

MEASUREMENTS OF THE DISPERSION OF LIQUID INDUSTRIAL WASTE DISCHARGED INTO THE WAKE OF A DUMPING VESSEL

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Abstract—100,000 t yr⁻¹ of acidic effluent with an organic content of 3–7% are dumped 15 km off the mouth of the River Tees in water 50 m deep. In order to achieve adequate dilution, the rate of discharge of this effluent has been restricted on the basis of calculations made using a formula adopted by the International Maritime Organisation (IMO, formerly IMCO). To ensure that these calculated minimum conditions were achieved in practice, field measurements of waste concentration in the wake of the dumping vessel were made on 3 days under different climatic conditions. The measurements were made by a number of methods, both *in-situ* and involving analysis in a laboratory onshore. The dilutions calculated from the “IMCO formula” were compared with those found in practice and the formula was found to underestimate dilution in this case. The results obtained are compared with other theoretical and practical studies.

Key words—dispersion, dilution, effluent, wake

INTRODUCTION

The disposal of industrial and other wastes at sea from England and Wales is controlled by the Ministry of Agriculture, Fisheries and Food (MAFF) and the Food and Environment Protection Act (Great Britain—Parliament, 1985). Before a licence is granted, wastes are tested for toxicity, and restrictions are imposed on the methods of disposal so as to ensure that the concentration of waste in the wake of the dumping vessel is reduced below the 96 h LC₅₀ within 5 min after dumping. This is intended to give a sufficient safety factor and so eliminate possible toxic effects, and takes due account of the restricted nature of the tests undertaken, e.g. involving a limited number of species (Franklin, 1980). The conditions required to achieve a “safe” dilution are estimated using the “IMCO formula” (Tromp, 1976), adopted by the International Maritime Organisation (formerly the Intergovernmental Maritime Consultancy Organisation: IMCO) for the purpose of estimating the dilution of tank washings discharged from chemical product tankers. The critical parameters in this formula are the size and speed of the vessel and the rate of discharge of the waste. Recently, however, studies have indicated that this formula does not adequately describe the processes of dilution occur-

ring behind dumping vessels (Delvigne, 1983; Lewis, 1985). These studies, and an increase in concern over the state of health of the North Sea (Anonymous, 1984), led MAFF to carry out field studies intended to establish whether the predicted dilution characteristics were being achieved during waste disposal. Measurements of waste concentration were made on three occasions during 1984 and 1985 in the wake of a vessel dumping industrial waste off the River Tees, NE England (Fig. 1).

METHODS

A large individual disposal of industrial waste takes place at a site outside Tees Bay, 15 km from the coast. At the time of these investigations, 100,000 t of chemical effluent from a single industrial process were discharged each year into an area of 150 km², with an average water depth of 50 m. The major physical characteristics of this aqueous effluent are density, 1.4×10^3 kg m⁻³; pH, <2; with an organic content of 3–7% and containing 15–20% sulphuric acid and 40–45% ammonium bisulphate. The measurements of waste concentration were made by a variety of techniques with the aim of making dilution estimates by as many different methods as possible.

Design of sampling programme

On each occasion, a survey of the disposal area was made prior to the start of dilution studies to check for the presence of stratification which would impede the dispersion of the waste. In addition, samples of waste were taken from each of the dumping vessel's tanks for use in calibration of the measurement techniques. The research vessel was then anchored by the stern near the middle of the disposal site, and a direct reading current meter and an instrument package deployed over the side. The dumping vessel (*MV Yarrow*, see Table 1) then made a series of traverses up current of the research vessel and perpendicular to the

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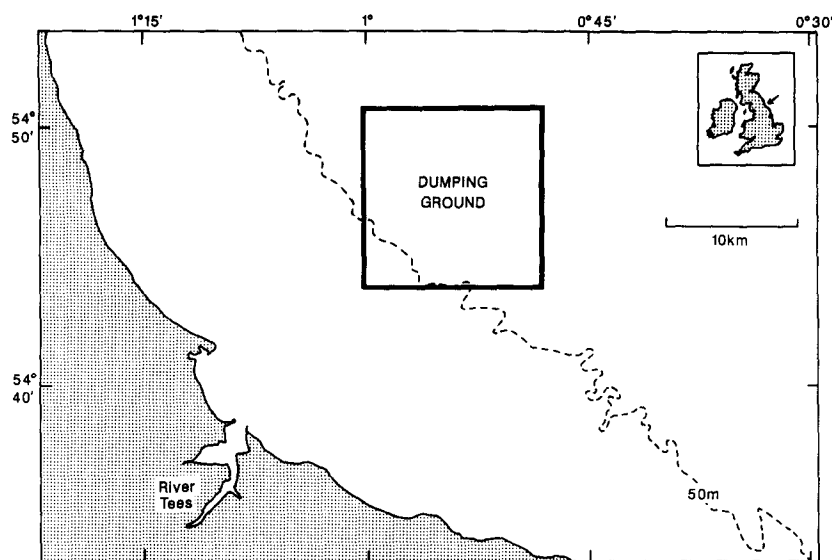


Fig. 1. The location of the dumping ground off the River Tees (NE England).

current direction, so that the waste plume was carried to the research vessel by the current (Fig. 2). The effluent was discharged between 0.7 and 2.1 m below the water surface at a rate of 120 t h^{-1} through two openings in a single pipe passing over the stern of the dumping vessel whilst steaming at 8–9 knots. The depth of discharge varied as the dumping vessel rose in the water during the discharge operation (see Table 1). The distance between the two vessels was varied during each traverse so as to vary the sampling time after discharge (84–2130 s), and the instrument package was positioned at different depths (1.5–22.8 m). The time after discharge was determined by noting firstly the time at which the dumping vessel passed directly up current of the research vessel, and then the time at which the waste was detected by the instrument package. In March 1985, the distance between the two vessels was also determined using an optical rangefinder.

Analytical methods

In-situ techniques. The waste being studied had a natural fluorescence associated with a component of the organic fraction. This enabled the use of a continuously-reading underwater fluorimeter as one method of identifying the distribution and measuring the concentration of the waste. The acid nature of the waste also suggested that measurement of pH would be a useful way of measuring the waste concentration. The instrument package deployed in these studies contained a submersible fluorimeter (UV-Aquatracka; Chelsea Environmental Instruments Ltd, London) whose use in a towed system has been described previously (Law, 1984). The filters used in the fluorimeter were a 240 nm interference filter (bandpass 25 nm) for selection of the excitation wavelength and an OX7 filter (peak transmission 350 nm, approximate bandpass 100 nm) for emission. The sampling rate of the fluorimeter was 3.5 Hz. The instrument package also housed a CTD unit (model 8770; Guildline Instruments Ltd, Smith's Falls, Canada) equipped with a pH probe and devices to continuously determine depth, salinity and temperature. Data from these instruments were transmitted to the research vessel via the cable used to deploy the package, where it was processed and stored by an HP-85 microcomputer (Hewlett-Packard Ltd, Winnersh, Berkshire) and simultaneously displayed on a chart recorder.

On two of the three occasions (July 1984 and 5 March 1985), Rhodamine B dye was added to the waste as a tracer

and a second fluorimeter, set to appropriate wavelengths, mounted in the instrument package. The dye was added to the dumping vessel's tanks slowly during loading of the waste so as to ensure that adequate mixing took place. This was then confirmed after loading by the collection and analysis of samples from various depths within each tank. In the event, no *in-situ* measurements of dye concentration at sea were made owing to instrument failure, although they were determined in discrete samples (see next).

Discrete samples. During the field studies, discrete water samples were collected for analysis onshore by three techniques; measurement of pH, fluorescence, (both of the waste itself and of the added dye), and an oyster embryo bioassay.

Sampling

Water samples were collected by three methods. In July 1984, 2.7 l samples were collected in glass Winchester bottles as for hydrocarbon analysis (Law, 1984). On 5 March 1985, 1 l samples were collected by a similar method, but using smaller bottles to reduce the filling time. On 8 March 1985, a submersible pump was attached to the instrument package and 1 l samples were collected on board the research vessel from a pipe connected to the pump. All samples were sealed, taken ashore, and analysed within 24 h.

Measurement of pH

The pH of samples was determined using a pH meter (model 3030; Electronic Instruments Ltd, Richmond, Surrey). This was calibrated with samples of the discharged waste taken from the tanks of *MV Yarrow* during the dumping operation. The detection limit of this method was $1 \text{ mg of waste l}^{-1}$.

Table 1. Description of the dumping vessel, *MV Yarrow*

Length	65 m
Beam	11 m
Draught	3.77 m (fully loaded)
Deadweight	1090 t
Depth of discharge orifices (2)*	2.1 m (fully loaded)
below sea surface	0.7 m (empty)
Speed during discharge operations	8–9 knots

*As the two discharge orifices were very close together, the calculated dilutions are based on the formula for a single discharge (Lewis, 1984).

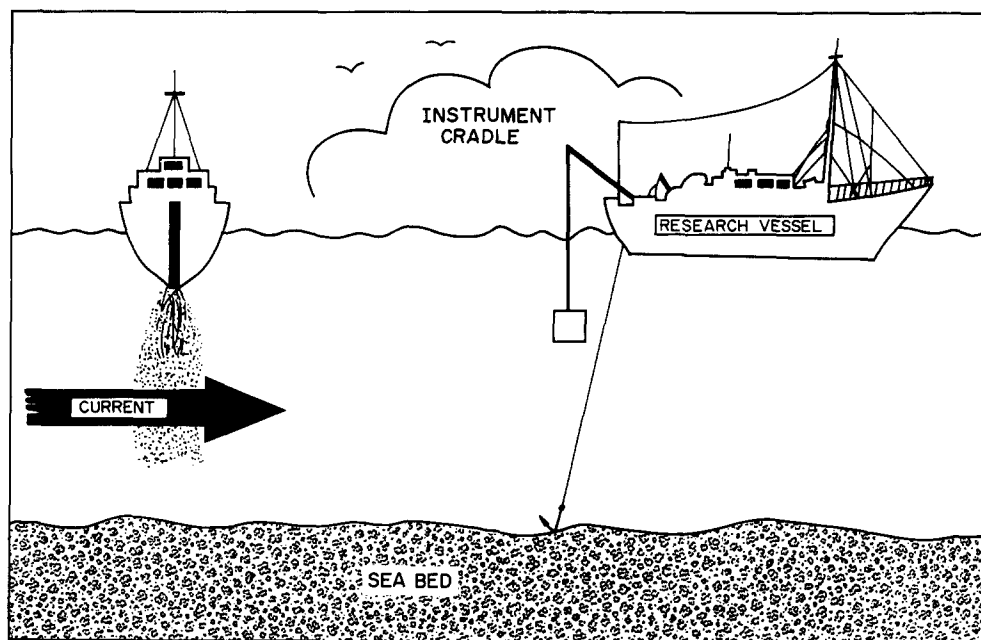


Fig. 2. Diagram of the positions of vessels and instruments during the field study.

Fluorescence spectroscopy

Measurements of fluorescence were made using an LS-5 luminescence spectrometer (Perkin-Elmer Ltd, Beaconsfield, Buckinghamshire) at two sets of wavelengths. The fluorescence of the waste itself was measured at 360 nm (excitation 240 nm), and the fluorescence of the Rhodamine B dye at 600 nm (excitation 500 nm). The slit widths used were 15 nm for excitation and 20 nm for emission, and the detection limits in both cases were found by calibration with samples of the discharged waste to be around 1 mg l^{-1} .

Bioassay

The oyster embryo bioassay was based on observation of the development of Pacific oyster (*Crassostrea gigas*) embryos exposed for 24 h to the water samples (Thain and Watts, 1984) and to known dilutions of the discharged effluent. The proportion of embryos that developed successfully was progressively reduced in higher waste concentrations. In other studies, Rhodamine B dye has been shown to affect the development of oyster eggs and larvae, but in these experiments the waste concentrations observed were below those at which effects have been recorded (Panciera, 1967).

To determine possible variations in water quality, unconnected with the disposal operation, which could affect the results of the bioassay (such as the presence of harmful algal blooms) two water samples were taken for bioassay during each passing of the dumping vessel. The first was taken prior to the discharge run (and after the passage away from the sampling point of effluent from a previous run) and the second in the effluent plume itself, both as indicated by the *in-situ* instruments. Samples of clean offshore water were also taken for use as controls and in the preparation of dilutions of the discharged waste for calibration purposes. The limit of detection of the bioassay was about 1 mg l^{-1} .

Calibration

Calibration of all measurement techniques was carried out in the onshore laboratory using dilutions of the waste discharged that day in clean offshore seawater. In the case of the Aquatracka, calibration standards were placed in a quartz cell within the light-path, so as to minimize the volume of standard required.

RESULTS

Figure 3 shows the output signals from the *in-situ* instruments during a typical run. The upper trace shows the signal from the pH probe and the lower that from the Aquatracka. A signal timing marker can be seen at the start of each trace. The traces show the change in water waste concentration as the slick, carried by the current, flows past the instrument package. Several parameters related to the depth at

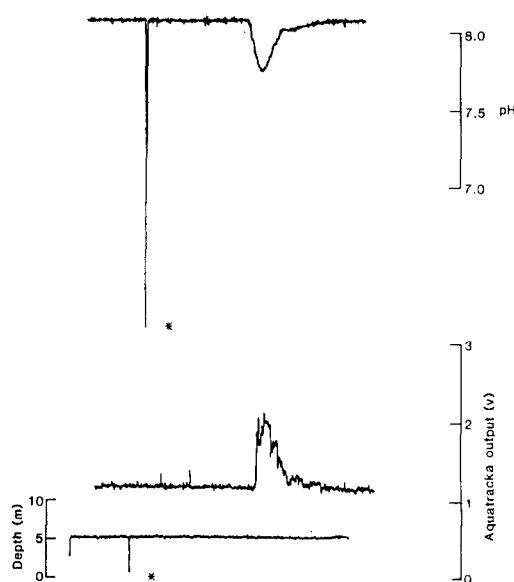


Fig. 3. Chart recorder output showing the detection of the effluent plume by both the "Aquatracka" and the pH probe. *Indicates signal timing marker spikes.

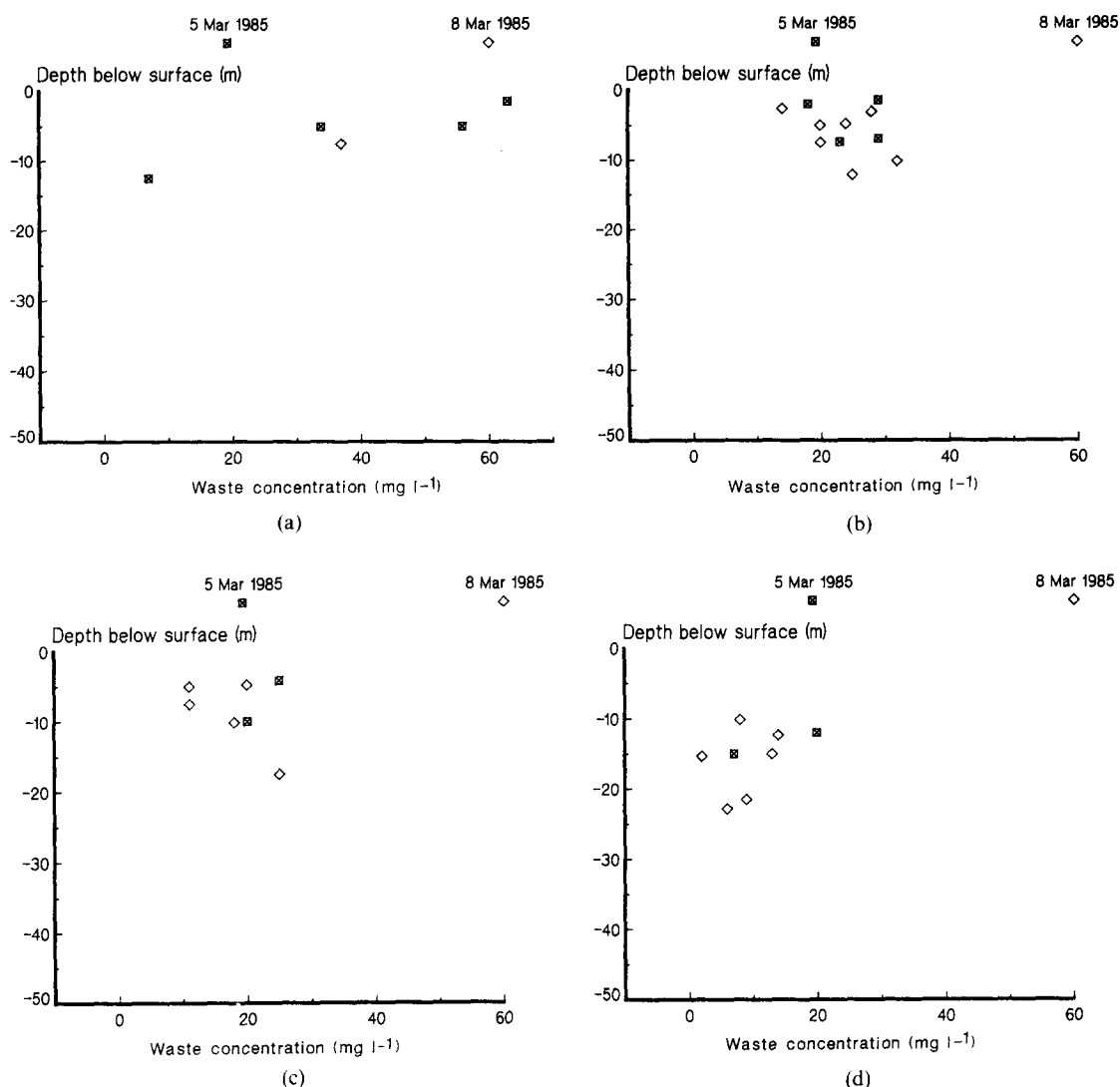


Fig. 4. The variation of observed waste concentration with depth derived from *in-situ* fluorescence measurements: (a) <3 min after discharge; (b) 3–6 min after discharge; (c) 6–9 min after discharge; (d) >9 min after discharge (water depth at the dumping ground is around 50 m).

which the instrument package is located can be derived from these traces (the maximum concentration of the waste, the width of the waste slick, and the distribution of the waste within the slick). It can be seen that in cross section the slick has a sharp leading edge and a sloping trailing edge. This asymmetry has also been seen by one of us (RL) in studies of experimental oil spills, and has recently been demonstrated by Vandellannoote *et al.* (1987) in a study of another waste dumping operation.

The maximum waste concentrations measured during each run by both *in-situ* and other techniques are given in Table 2. Also included for reference are the maximum waste concentrations predicted for the time after discharge using the "IMCO formula", and the theoretical maximum concentration calculated using a method suggested by Lewis (1985). The maximum concentrations derived from the *in-situ*

measurement of waste fluorescence have been grouped together for various time intervals and are shown in Fig. 4, according to depth.

DISCUSSION

Dilution

The results of our study indicate that the "IMCO formula" underestimates the actual minimum dilution obtained by between 3- and 10-fold under the conditions prevailing (Table 2). It is also apparent that the waste studied did not sink rapidly to the bottom despite its high specific gravity, but remained in the upper half of the water column (above 25 m) for the duration of our experiments (Fig. 4). Lewis (1984), in a study of the same waste, found that it remained within the upper 8 m of the water column after discharge. Roekens and van Grieken (1983)

Table 2. Waste concentrations determined by *in-situ* measurement of waste fluorescence and analysis of discrete samples, compared with the concentrations calculated from the "IMCO formula" (Tromp, 1976; Lewis, 1985)

Run No.	Time after discharge (s)	Depth (m)	Effluent concentration (mg l ⁻¹)					Calculated maximum concentrations			
			Discrete samples			<i>In-situ</i>		(Maximum concentrations)			
			Oyster bioassay	Waste fluorescence	pH	Rhodamine fluorescence	Depth (m)	Waste fluorescence	pH	IMCO	Lewis
(a) July 1984											
1	55	5.0	20	18	NR	18					
2	NR	5.0	3	5	NR	4					
3	113	5.0	2	3	NR	6					
4	102	5.0	NR	5	NR	3	1.7	14	19	200	250
5	188	5.0	3	8	NR	NR	5.0	31	23	143	125
6	286	5.0	5	7	NR	6	7.7	24	21	125	83
7	251	5.0	2	4	NR	NR	12.0	13	12	125	100
8	292	5.0	22	14	NR	15	3.7	33	29	125	83
(b) 5 March 1985											
2	525	2.5	NR	3	NR	2.5	10.0	NR	*	100	48
3	84	2.5	6	10	10	14	1.5	63	*	200	333
4	258	2.5	3	NR	2	3	1.5	29	*	125	100
5	377	2.5	11	25	13	18	4.2	25	*	111	67
6	151	2.5	3	NR	2	2	5.0	56	*	167	167
7	295	5.0	12	13	20	22	7.5	23	*	125	83
8	500	5.0	NR	NR	3	3	10.0	20	*	100	50
9	118	5.0	2	NR	2	2	12.5	7	*	167	200
10	96	5.0	23	26	30	40	5.0	34	*	167	250
11	552	5.0	3	4	3	5	12.0	20	*	100	45
12	251	5.0	2	3	NR	4	7.0	29	*	125	100
13	715	5.0	NR	NR	NR	NR	15.0	7	*	83	34
14	223	5.0	NR	NR	NR	NR	2.0	18	*	143	111
(c) 8 March 1985											
1	215	3.1†	31	17	33		3.1	28	*	143	111
2	324	5.0†	10	12	20		5.0	20	*	125	77
3	458	4.8†	6	5	16		4.8	11	*	100	53
4	194	4.8†	13	31	19		4.8	24	*	143	125
5	120	7.5†	NR	NR	NR		7.5	37	*	167	200
6	254	7.5†	6	9	10		7.5	29	*	125	100
7	226	10.2†	4	7	3		10.2	32	*	143	111
8	214		NS				12.2	25	*	143	111
9	299	3.0	9	9	16		2.6	14	*	125	83
10	399	3.0	17	13	19		5.0	11	*	111	63
11	485	3.0	13	8	17		7.5	18	*	100	50
12	530	3.0	18	25	23		10.1	25	*	100	48
13	610		NS				12.3	14	*	91	42
14	650	3.0	NR	NR	NR		15.0	13	*	91	38
15	535		NS				17.5	9	*	100	48
16	623		NS				21.5	9	*	91	40
17	1338		NS				22.8	6	*	67	19
18	1050	10.1†	6	2	10		10.1	8	*	71	24
19	2130	15.3†	NR	NR	2		15.3	2	*	56	12

*No *in-situ* pH measurements made owing to failure of the probe. †Samples taken by submersible pump. NR = No results. NS = No sample.

Table 3. The width of waste plumes

Run No.	Depth (m)	Time after discharge (s)	Plume width (m)
(a) 5 March 1985			
3	1.5	84	5.3
1	2.5	145	6.3
6	5.0	151	8.0
9	12.5	118	2.5
(b) 8 March 1985			
9	2.6	299	25.2
6	7.5	254	16.2
7	10.2	226	19.2
8	12.2	214	16.5
12	10.1	530	28.5
14	15.0	650	36.0
15	17.5	535	25.2
16	21.5	623	19.5
18	10.1	1050	90.0

reported a similar experience with a titanium dioxide waste of roughly the same specific gravity. On no occasion in our study was any evidence found for stratification of the water column which could have confined the diluting waste to the upper half of the water column.

Table 3 summarizes the variation in the width of the waste plumes (derived from the current speed and measurements of the time across the plume from the Aquatrack records) with time after discharge and depth. Close to the surface the width of the plume is less than the beam of the dumping vessel, and even 8–10 min after discharge is only 2–3 times wider. Seventeen minutes after discharge, on 8 March 1985, the plume width was 90 m at 10 m depth, in agreement with reports by Csanady (1981). Vandellannoote *et al.* (1987) found plume widths much larger than those reported here shortly after dumping, probably due to the much higher discharge rates and vessel speed in their study.

The differences between the concentrations of waste for *in-situ* measurements and the analysis of discrete samples seen in Table 2 is probably due, in part, to the relatively long time required to fill bottles used for collection of the discrete samples (approx. 10 s l^{-1}) which makes the bottle samples an integral of the concentration in a cross-section of the effluent plume, and, in part, to the difficulty of locating the sample bottle within the plume. These problems were overcome on 8 March 1985 by the use of a submersible pump mounted on the instrument package, thereby ensuring that both sets of results related to the same body of water, and the agreement between the two sets of results is considerably closer for 8 March than for the other two days.

Estimates of the concentration of waste present in a discrete sample by the methods employed (bioassay, fluorescence and pH) generally varied by a factor of 2. This work has demonstrated the usefulness of the oyster embryo bioassay as a method of estimating waste concentrations as well as indicating general water quality, the purpose for which it was originally developed.

The influence of weather conditions on dilution is not clear from this study. Very different conditions prevailed in 1984 and 1985 (in July 1984 the sea state was rough and a considerable breeze was blowing, in March 1985 the wind was <10 knots and the sea calm) but no clear differences could be seen in dilution. This may, in part, be a consequence of the sparsity of the 1984 data, as the heavy weather caused curtailment of the work programme.

Dispersion

The process of dispersion can be described in three stages as outlined by Delvigne (1983). The first stage, initial dilution, takes place within the turbulent boundary layer surrounding the dumping vessel. The second stage, near-field dilution, takes place within the developing wake of the dumping vessel; and the final stage, far-field dilution, takes place solely by turbulent diffusion. This paper studies the process of near-field dilution, i.e. from the time of the production of the wake to the time at which the influence of the dispersing wake ceases and is replaced by natural diffusion processes. This end-point has been variously reported as approx. 12 min and several hours after discharge (Delvigne, 1983; Farmer and Lemon, 1975; Lewis, 1984).

The "IMCO formula" was originally derived for the purpose of estimating the discharge rate of tank wash waters from chemical tankers and *not* for the specific case of dumped waste. The formula was based on three field measurements of the dilution of radio-labelled discharges from tankers and a number of tank experiments. The tankers used in the field trials were considerably larger than the small coastal vessel currently used for waste disposal off the Tees. The results of all these studies were drawn together and an empirically derived equation produced which describes the minimum dilution achievable for varying parameters such as speed, discharge rate, etc. Unfortunately, the field studies did not comprehensively cover the range of speeds, discharge rates, depth of water, etc. and, since only discrete samples were taken, it cannot be assumed that the peak concentration of waste was always determined.

The "IMCO" formula is:-

$$D = \frac{k \times t^{0.4} \times V^{1.4} \times L^{1.6}}{Q}$$

where

D = dilution at time t ,

k = constant with a value of 0.0030 for one discharge point and 0.0045 for two,

t = time after discharge,

V = speed of the dumping vessel,

L = waterline length of the dumping vessel,

and

Q = effluent discharge rate.

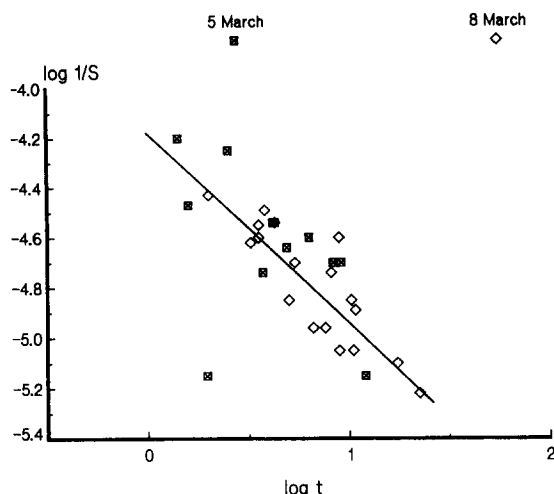


Fig. 5. The log reciprocal dilution plotted against log t for *in-situ* measurements made on 5 and 8 March 1985. The linear regression line calculated is also shown.

Other workers have obtained similar results to our own. Delvigne (1983) reported that from his experiments the "IMCO formula" underestimated dilution by 2.5- to 3-fold. Our data have been plotted as the log of the reciprocal of dilution against log of the time after discharge as Delvigne did in order to elucidate the relationship between dilution and elapsed time, and to compare the results with those from his studies. All data points obtained from *in-situ* measurements of waste fluorescence on 5 and 8 March 1985 have been included, except run 19 on 8 March which lies within the far-field rather than the near-field phase of dilution. Those obtained in July 1984 were not included as the weather conditions were so different. In the resulting plot (Fig. 5), there is one anomalous data point, suggesting that 118 s after discharge (5 March 1985, run 9; see Table 2) the waste plume had not penetrated to 12.5 m depth in the water column.

Linear regression analysis of this data yielded the relationship:

$$\log 1/S = -4.192 - (0.763 \times \log t) (r = 0.801)$$

from which the dilution rate may be expressed as:

$$S \propto t^{0.76},$$

where

S = dilution of the effluent,

and

t = time.

(In this relationship, dilution proceeds more rapidly with higher powers of t , i.e. as x increases in t^x).

Delvigne (1983) reports three sets of results of $t^{0.4}$ (as suggested by the "IMCO formula" for the near-field phase of dilution), and one set (at a faster discharge rate) of $t^{0.7}$. All of the discharge rates in his

studies were considerably higher than our own. Lewis (1984), also studying the *MV Yarrow* disposal operation, reported $t^{0.5}$. Farmer and Lemon (1975) reported $t^{1.03}$ and $t^{2.78}$ for their two experiments which continued up to 17 h after discharge, well outside the influence of near-field dilution. Ball and Reynolds (1976) summarized the data for several American studies dating back to 1948. The dilution varied in proportion to t from $t^{0.4}$ to $t^{1.6}$, and again the discharge rates were greater (up to 20 times) than in our own study.

The large spread in the results from the various studies should not be regarded as surprising, given the problem encountered in the conduct of such studies and the variations in weather, ships, discharge rates, etc.

Lewis (1985) has derived a theoretical equation for the estimation of dilution, and this was used to make the predictions given in Table 2. The ratio of Lagrangian to Eulerian time scales used was 0.4, taken from studies of the atmosphere as no suitable figure was available from ocean studies (Smith and Hay, 1961), and the block coefficient used was suitable for vessels of the size of *MV Yarrow*. Lewis's equation relates dilution to the energy of the wake turbulence which in turn is related to the energy that is needed to overcome the frictional resistance of the ship. For "intermediate" times after discharge, the model predicts that dilution is linearly dependent on time, however the model also assumes the turbulence created by the ship to be uniform in space and steady in time, and so is only a first approximation. Despite all the approximations, the predictions made using Lewis's equation are generally closer to our measurements than those derived using the "IMCO formula".

CONCLUSIONS

Our results have shown that, for the particular set of circumstances studied, the maximum waste concentrations calculated using the "IMCO formula" are an overestimate by 3- to 10-fold of the actual *in-situ* measurements. It would appear, therefore, that the formula can be used to give only an order of magnitude estimate of dilution, and that if a more accurate figure is required then specific studies must be undertaken.

Our study has also amply demonstrated the difficulties inherent in obtaining accurate measurements of the maximum waste concentrations using discrete water samples. Even when discrete sample collection was timed using signals from the instrument package, the dilution estimates from discrete and *in-situ* techniques were only rarely in agreement within a factor of 2, discrete samples almost invariably giving an overestimate of the dilution achieved. Thus, caution is necessary when using dilution estimates based on the results obtained from discrete samples.

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