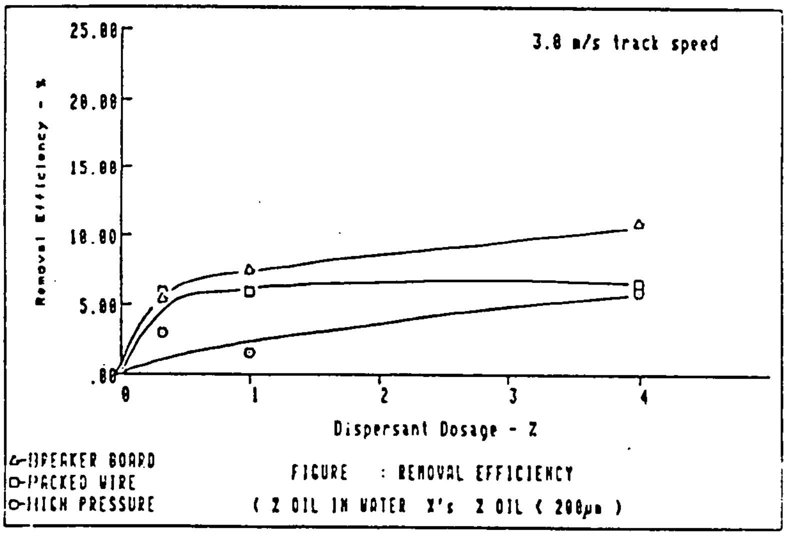

FIGURE : REMOVAL EFFICIENCY
(% OIL IN WATER X's % OIL < 200μm)

FIGURE 1 COMPARISON OF DISPERSING EFFICIENCIES OF 3 MIXING SYSTEMS (2 TOWED DEVICES PLUS HIGH PRESSURE WATERJET) of the nozzle was increased, the amount of energy supplied by the jets per unit area of slick treated decreased. It seemed reasonable to believe that if the flow energy from the jets were to increase at least in proportion to the ship speed, then the water jet systems would maintain a superior performance over the towed systems. It was also reasonable to suppose that the variables of pressure and nozzle stand-off distance could also be changed to improve mixing energies and, hence, dispersant effectiveness.

1.2 STUDY OBJECTIVE

The objective of this study was to develop an efficient, ship-based dispersing system using a high-pressure water jet mixing concept. This study evaluates three parameters (flow rate, pressure, and nozzle-to-water separation) as they affect oil dispersion efficiency. It should be noted that the efficiencies measured in the laboratory may not reflect actual field efficiencies. Therefore, to give some operational meaning to the laboratory results we compared the efficiencies measured for the water jet systems with those measured for the WSL breaker board system. Most operators are familiar with the WSL system and can therefore evaluate the likely field effectiveness of the water jet system by comparison with the breaker board's efficiency.

2.0 STUDY DESIGN CONSIDERATIONS

2.1 TESTING PROGRAM

The tests conducted in the project followed a protocol similar to those carried out in the 1983 study. Experiments were accomplished by studying the effects of a single, full-scale water jet moved at actual operational speeds. A field system would consist of several of these nozzles mounted on a boom extended from the side of the ship.

Measurements of the "instantaneous" dispersion created by the high-pressure water mixing were used to judge the performance of each test configuration. No attempt was made to model natural ocean turbulence in the tank during the experimentation because of the difficulty of accurately reproducing such mixing. Natural ocean turbulence would simply improve the dispersibility of the oil.

The dispersing efficiency of each high-pressure configuration was based on a combination of the total amount of oil dispersed and the drop-size distribution of the generated dispersion. Not all oil driven into the water column will remain permanently dispersed because the buoyancy of the larger drops can overcome the natural turbulent diffusive forces of the ocean and resurface. The true efficiency of a mixing system is therefore measured by the percentage of oil dispersed into the water times the fraction of that oil which is of small enough drop size to remain permanently in the water column.

2.2 OIL DROP SIZE NECESSARY FOR SUSTAINED DISPERSION

The suspension of the droplets is controlled by the level of natural ocean turbulence present during the dispersion. Unfortunately little information is available concerning small-scale ocean turbulence and its variation with wind speeds and sea states. Therefore it is difficult to predict with confidence which oil drops will be dispersed permanently once driven into the water column. There is some suggestion in the literature that only those dispersed oil drops smaller than about 100 - 200 μm in diameter will remain in the water column and will not resurface as a slick (Lee 1980; Cormack 1983).

Some simple calculations can be made to check these drop diameters. It is known that the action of winds blowing over a water surface creates regular roll vortices called Langmuir circulations. Raj (1977) has reported that the downwelling velocities resulting from these circulations can reach about 0.85% of the wind speed. Csanady (1973) has measured downwelling velocities of 0.4 cm/s resulting from these circulations and Lee (1980) has indicated that ocean eddies with velocities of 0.2 cm/s are common. Oil drops will rise through water according to Stoke's law, and the rise velocity of a drop can be estimated by equating the buoyancy of the drop to its weight plus a resisting force. The resulting equation for drop rise velocity is:

$$U = \frac{d^2(\rho w - \rho o)g}{18\mu}$$

where:

U = oil drop rise velocity (m/s)
ρw = density of water (kg/m^3)
ρo = density of oil (kg/m^3)
g = gravitational constant (m/s^2)
μ = absolute viscosity of water (kg/sm)
d = oil drop diameter (m).

When the eddy velocity exceeds this rise velocity, the drop will be held in permanent suspension in the water mass (unless the water mass carries the drop to the surface and it re-coalesces as a slick). The left-hand side of this equation has been equated to Lee's eddy velocity value of 0.2 cm/s to establish a possible range of maximum oil drop sizes which could be expected to permanently disperse. The drop diameters with rise velocities equal to this eddy velocity can then be calculated as a function of oil density (Figure 2). The oil used in this study, Alberta Mixed Blend, has a density of about 850kg/m^3 (5°C) when fresh and 875 kg/m^3 when sightly aged. It is seen from Figure 2 that droplets of this oil less than about 200 µm in diameter would not re-surface once dispersed in the ocean, assuming the average eddy velocity exceeded 0.2 cm/s. Therefore, for the purposes of this study it will be assumed that only oil drops with diameters of 200 µm and less can be considered permanently dispersed. During an actual ocean spill this cut-off diameter may vary dramatically as a function of the actual ocean turbulence level.

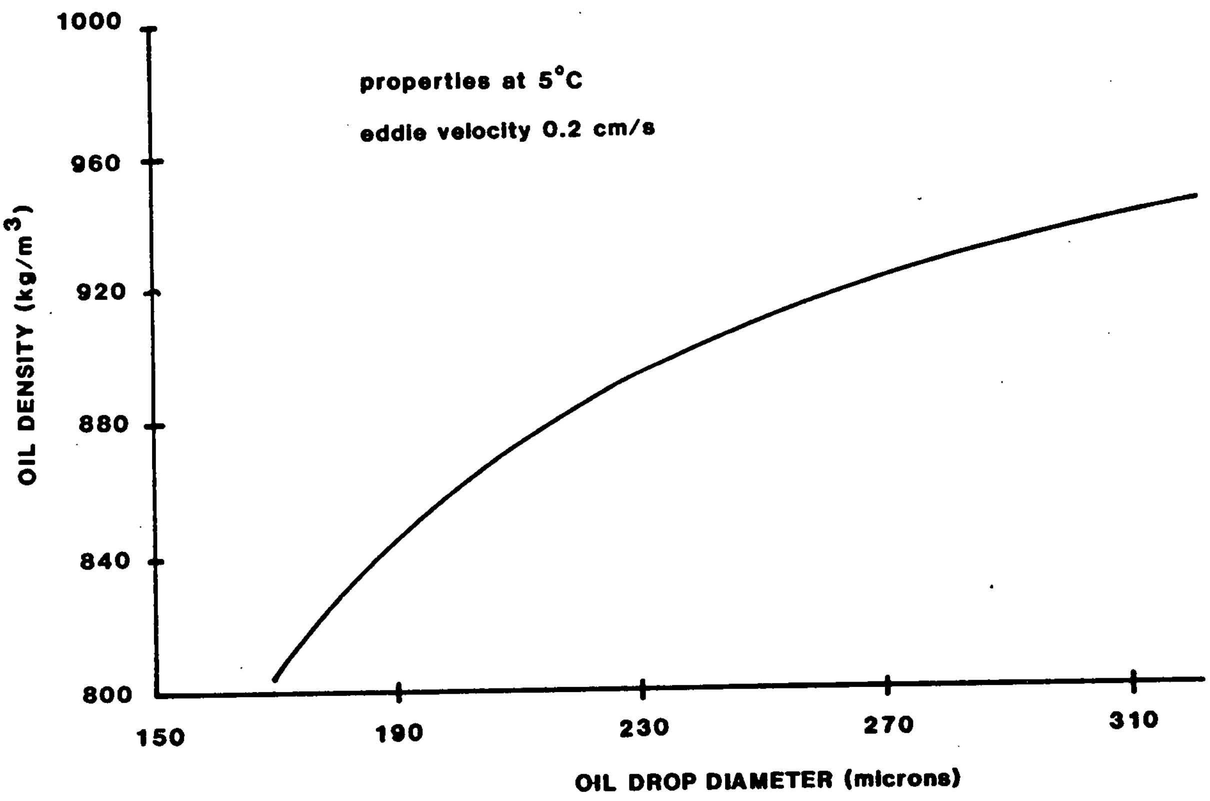

FIGURE 2 Maximum Oil Drop Size Which Will be Permanently Dispersed

3.0 TEST APPARATUS

3.1 TEST APPARATUS

Detailed technical specifications for most of the test equipment used in the study have been reported elsewhere (S.L. Ross Environmental Research Ltd. 1983). The only major change in the apparatus is the high-pressure pump used to supply water to the mixing jets. The following brief descriptions of the apparatus serve as background for the discussion of the experimental procedures adopted for this work.

Plates 1 and 2 show the tank used in these experiments. Its overall length, depth, and width are 11.0 m, 1.2 m, and 1.2 m, respectively. The three horsepower, variable-speed, d.c. motor and cable mechanism used to drive a cart across the test area are shown in Plate 1 (bottom left corner). The linear bearing shaft and cart are also evident in these photos. Deceleration of the cart was accomplished by the weight and elevated pulley arrangement seen near the far end of the tank (left side, Plate 1). An unobstructed view of the dispersion was possible through the glass front of the main tank section.

Gravity-fed water sampling ports, located at five different depths (2 cm, 12 cm, 25 cm, 50 cm, and 75 cm), have been built into the back of the central portion of the tank. As can be seen in Plate 2, two sets of tubing were installed to provide separate sampling networks for photographic documentation and water sample collection.

The photographic set-up for recording oil droplet distributions is shown as Plate 3. Photos were taken at a high shutter speed (1/1000th of a second) with a constant flow of water passing through the cells to a nearby drain. The water sampling ports were also set to flow constantly to a drain, keeping the lines clear of oil. Water grab samples were then taken by tapping these lines. (Plates 4 and 5).

PLATE 1: Overall View of Test Basin

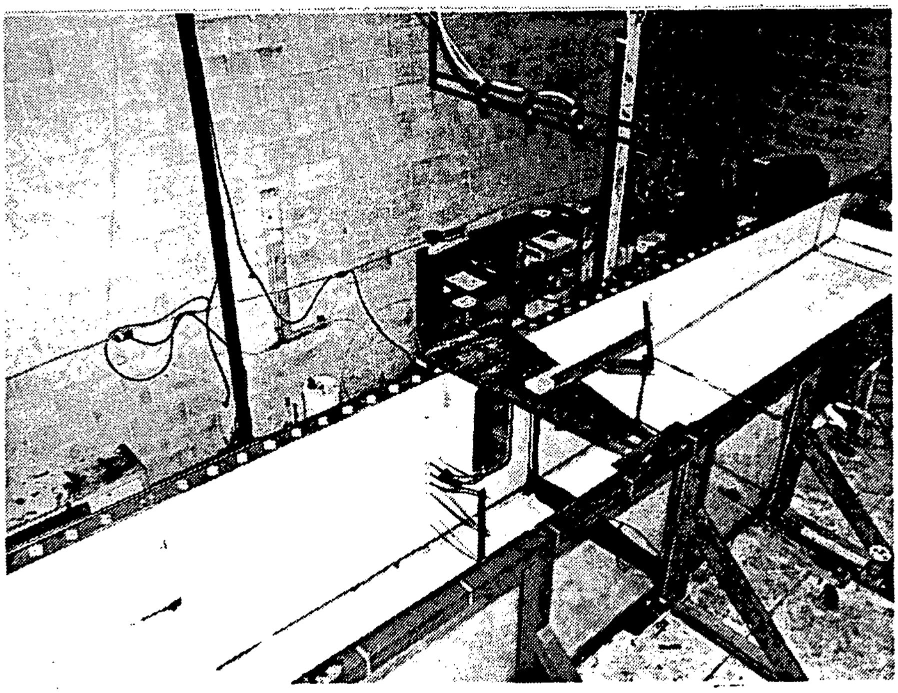

PLATE 2: Centre Portion of Test Basin

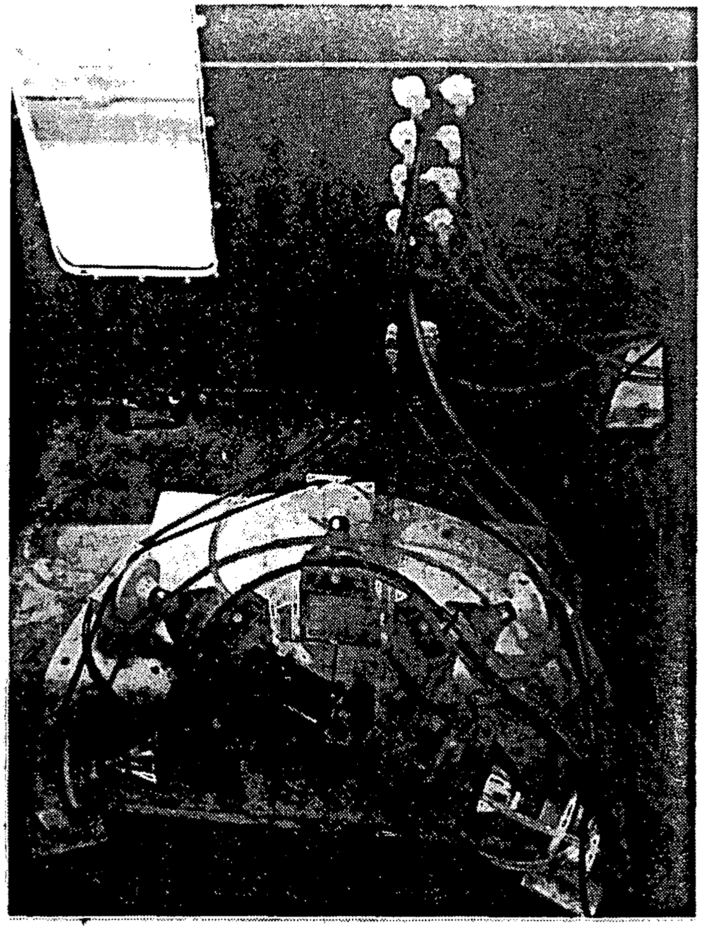

PLATE 3: Set-up for Drop-size Photography

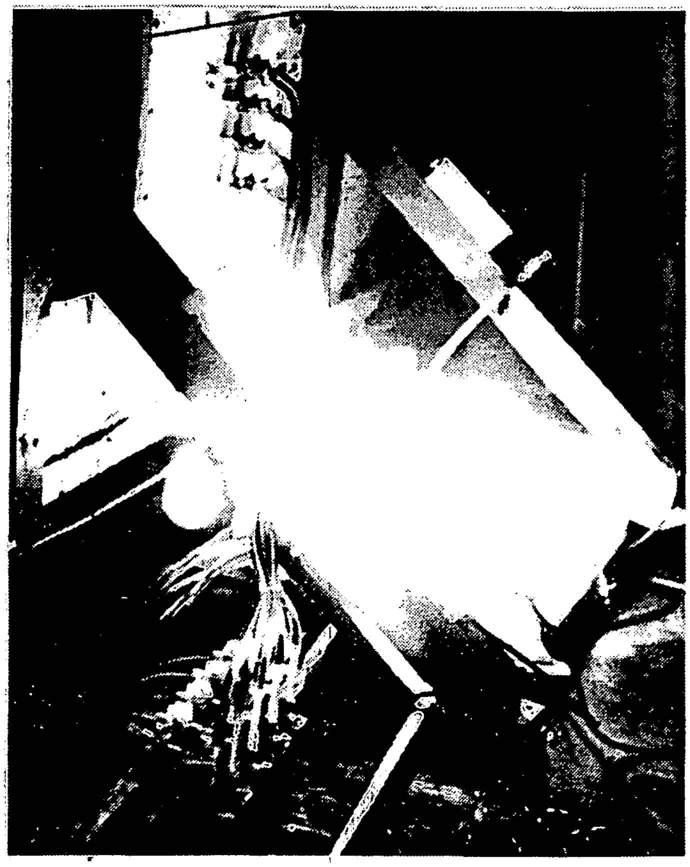

PLATE 4: Water Sampling Network

PLATE 5: Close-up of Sampling Valves

Dispersant was applied, via a gear pump at 100 psi, through nozzles attached to the overhead boom (see top of Plates 1 and 2) which was attached to the arm of a pendulum. The dispersant was applied to the water surface during one sweep of the pendulum. The drop-size distribution of the dispersant was measured by a Kromecote card technique. A photographic enlargement of a card is shown as Plate 6. Table 1 summarizes the dispersant drop size distribution calculated from this photo. The volume median drop size of the applied dispersant was about 925 μm.

A video camera (VHS recorder) was used to record each test. The video record was used to calculate the speed of the mixing system and to provide a permanent visual record of each generated dispersion for future comparison.

3.2 TEST CONDITIONS

The ultimate goal of the work was to identify the effects of mixing jet pressure, mixing jet flow rate, jet stand-off distance, and cart speed on the dispersion process. This identification has been accomplished by maintaining a standard set of conditions during the testing and then varying these four parameters to study their effects. The conditions kept constant during the testing are listed in Table 2.

TABLE 1 DISPERSANT DROP-SIZE CHARACTERISTICS

Maximum Drop-Size :1364.0
Minimum Drop-Size : 0.0
Ave Drop-Size(D10) : 126.1
Vol Mean Dia (D30) : 368.5
Sauter Mn Dia(D32) : 785.3

OIL DROP-SIZE DISTRIBUTIONS

Range µm	# of Drops	% of Drops	% Less Than	Vol %	% Vol Less
0 - 75	540	72.2	72.2	.10	.10
75 - 150	77	10.3	82.5	.26	.36
150 - 225	18	2.4	84.9	.34	.70
225 - 300	24	3.2	88.1	1.21	1.91
300 - 375	12	1.6	89.7	1.32	3.23
375 - 450	11	1.5	91.2	2.05	5.28
450 - 525	6	.8	92.0	1.88	7.16
525 - 600	13	1.7	93.7	5.65	12.81
600 - 675	9	1.2	94.9	6.13	18.94
675 - 750	12	1.6	96.5	11.00	29.94
750 - 825	4	.5	97.1	5.13	35.07
825 - 900	2	.3	97.3	3.67	38.73
900 - 975	9	1.2	98.5	20.12	58.85
975 -1050	5	.7	99.2	14.29	73.14
1050 -1125	3	.4	99.6	10.54	83.68
1125 -1200	1	.1	99.7	4.30	87.98
1200 -1275	1	.1	99.9	5.24	93.22
1275 -1350	0	0.0	99.9	0.00	93.22
1350 -1425	1	.1	100.0	6.78	100.00

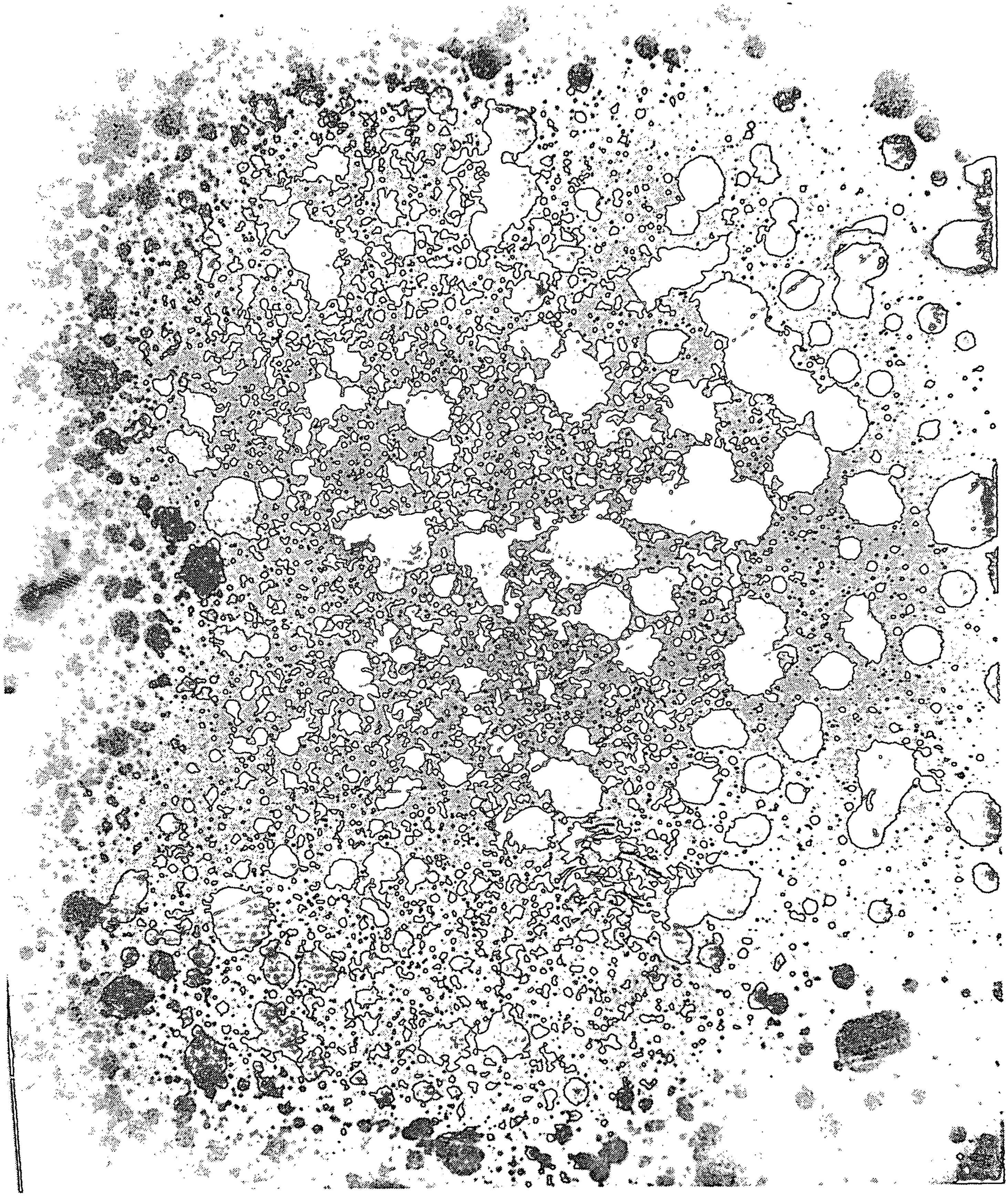

PLATE 6: Photographic Blow-up of Dispersant Drop-size Pattern on a Kromecote Card

TABLE 2

Fixed conditions during testing

Oil type	Alberta Sweet Mixed Crude Oil
Oil thickness	0.5 mm
Oil age	Fresh
Dispersant type	Corexit 9527
Dispersant dosage	1:100
Dispersant drop size	925 µm volume median diameter
Water salinity	32 ppt
Water temperature	15 to 20°C
Air temperature	20 to 25°C
Nozzle type	flat fan (20° or 30° divergence)

Table 3 shows the values of the other parameters that we attempted to achieve during testing. Because of limited nozzle selection and pump capacity we were unable to match all combinations of pressure and flow rates. For the actual test conditions during each run the reader is referred to the results section of this report.

TABLE 3

Range of parameters studied

Parameter	Tested Value
Jet stand-off distance	0.6 and 1.5 m
Jet pressures	7 000, 28 000, and 50 000 kPa
Jet flow rates	15, 30, and 45 L/min
Cart speeds	1, 2, and 3 m/sec

3.3 TEST PROCEDURE

The following is a brief description of the test procedure. The steps listed are for a standard test which involved the use of dispersant. For control tests involving no dispersant, steps 1, 7, 12, and 22 were omitted.

3.3.1 Preparation

1) Spray boom and nozzles were chosen to apply a dispersant dosage of 1:100;
2) the test tank was filled 1-m deep, with cold salt water (32 ppt);

3) the mixing nozzle providing the desired flow rate at the test pressure was selected and attached to the cart at the test height above the water surface;

4) the cart was attached to the drive cable;

5) the deceleration "catch-rope" was positioned;

6) the driver motor controller was set to the desired speed;

7) the spray boom was charged;

8) six litres of oil was spread evenly over the water surface and was allowed to equilibrate;

9) eight sample port valves were opened and a continuous flow was established through the photographic cells and the water sampling tubes; and

10) the photographic and video lights were turned on.

3.3.2 The Run

11) The video camera was started;

12) the dispersant pump was started and the spray boom was released to apply the dispersant;

13) the high-pressure water jet was started;

14) the driver motor was started, propelling the cart across the sampling area;

15) at the first sighting of oil in the photographic cells, drop-size photography and water sampling were started simultaneously. One to three photographs and eight to ten water samples were taken at each depth to "catch" the peak concentration of dispersed oil; and

16) the sample port valves were closed and all lights and video equipment were turned off.

3.3.3 Sample Preparation

17) The water samples with peak oil concentrations were chosen for each depth;

18) oil was extracted from the samples with toluene. The volume of each sample was recorded and the extraction was labelled and stored. The oil content of the extractions was later established by a UV spectrophotometer;

19) the number and sequence of photographs taken were noted, and prints were made later for the drop-size analysis; and

20) the cart speed and dispersion characteristics were noted from the video playback.

3.3.4 Preparation for the Next Test

21) After allowing the oil to re-surface, the surface oil was skimmed over the end weir for disposal;

22) the spray boom was reset;

23) the tank water level was replenished; and

24) the towing cart and drive cable were re-positioned at the end of the tank.

Plates 7 through 10 illustrate the sequence of main events during a test. Plate 7 shows the tank after addition of the oil; Plate 8 after dispersant was applied; Plate 9 the passage of the mixing jet; and Plate 10 the surface of the tank immediately after the mixing jet pass.

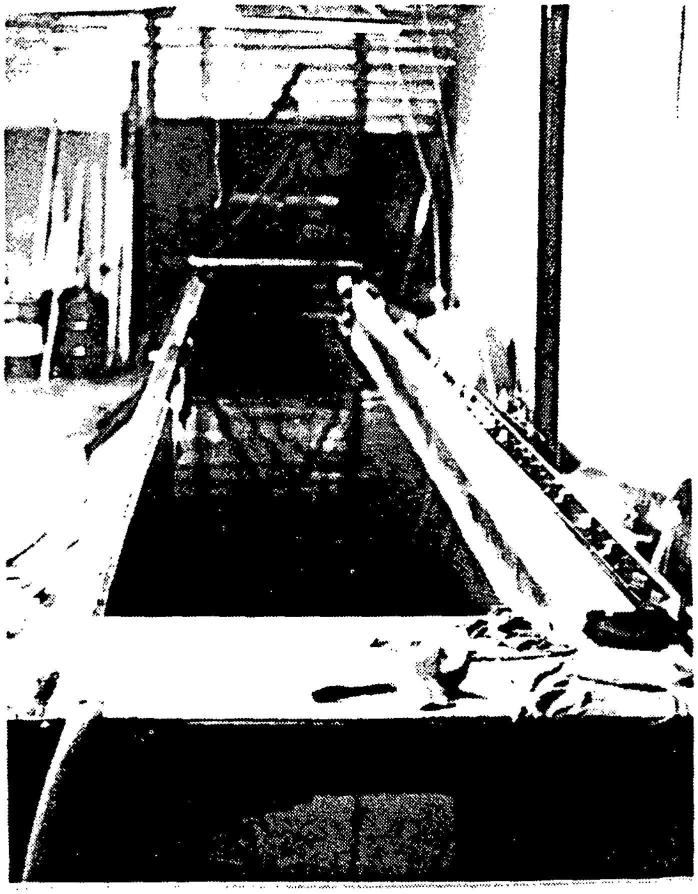

PLATE 7: Oil Slick in Place on Tank

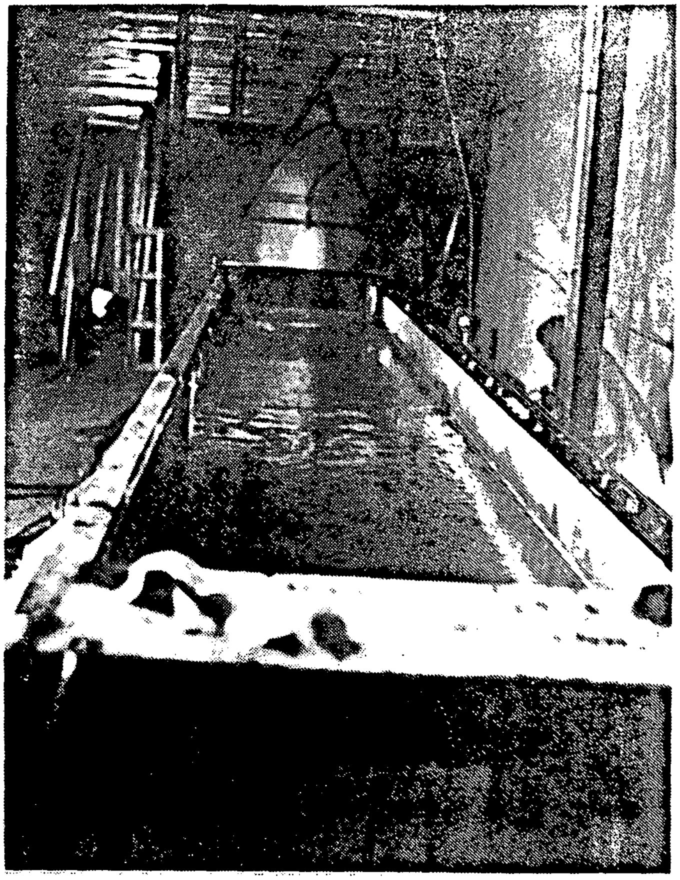

PLATE 8: Oil after Dispersant is Applied

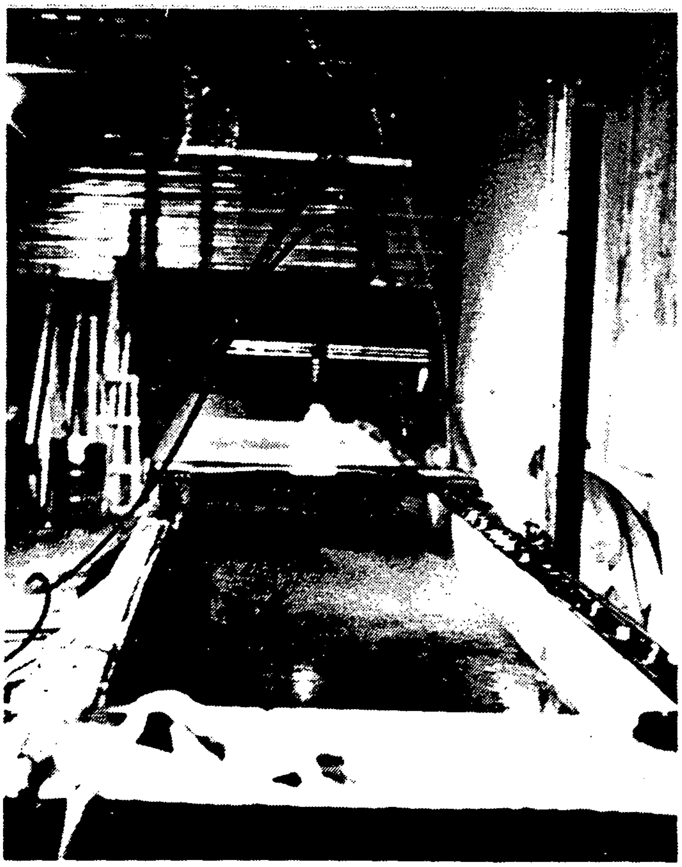

PLATE 9: Passage of Mixing Jet

PLATE 10: Water Surface after Jet Passes

4.0 ANALYTICAL TECHNIQUES

Three types of data were collected during each test. Oil concentrations were measured immediately after the dispersion by taking grab samples of water from four depths in the tank. The oil-in-water dispersions were photographed at each of these four levels for determining oil drop-size distributions. Finally, a video record of each test was taken to document track speed, dispersion depth, and general dispersion appearance.

In-water oil concentrations were measured to provide an accurate picture of the quantity of oil dispersed in each test. Water samples were taken from gravity-fed sampling tubes which were constantly flowing to a drain during the testing. Immediately following each test the volume of each sample was recorded and was then placed in a separatory funnel. The oil was then extracted by adding about 15 mls of toluene to the separatory funnels, vigorously shaking the mixtures, and then waiting for the separation of the solvent with oil and water components. The solvent and oil solutions were then drawn off to vials and stored until analysed (generally less than one week storage time). The volume of the solvent was then measured and its oil content determined by a UV/VIS spectrophotometer. The concentration of oil in the water sample was then calculated using the known sample volume, solvent volumes, and oil-in-solvent concentration.

The drop-size distribution of each dispersion was measured photographically. A second set of sampling tubes carried the oil-in-water dispersion to the series of photographic cells, (see Plate 3). Photographs of the oil drops generated in each test were taken using a 35-mm, single-lens-reflex camera fitted with an extension bellows; a 50-mm, f/1.4 lens; and a 400-ASA, black-and-white film. The photocells were back lit with 150-watt spot-lights thus allowing a lens setting of f8.0 and a shutter speed of 1/1000th of a second. The scale for the photos was established by photographing a 10 mm x 10 mm grid with the identical camera settings used in the drop-size pictures. The negatives of both the scale and the oil drops were then printed in an 8 in x 10 in format resulting in a magnification of about 20 times. The oil drop-size distributions were then determined through the use of a digitizing tablet and micro-computer data acquisition and processing system. Examples of a typical oil droplet photo and the drop-size distribution, as measured with the data acquisition system, follow as Plate 11 and Table 4.

The appearance of each dispersion was recorded by a VHS video camera and recorder. This recording was necessary because time was not available to view the overall test while it was underway due to the amount of sampling required. This permanent visual record of each test was invaluable in the final data analysis and interpretation process. Additionally, the video's timing mechanism was used to determine the mixing system's speed during each test and the depth of each dispersion was scaled from the video record.

PLATE 11: Typical Oil Dispersion Photograph

TABLE 4 OIL DROP-SIZE DISTRIBUTION

Date of Run [D/M/Y] : 11/07/85 11JLR12 DAT

Type of Mixing System : 56 000 kPa / 15 l/min / 0.6 m

Dispersant to Oil Ratio : 1:100

Track Speed [M/S] : 2.60

##

GENERAL OIL DROP-SIZE INFO (MICRONS)

Maximum Drop-Size	: 271.3
Minimum Drop-Size	: 4.6
Ave Drop-Size(D10)	: 52.5
Vol Mean Dia (D30)	: 89.1
Sauter Mn Dia(D32)	: 142.1
Volume Median Dia	: 179.5

OIL DROP-SIZE DISTRIBUTIONS

Range (μm)	# of Drops	% of Drops	% Less Than	Vol %	% Vol Less
0 - 50	215	65.7	65.7	2.54	2.54
50 - 100	69	21.1	86.9	11.92	14.45
100 - 150	22	6.7	93.6	15.82	30.28
150 - 200	14	4.3	97.9	31.66	61.94
200 - 250	5	1.5	99.4	20.84	82.78
250 - 300	2	.6	100.0	17.22	100.00

TOTAL # DROPS - 327 TOTAL OIL VOLUME (ML) = .00012131

NUMBER OF DROPS REJECTED FROM DIST. = 0

5.0 RESULTS

A total of 65 large-scale tests were completed during the study. From these 65 tests, 40 distinct conditions of nozzle pressure, flow rate, and stand-off distance were studied. The 25 additional tests are accounted for as follows. Eight of the initial tests were completed without dispersant application during the shake-down of the experimental set-up. Several tests experienced equipment malfunction or operator error; however, the good data from these tests have been used where possible to supplement and validate the data acquired in the 40 complete tests.

As stated earlier, for the purpose of this study dispersion efficiency of the system is defined as the percent of the total oil dispersed in the form of droplets less than 200 µm in diameter. This measured efficiency may or may not be indicative of what could be achieved by an actual operational system in this field. Therefore, to better appreciate these efficiency measurements we have compared them to the efficiencies of the WSL breaker board system tested in our laboratory setting.

The water jet dispersion efficiencies are plotted against the nozzle flow rate and nozzle pressure for each of the three track speeds and nozzle heights. The trends that were identified by these graphs are discussed in the following sections.

5.1 DISPERSION EFFICIENCY VS NOZZLE FLOW RATE

Figures 3, 4, and 5 illustrate the effect of nozzle flow rate on the dispersion efficiency for the three pressure conditions (7 000, 28 000, and 50 000 kPa) and the low nozzle position (0.6 m from the water surface) at three operating speeds (1, 2, and 2.5 m/sec). At all pressures the increase

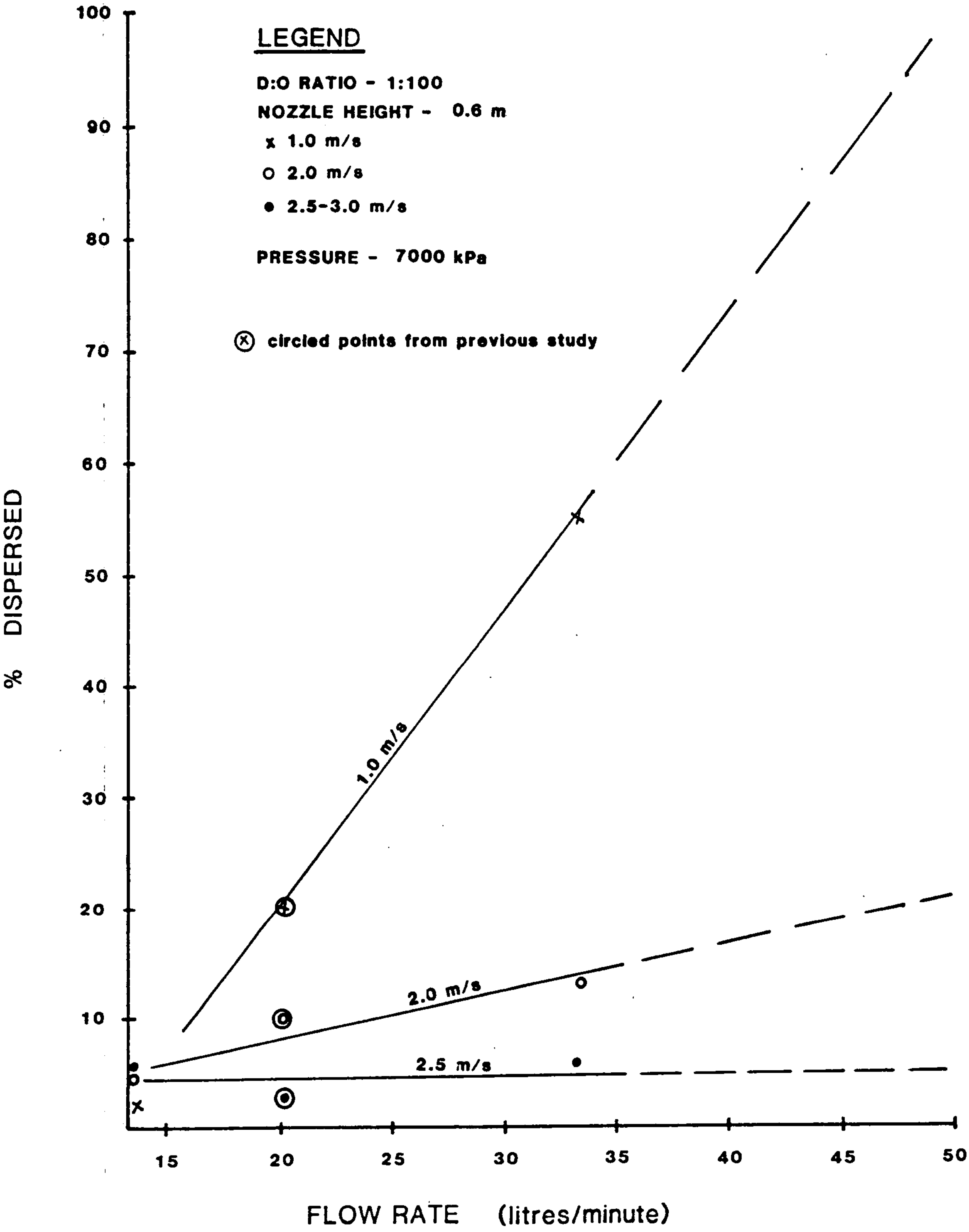

FIGURE 3 Dispersion Efficiency vs Nozzle Flow Rate
(7000 kPa and 0.6 m standoff)

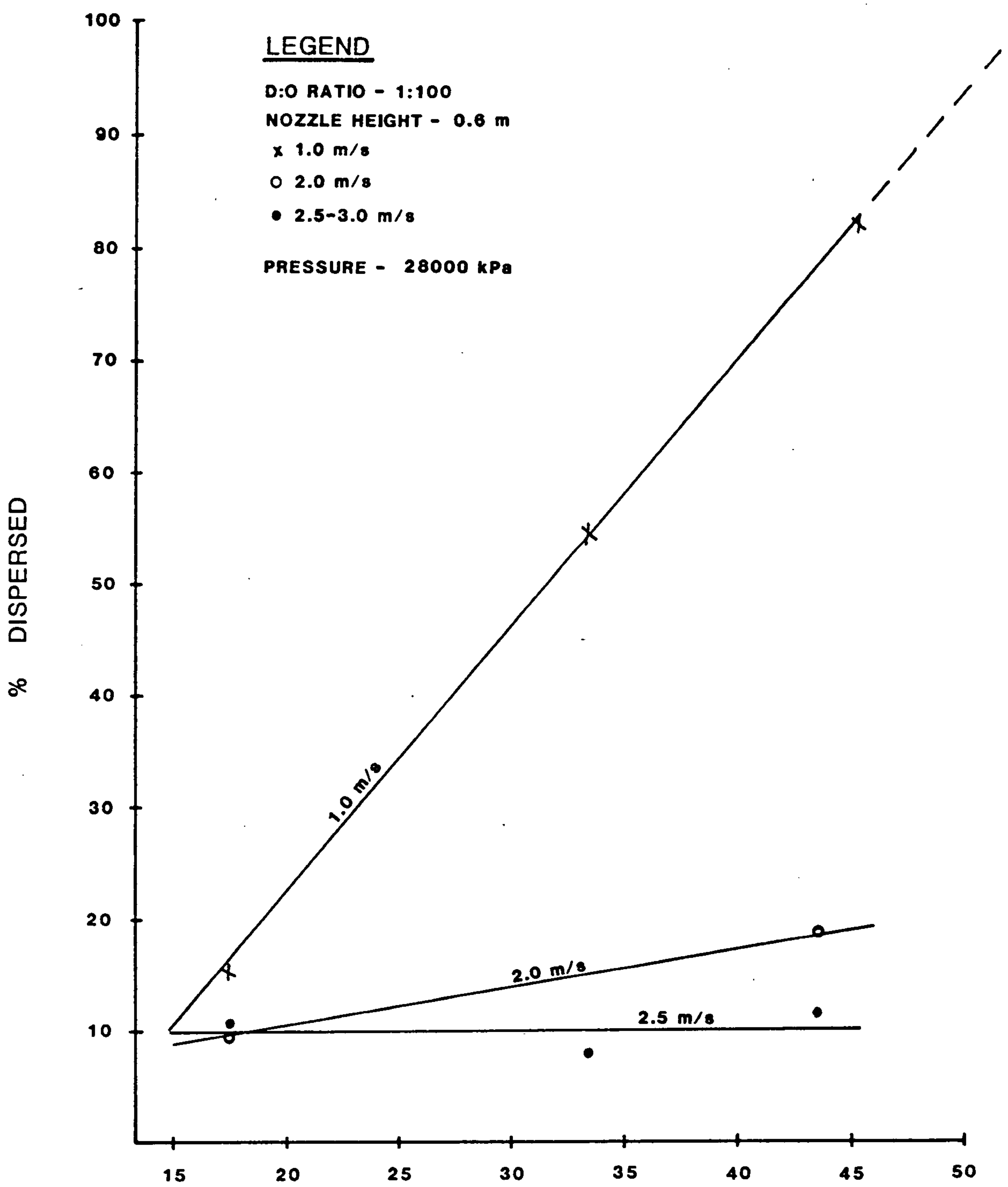

FIGURE 4 Dispersion Efficiency vs Nozzle Flow Rate (28000 kPa and 0.6 m standoff)

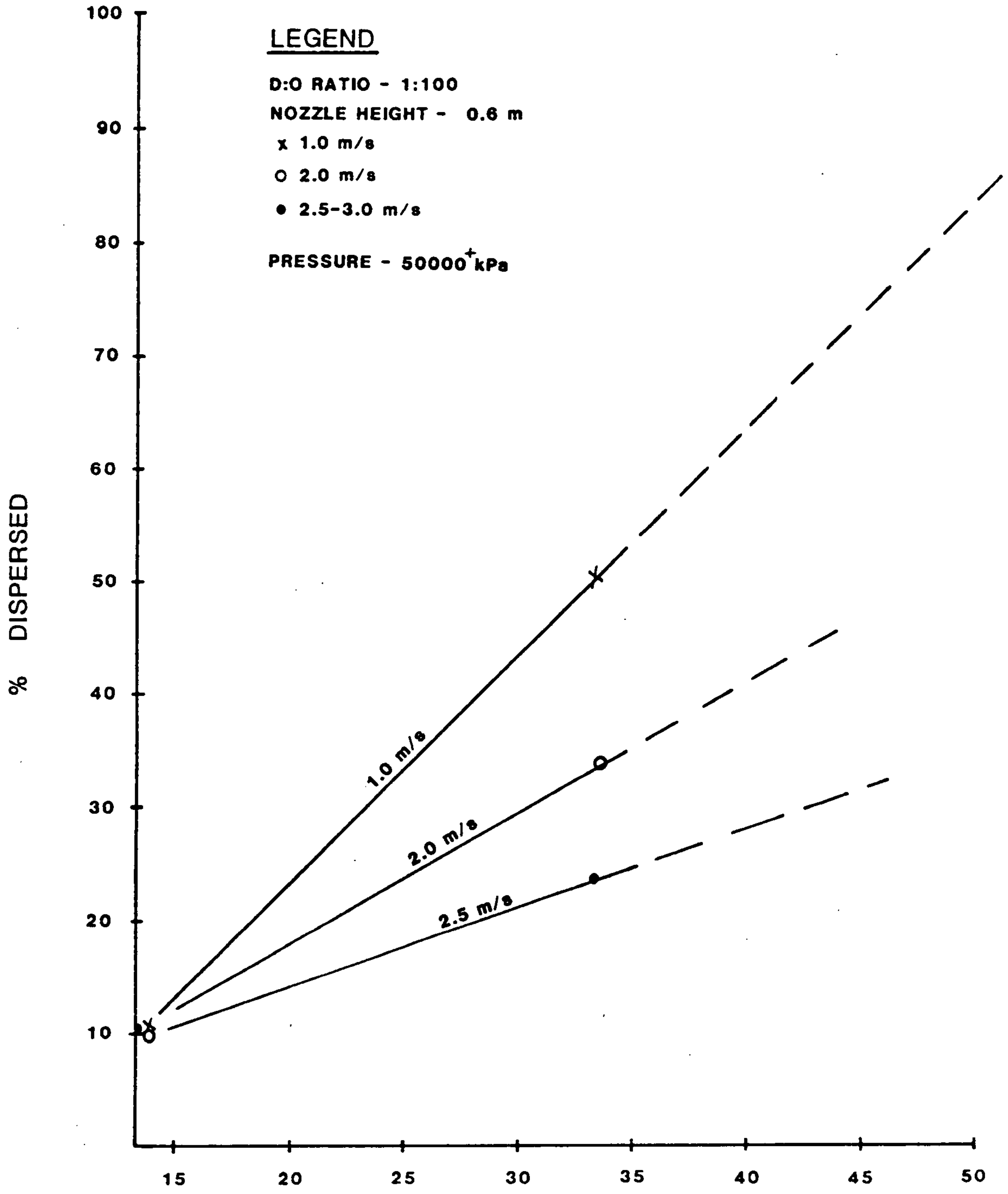

FIGURE 5 Dispersion Efficiency vs Nozzle Flow Rate (50000+kPa and 0.6 m standoff)

in nozzle flow rate dramatically increased the dispersion efficiency at the slowest track speed (1.0 m/s). If this tendency carries on past the measured flow conditions, it is possible that 100% dispersion could have been achieved in the laboratory with a flow rate of about 55 L/min at an operating speed of 1.0 m/s (see Figures 3, 4, and 5). The reader is reminded that the best efficiency measured for the breaker board system was about 15% (see Figure 1).

For the higher track speeds the gain in dispersion efficiency resulting from higher flow rates was not as dramatic, expecially at lower pressures. For the tests at 7000 and 28 000 kPa and 2.0 m/sec, a doubling of the flow rate resulted in a slightly less than two-fold increase in dispersion efficiency. At higher speeds, at these pressures, the increased flow rate had little effect on the resulting dispersion.

When the pressure was increased to 50 000 kPa, the operating speed did not have as dramatic an effect on the resulting efficiency (see Figure 5).

Figures 6, 7, and 8 demonstrate the effect of nozzle flow rate on dispersion efficiency for the high nozzle position. Unfortunately, the data set collected for the higher nozzle position is neither as complete nor as consistent as that from the lower position. The following general trends can, however, be speculated with help from the results of the lower nozzle position.

At the lowest flow rate tested (about 12 L/min) dispersion efficiency was generally less than about 5% at all track speeds. (The efficiencies calculated for the tests at 28 000 kPa with this low flow rate are unusually high when compared to the other pressures at this nozzle height and with the efficiencies measured at the lower nozzle position. The reason for this discrepancy is not apparent.) An increase in flow rate, to about 30 L/min, resulted in only slightly improved dispersing efficiencies (up to 10%) at the low and medium pressures at all track speeds. At the highest pressure tested

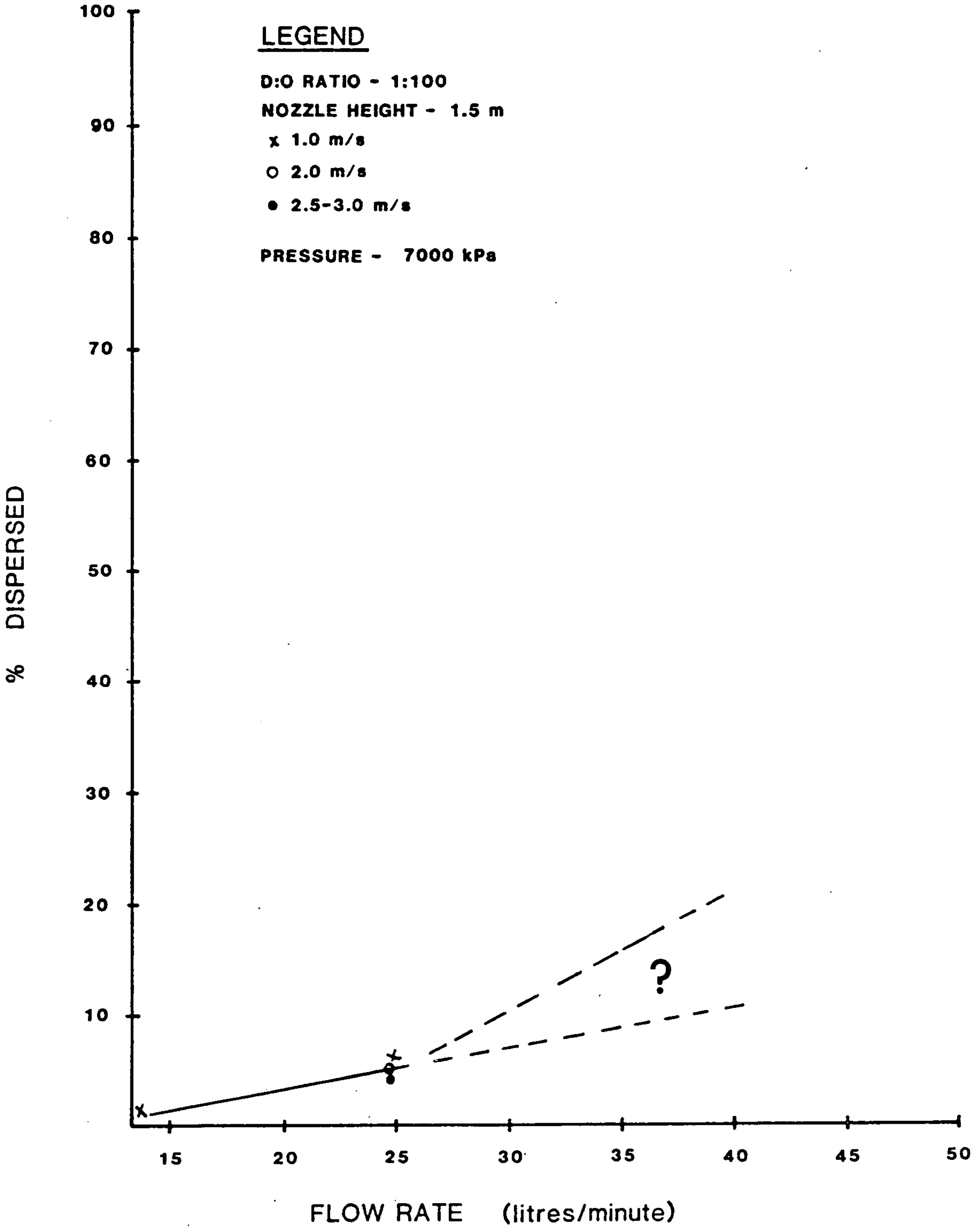

FIGURE 6 Dispersion Efficiency vs Nozzle Flow Rate (7000 kPa and 1.5 m standoff)

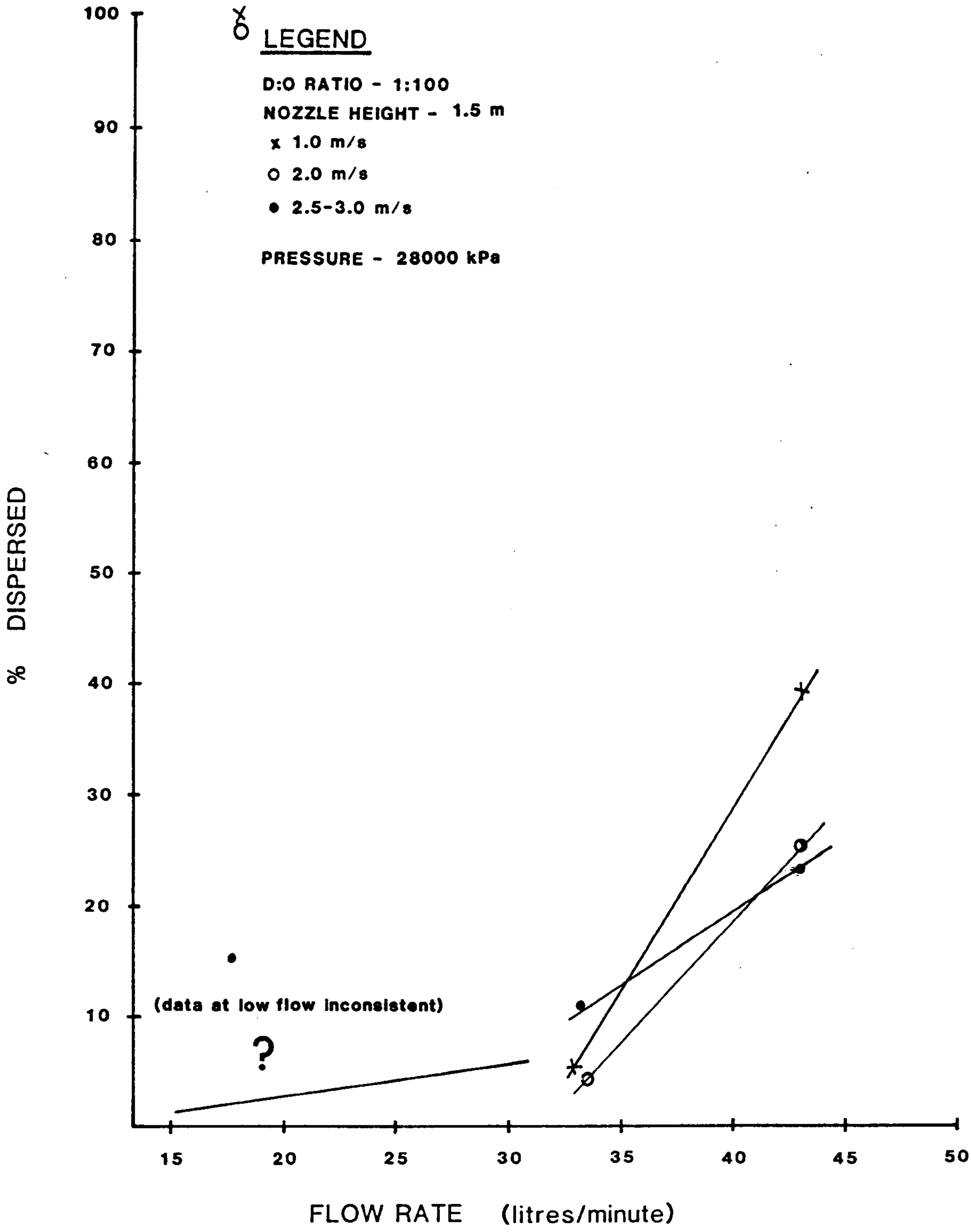

FIGURE 7 Dispersion Efficiency vs Nozzle Flow Rate (28000 kPa and 1.5 m standoff)

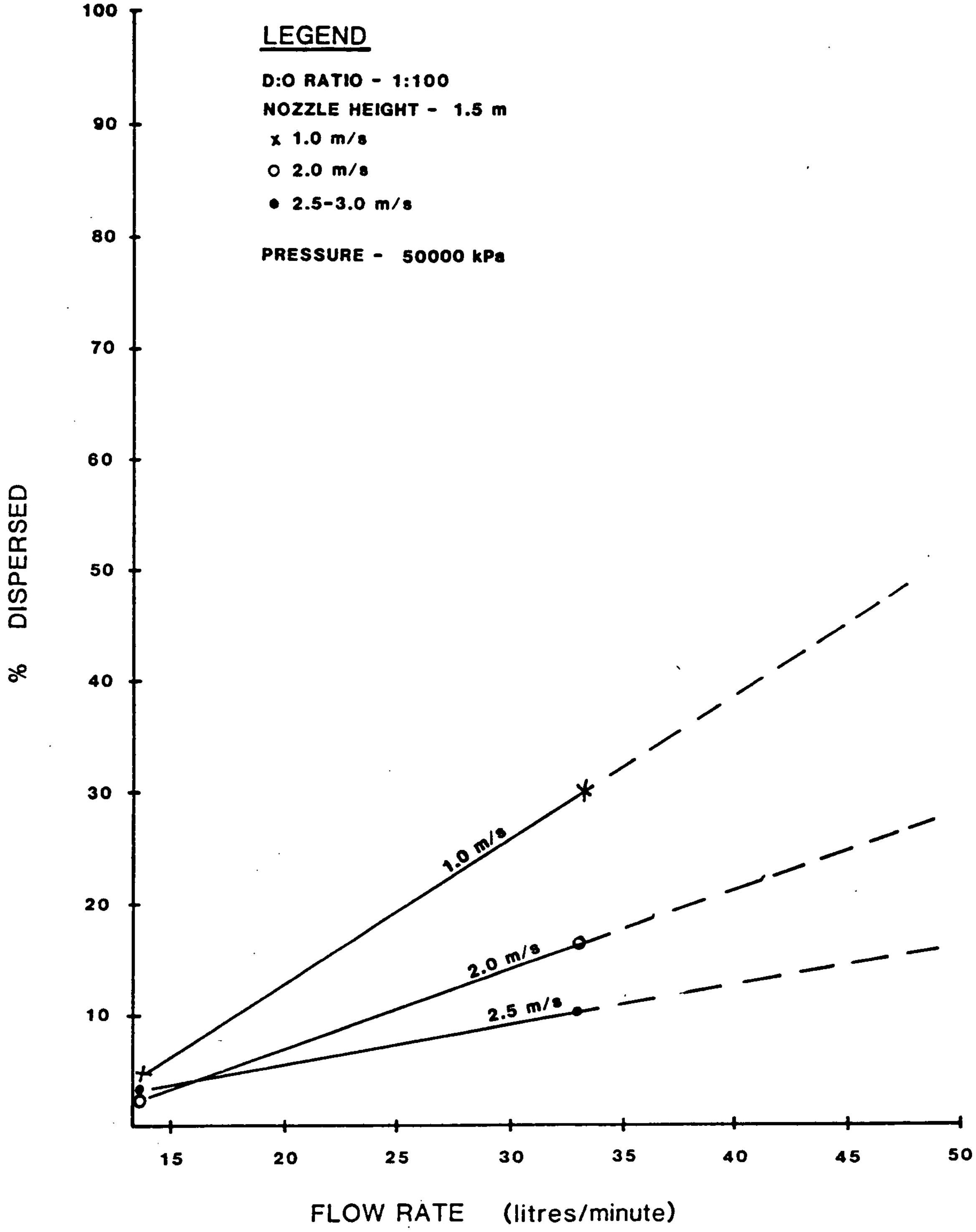

FIGURE 8 Dispersion Efficiency vs Nozzle Flow Rate
(50000 kPa and 1.5 m standoff)

(50 000$^+$ kPa) a more pronounced improvement was recorded (see Figure 8). A further increase in flow rate to about 45 L/min resulted in a marked improvement in efficiency (to about 40%) at the medium pressure condition (see Figure 7). Tests were not conducted at the high flow rate/high-pressure condition because of the limited capacity of the pump used in the testing. A suitable nozzle was not available to provide the high flow/low pressure conditions.

The data show that when the high-pressure mixing system was mounted further from the water (at 1.5 m or 5 ft), it was efficient only for the high flow rate/high-pressure conditions. When the jet was mounted close to the water surface (0.6 m or 2 ft) the higher pressures were not needed to achieve good dispersion, and efficiency improvements resulted primarily from increased flow rates (especially at the lower track speeds). The effect of nozzle pressure on dispersion efficiency is discussed further in the following section.

5.2 DISPERSION EFFICIENCY VS NOZZLE PRESSURE

Figures 9, 10, and 11 illustrate clearly that, for the slower operating speed, an increase in nozzle pressure does little to increase the efficiency of the mixing jet (for the small jet stand-off distance). At the higher track speeds, increasing the pressure resulted in improved dispersion but significant gains were achieved only at the highest pressure (50 000$^+$ kPa). It seems that the high-pressure/high flow rate jet eventually overcomes the inefficiency associated with higher operating speeds (see Figures 10 and 11). If these curves are extrapolated beyond the measured pressures, they eventually meet the 1.0 m/s curve at about 75 000 - 80 000 kPa (10 500 - 11 500 psi). Although it is much more practical to operate at only 7000 - 8000 kPa and 35 L/min rather than at these higher pressures, it may be impractical from a logistical point of view to treat slicks at only 1.0 m/s. The difficulty of providing such high-pressure (80 000 kPa)/high flow rates (35 L/min) on a ship of opportunity would have to be weighed against the oil-encounter inefficiency of a slow-moving system.

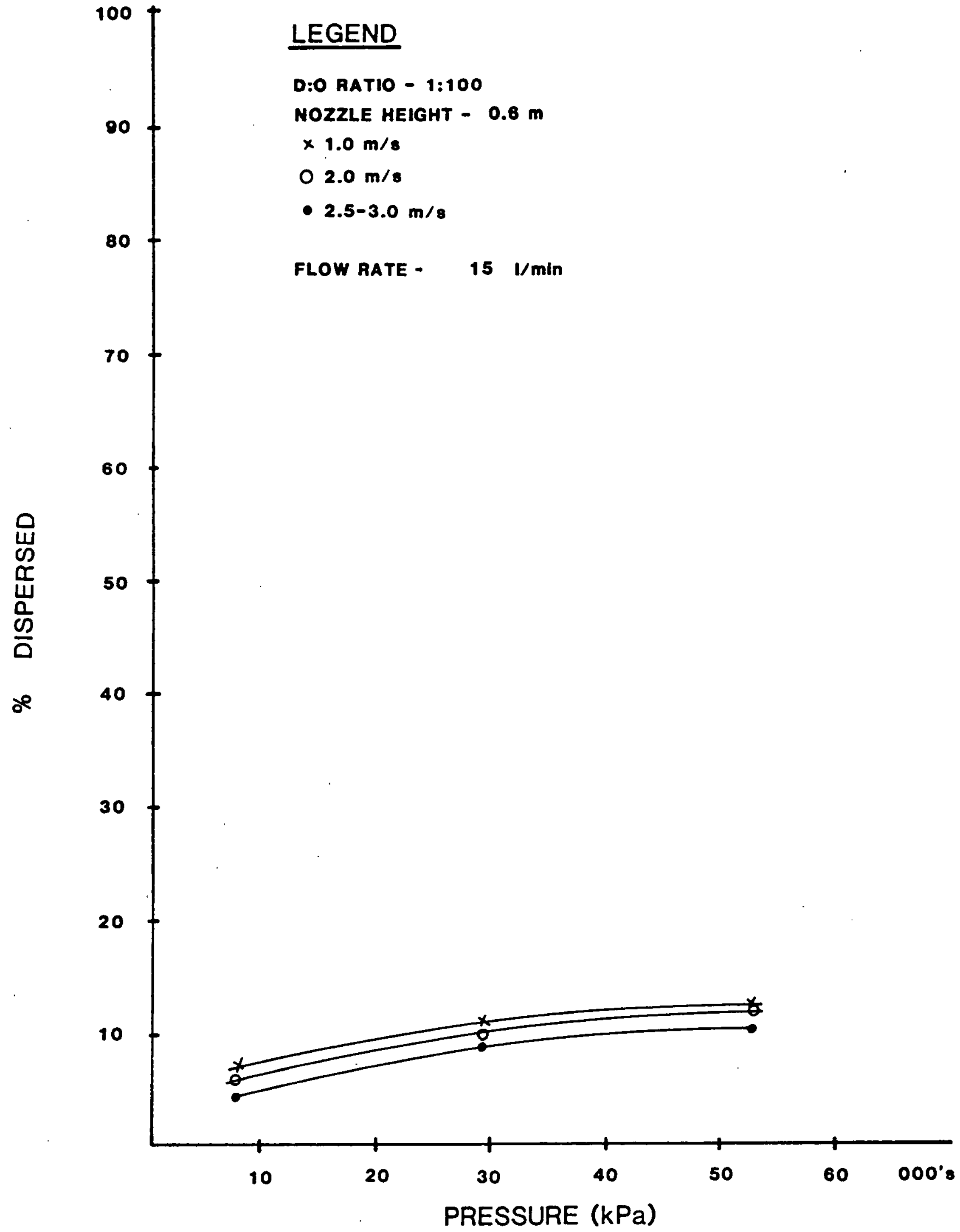

FIGURE 9 Dispersion Efficiency vs Nozzle Pressure (15 l/min and 0.6 m standoff)

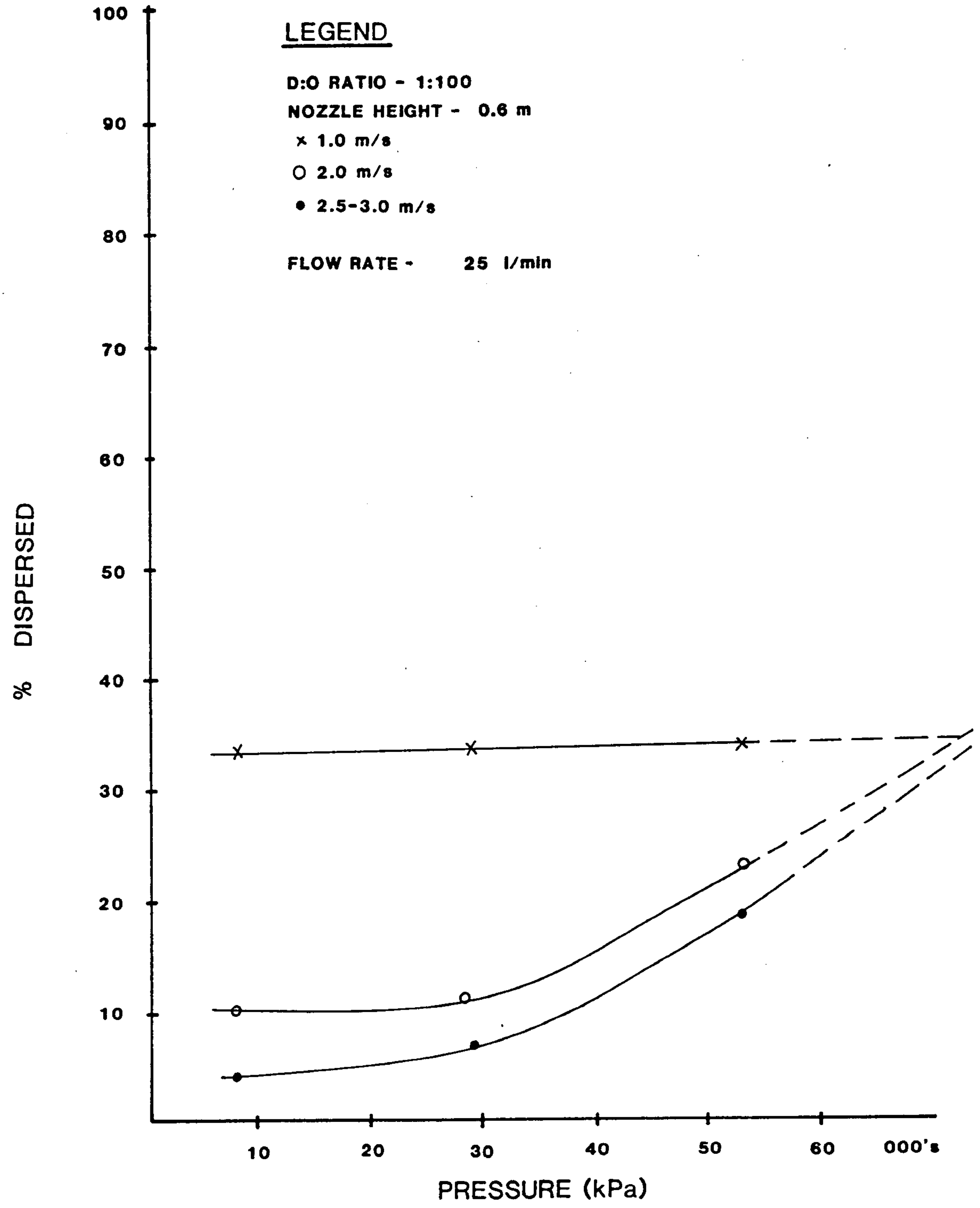

FIGURE 10 Dispersion Efficiency vs Nozzle Pressure
(25 l/min and 0.6 m standoff)

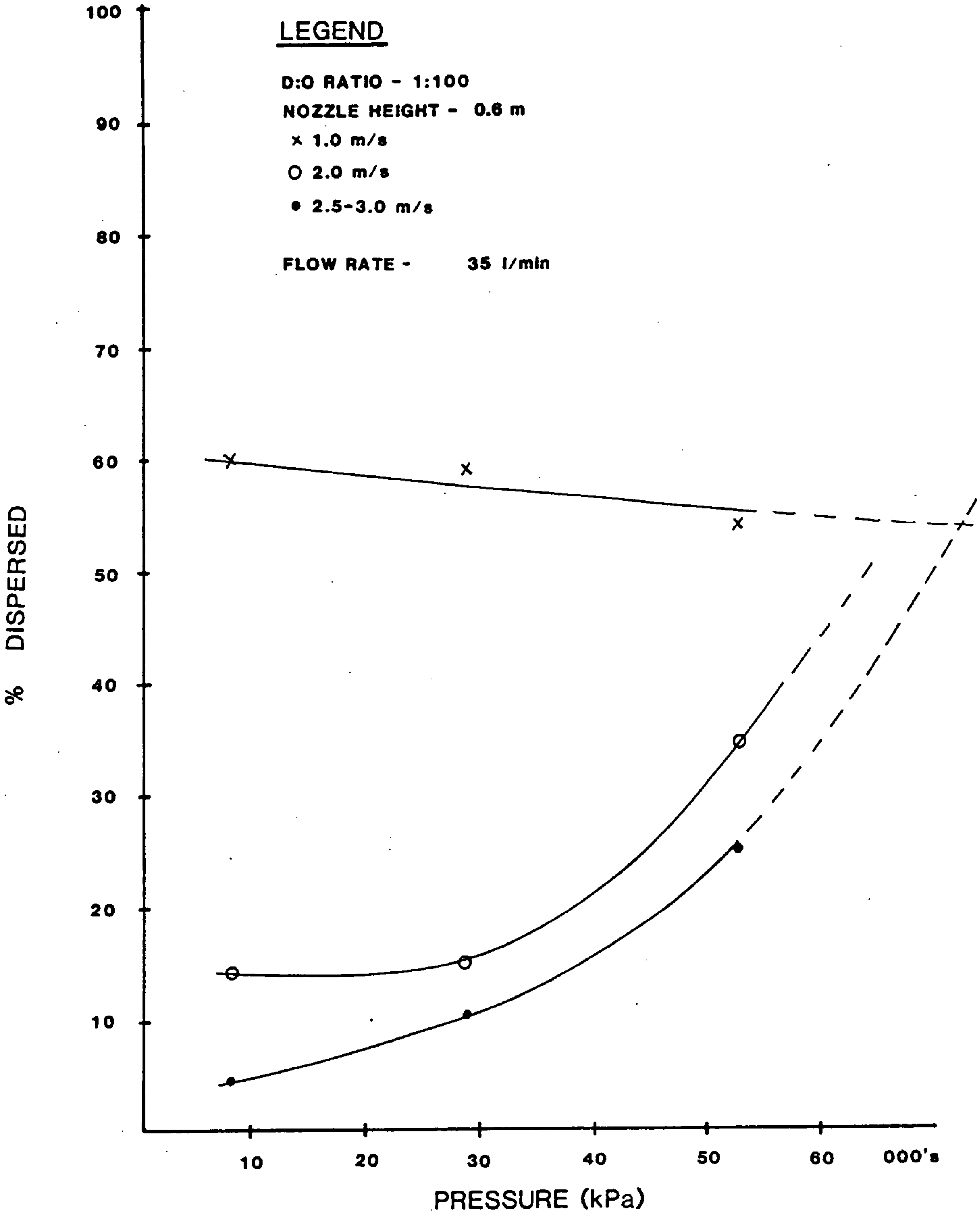

FIGURE 11 Dispersion Efficiency vs Nozzle Pressure
(35 l/min and 0.6 m standoff)

Figures 12, 13, and 14 illustrate the effect of nozzle pressure on dispersion efficiency for the larger jet stand-off distance. At the low flow rate (see Figure 12) dispersion efficiency is poor at all pressures and all track speeds. As the flow rate increases (see Figures 13 and 14), increased pressure improves efficiency but only up to a maximum of 30% for the 1.0 m/s operating speed. Unlike the results for the lower stand-off distance (see Figures 9, 10, and 11), the dispersion efficiency at the 1.0 m/s operating speed is not independent of jet pressure, likely as a result of excessive energy losses in the jet as it passes through the air over the larger distance.

5.3 DISPERSION EFFICIENCY VS JET STAND-OFF DISTANCE

As would be expected, dispersion efficiency dropped off when the nozzle was vertically raised from the water surface (from 0.6 m to 1.5 m). The degree of loss in efficiency was a function of both the jet flow rate and pressure combined. This loss in efficiency is best illustrated by comparing the curves in Figures 9 through 14.

At the low flow rates (see Figures 9 and 12), poor dispersion resulted at both jet levels. However, the efficiency achieved with the larger jet stand-off distance was only about one-half that of the close jet position for all pressure conditions.

At the medium flow rate (see Figures 10 and 13) there is a pronounced improvement in efficiency when the jet is moved close to the water surface for the 1.0-m/s operating speed, especially at low pressures. Only marginal improvements were made by close jet placement for the higher track speed/low and medium pressure situations. When the pressure was increased to the 50 000$^+$ kPa level, the closer jet position was again about two times as effective for all track speeds.

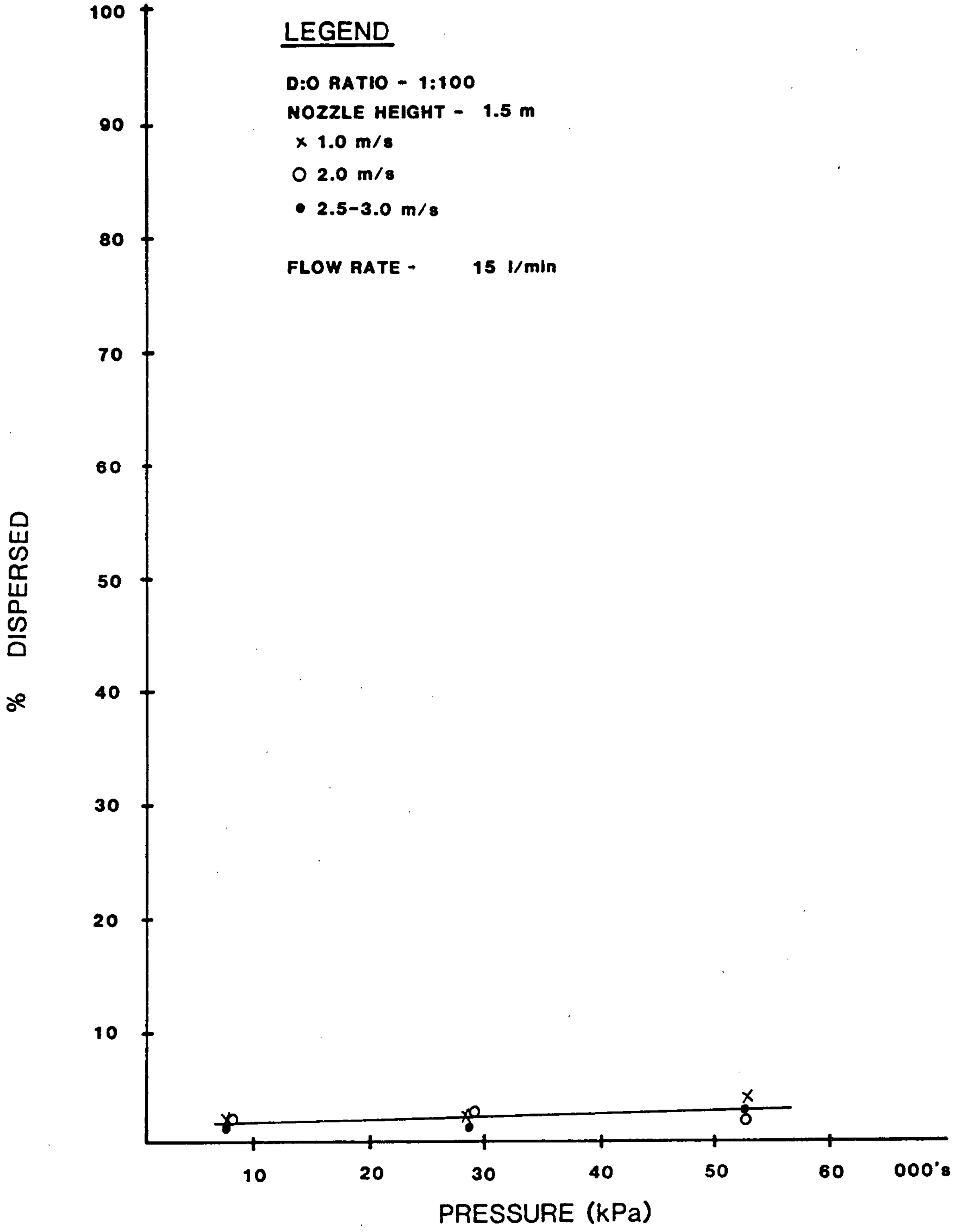

FIGURE 12 Dispersion Efficiency vs Nozzle Pressure
(15 l/min and 1.5 m standoff)

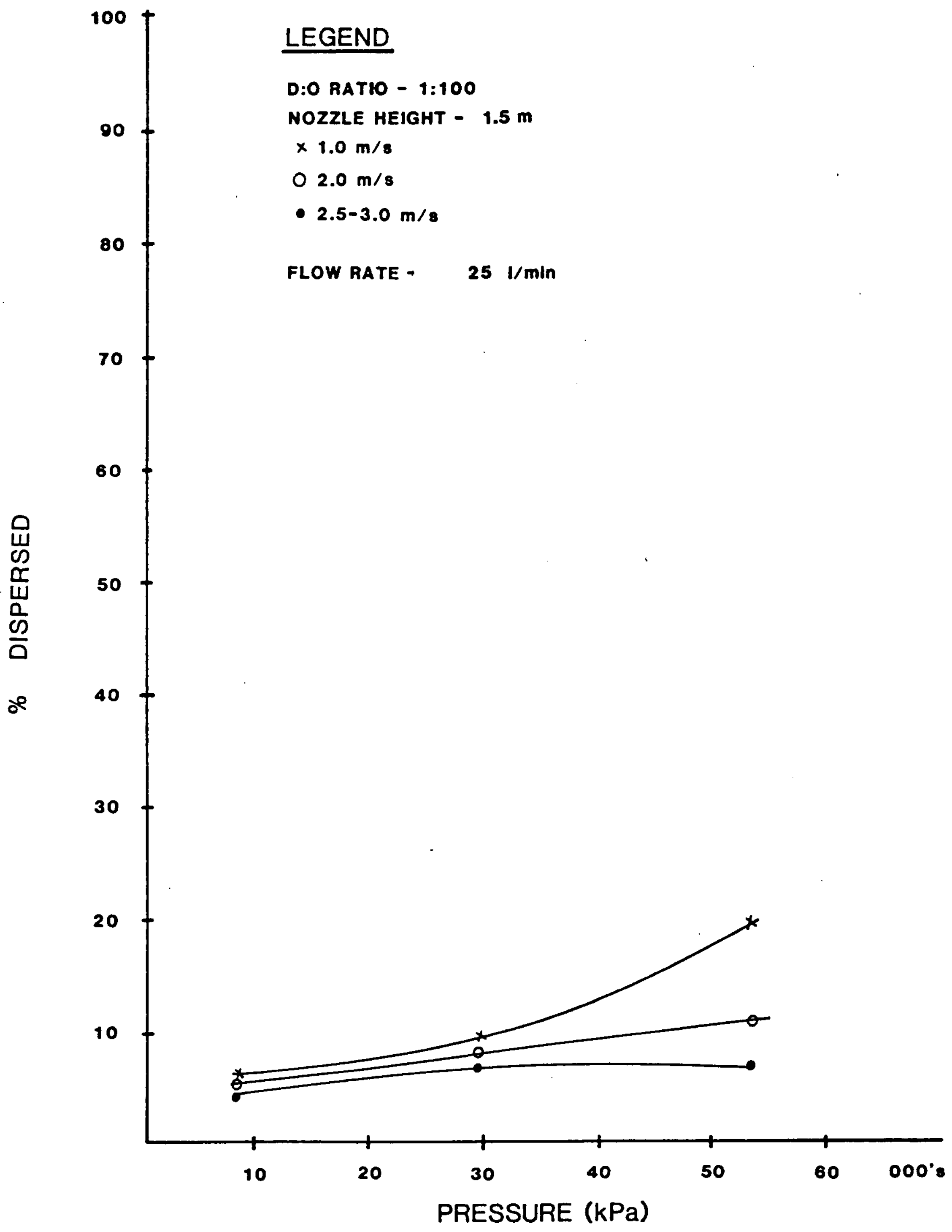

FIGURE 13 Dispersion Efficiency vs Nozzle Pressure
(25 l/min and 1.5 m standoff)

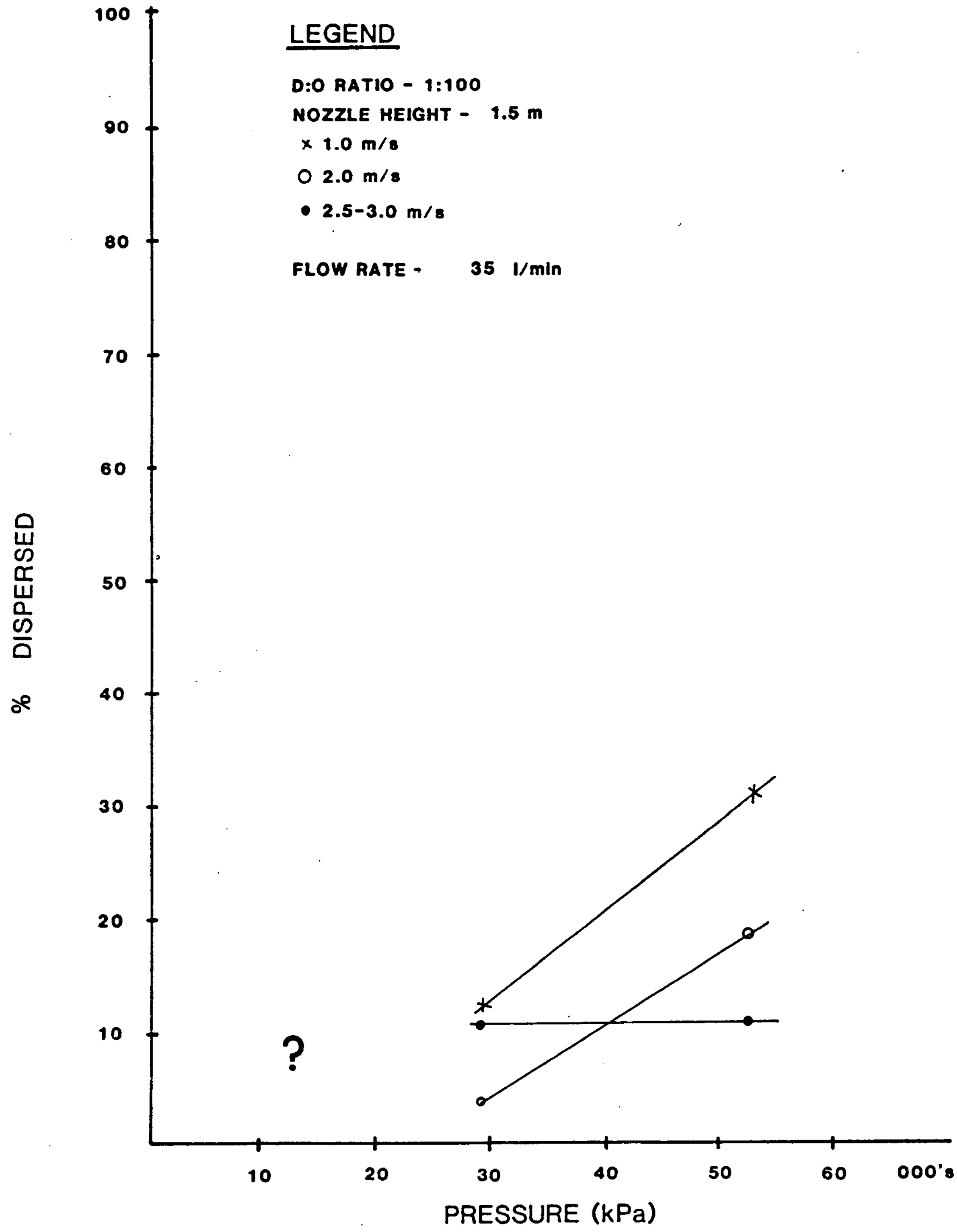

FIGURE 14 Dispersion Efficiency vs Nozzle Pressure (35 l/min and 1.5 m standoff)

A complete data set was not collected for the 1.5-metre stand-off position at the 35 litre/min flow rate (see Figures 11 and 14). However, the available data indicate a similar trend to that evident in the 25-L/min tests.

In general, the shorter stand-off distance resulted in at least a two-fold improvement in dispersal efficiency. For the 1.0-m/s operating speeds at low and medium pressures, and medium and high flow rates (i.e., efficient jets), improvement was more pronounced and the close jet was from three to seven times more efficient.

5.4 PRACTICAL IMPLICATIONS OF RESULTS

5.4.1 Flow Rate

It appears from the data that close to 100% dispersion in the laboratory test can be achieved with nozzle flow rates of about 50 - 60 L/min at relatively low pressures (maximum of 1000 psi and likely less), small jet stand-off distances (0.6 m or less) and slow operating speeds (1.0 m/s or less). A reduction in flow rate at these optimal operating conditions results in a loss in efficiency. The actual relationship between percent dispersed and flow rate at these conditions was: % Dispersed = 2.665 x Flow rate - 33.3. This also does not vary significantly with a change in pressure. If either the track speed or the nozzle stand-off distance (or both) is increased, the efficiency of the jet is reduced dramatically.

5.4.2 Pressure

Dispersion efficiency appears to be independent of nozzle pressure at the slow operating speed (1.0 m/s) and short stand-off distance. At the higher operating speeds an increase in pressure improves the dispersion efficiency. In fact, extrapolation of the data collected in this study indicates that dispersion efficiencies similar to those acheived at 1.0 m/s speeds can be realized at the faster operating speeds (2.0 - 2.5 m/s) if the nozzle pressure is increased to about 80 000 kPa (12 000 psi). This result is evident for both the 25 and 35 L/min flow rates.

5.4.3 Jet Stand-off Distances

Although the closer the jet is to the water the more efficiently it operates, the degree of efficiency is important in determining where to best locate the jet. A trade-off must be considered between efficiency and the problems of positioning a jet close to a water surface when mounted on a ship. At slow speeds and medium or high flow rates, there is a pronounced improvement in efficiency when the jet is placed near the water (up to seven times greater efficiency). At the faster operating speeds the close jets are about twice as efficient, but the increased flow rate and pressure that would be needed to compensate for the increased stand-off distance would be excessive when one considers the capacities of readily available pumps. A practical water jet mixing system would likely have to be mounted close to the water's surface (i.e., 0.6 m or closer).

6.0 IDEAL AND "PRACTICAL" OPERATIONAL MIXING SYSTEMS

Based on the experimental results and analysis, the ideal water jet mixing system should have the following minimum specifications:

- 55 L/min per nozzle water flow rate
- 80 000 kPa nozzle pressure
- 0.6 m (maximum) nozzle-to-water separation.

Such a system could likely operate efficiently (near 100% dispersal) at speeds up to 2.5 or 3.0 m/sec.

Unfortunately high-pressure water pumps able to provide up to 1000 L/min (flow for 20 nozzles) and 80 000 kPa are not readily available. Figure 15 shows the capacities of many commercial pump types. The multistage or double-suction centrifugal pumps appear to be the most suitable for such an application. They have ample capacity but are generally able to provide only up to about 20 000 kPa.

A more practical design for a water jet mixing system would therefore have the following characteristics:

- 55 L/min/nozzle water flow rate
- 7000 kPa (or less) nozzle pressure
- 0.6 m (maximum) nozzle-to-water separation.

This system would operate efficiently (near 100%) at speeds up to only 1.0 m/sec. The width of influence of the system would be a function of the maximum boom length that could be supported either side of the ship of opportunity (and possibly be limited by the capacity of available pumps). Existing systems for the application of dispersant extend a maximum of about 10 m out from the side of the ship. Based on this width and the need for a high-pressure nozzle every metre, a total of 20 nozzles would likely be used on

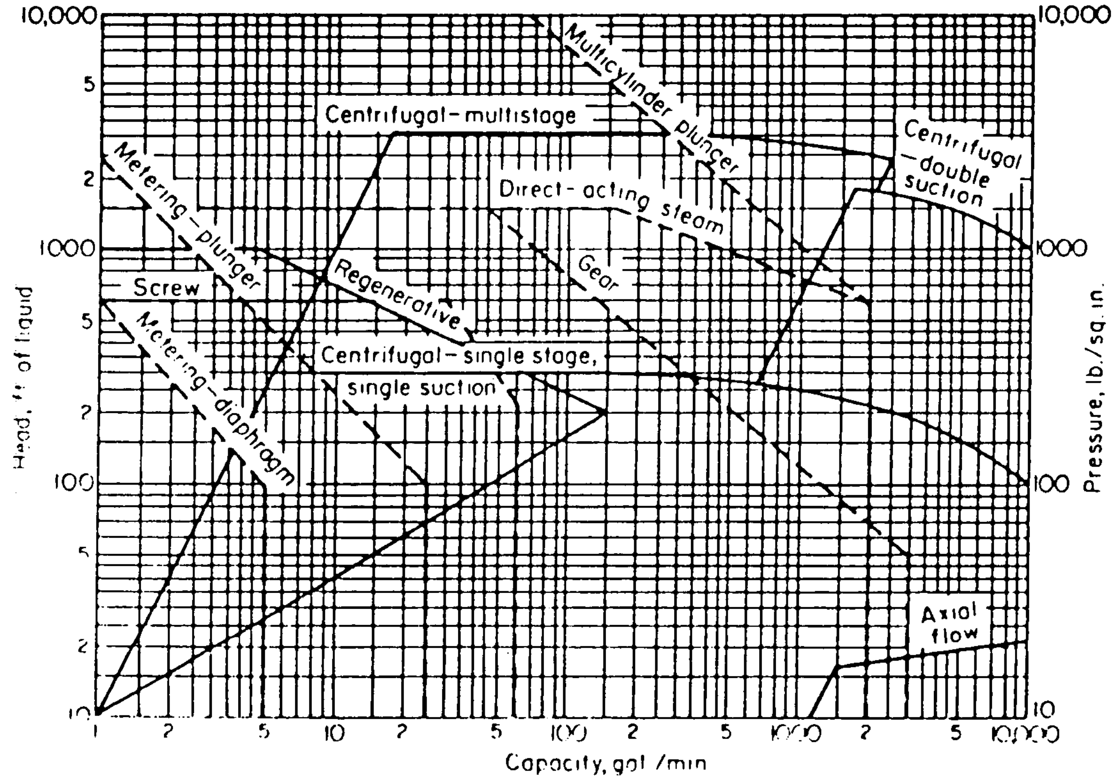

FIGURE 15 Capacities of Commercially Available Pumps

(from Perry and Chilton, 1973)

an offshore system. The feasibility of mounting these nozzles close to the water surface would have to be carefully considered by marine architects as it is by no means a simple task when one considers the roll of a ship, in even a calm sea, and the force of waves impacting on such equipment.

The benefits of such a system have to justify the effort that would be required to complete the detailed design and construction of an operational system. As discussed in the Introduction, ship-based dispersant application has merit for continuous oil well blowout situations and for near-shore protection work. The ability to add mixing energy to the oil/dispersant/water system has the advantages of improving dispersibility during calm conditions, of possibly reducing the amount of dispersant needed to effect dispersion, and of making an otherwise undispersible oil more dispersible. The high-pressure water jet system has the advantage of better manoeuverability over a WSL breaker board or other towed systems, and the results of this and the previous study indicate that it can also be a more efficient system. A comparison of efficiencies for the WSL system and the proposed "practical" water jet system can be seen in Figure 16.

Our laboratory tests indicate that, at slow operating speeds the high-pressure system is much more efficient than the WSL breaker board (100% vs 2%). Only when the operating speed reaches 2.5 - 3.0 m/s does the water jet system become slightly less efficient than the breaker boards but neither system appears to be efficient at these speeds (less than 10% dispersed). However, breaker boards historically have been considered more effective than the 10% efficiency measured in our test facility. Therefore, it is possible that the high-pressure system would also be more efficient at these higher speeds during field use. Regardless of the actual field efficiencies of the systems it is apparent that the high-pressure system would be much more efficient at slow speeds. Near-shore small-scale systems may have to be operated at slower speeds to prevent groundings or collisions and to improve ship control in reaching pockets of oil. The operating speed limitation of the

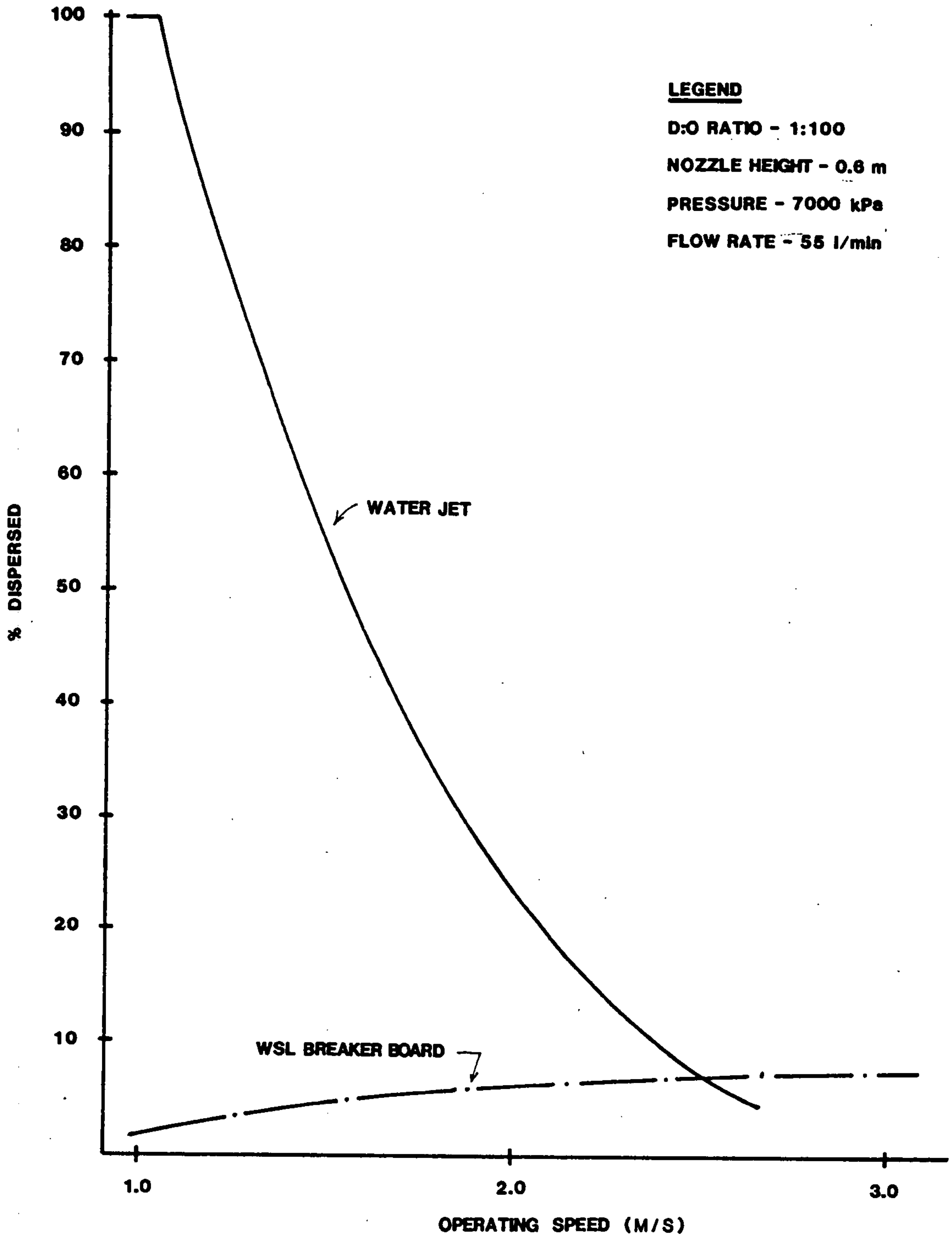

FIGURE 16 Comparison of Proposed Practical Water Jet System with WSL Breaker Board

high-pressure system would not be a problem in these applications. In the offshore environment a trade-off between dispersion efficiency and ship speed could be made to maximize the benefits of the dispersing operation. It may also be possible to improve the efficiency of the water jet system at higher speeds by providing double or multiple booms on each side of the ship to increase the mixing contact time.

7.0 RECOMMENDATIONS

Concerning the future development of the high-pressure water jet mixing concept we recommend that the following be carried out.

1. A near-shore duty dispersant application water jet mixing system should be built based on the following general specifications:
    - 55 L/min per nozzle flowrate
    - 7 000 kPa pressure
    - 0.6-m nozzle-water separation
    - practical boom length for ship/pump combinations.

2. The system should be tested under normal near-shore conditions to evaluate its handling, durability, and efficiency as a function of ship speed. The field-measured efficiencies could then be compared to our laboratory test results.

3. The potential of the system in the offshore environment could then be evaluated based on these trials. Modifications to the design might also be tested with this prototype to improve its usefulness offshore. Double or multiple water jet booms might be mounted on each side of the ship to improve mixing contact time and therefore to increase efficiency at higher operating speeds.

The phased development of the concept would give the project a high likelihood for success (in the near-shore) and provide valuable information needed to extend the system to the rougher, offshore environment. The initial costs to test the feasibility of the concept in the field would also be substantially lower.

8.0 REFERENCES

Cormack, D. 1983. The use of aircraft for dispersant treatment of oil slicks at sea. Report of a joint U.K. Government/Esso Petroleum Company Ltd. Investigation. prepared by Warren Spring Laboratory for the Department of Transport.

Csanady, G.T. 1973. Turbulent Diffusion in the Environment. D. Reidel Publishing Co., Boston.

Lee, M.A. 1980. The droplet size distribution of oils emulsified in sea water by concentrate dispersants. Warren Spring Laboratory, Department of Trade and Industry, P.O. Box 20, Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2BX, UK.

Perry, R.H. and C.H. Chilton, editors. 1973. Chemical Engineer's Handbook. Fifth Edition, McGraw-Hill Book Co.

Raj, P.P.K. 1977. Theoretical study to determine the sea state limit for the survival of oil slicks on the ocean. Department of Transportation, United States Coast Guard, Report No. CG-D-90-77.

S.L. Ross Environmental Research Limited. 1983. Laboratory testing and design of ship-based dispersing systems. prepared for the Canadian Offshore Oil Spill Research Association, December.