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# Some aspects of the dispersion problem in connection with marine dumping

by

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## INTRODUCTION

In considering dumping of waste at sea the conditions for dispersion in the area and the possibility of predicting the dispersion are of central importance. In particular this is relevant because a high or a low degree of dispersion can be desirable depending upon the type of waste. The physical dispersion in connection with marine dumping depends upon several factors: the method of disposal, the physical properties of the waste, the environmental conditions at the site, such as wind, waves, currents, water depth, and density distribution. Here some of the aspects of the dispersion will be considered with a view to obtain a review of our present means of estimating and predicting the dispersion after the dumping operation.

It is quite clear that the type of waste and its properties will have an influence on the dispersion, and in particular on the initial dilution which can be obtained during the dumping operation (see e.g. Rolfe 1973, Portmann and Wilson 1973). These factors must always be considered when trying to predict the dispersion, and the significance of the initial dilution should be stressed already at this stage.

## DISPERSION IN THE SURFACE LAYER

Waste of near-neutral density will become dispersed in the surface layer. During a dumping operation from a steaming barge a wake or line of contaminated water is formed. Clearly the initial dilution can be considerably influenced by the method of disposal. When an effective dispersion is desirable the initial dilution should be increased as much as is feasible from a practical and economical point of view. Experience suggests that the initial dilution in connection with sewage dumping from barges is in the range 1:100 to 1:500, and that it only rarely reaches 1:1000.

In the wind-mixed layer the vertical spread down to the primary density interface can be expected to be quite rapid, except possibly during very weak winds. Even though our present knowledge of the dispersion in the surface layer permits us to make a reasonable estimate of the subsequent dispersion there, we are far from able to construct reliable predicting models. One can for instance assume a Gaussian concentration distribution in the lateral direction (here denoted by y) and neglect the vertical and the longitudinal mixing (Ketchum and Ford 1952). The concentration distribution is then

$$C = \frac{M}{H_o v_o t_o \sigma_y \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \qquad (1)$$

with $H_o$ the surface layer thichness (considered as initial thickness of the waste line), $v_o$ the velocity of the dumping barge, $t_o$ dumping duration, M amount of waste, $\sigma_y$ lateral variance. This can be estimated a) by using the concept of a horizontal turbulent diffusion coefficient $K_y$ assumed to follow the 4/3-power law in scale-dependence, b) by using the horizontal diffusion velocity P (Joseph and Sendner 1958) which has been determined experimentally in many areas for various conditions. In open coastal waters and in the open sea a representative range is $0.4 \leq P \leq 1.5$ cm/sec. Calculations using (1) suggest that with P=1 cm/sec and a 10 m wide line of sewage the ratio $C_o/C_{max}$=90 after ten hours ($C_o$ and $C_{max}$ are the initial and the maximum concentration after ten hours, respectively).

The neglect of the vertical and longitudinal mixing is reasonable when the vertical current shear is negligible. However, in the presence of waves and wind current the shear is considerable. The shear effect, i.e. in the present context the combined action of vertical shear and vertical mixing generating an apparent horizontal dispersion, is a very important dispersion mechanism (Bowden 1965, Carter and Okubo 1965, Kullenberg 1972, Talbot and Talbot 1974). The important factors are the shear, the vertical mixing coefficient $K_z$, and the fluctuations of the current, e.g. tidal, inertial or meteorologically induced. The longitudinal shear effect due to a steady current in a vertically un-bounded field gives the following longitudinal variance:

$$\sigma_x^2 = \frac{2}{3} K_z \left(\frac{dU}{dz}\right)^2 t^3 \quad (2)$$

The coefficient $K_z$ is often difficult to estimate. Attempts have been made to relate $K_z$, as observed by means of tracer experiments, to various factors, such as the wind, the shear, and the stratification (Kullenberg 1971, Bowden et al. 1973). It seems to be clear that the wind will influence the surface-layer mixing for wind velocities above 5 m/sec. A representative range of $K_z$ appears to be 1-100 $cm^2$/sec.

When the longitudinal shear effect is included in the calculations one finds that for large diffusion times the dilution is considerably increased. For $dU/dz=0.02\ sec^{-1}$, $K_z=10\ cm^2/sec$, and P=1 cm/sec, it is found that $C_o/C_{max}=180$ after 10 hours. The example shows how important it is to include this effect, and that estimates using only two-dimensional models are liable to be in considerable error.

It should also be stressed that these calculations apply only to the average concentration distribution. In many applications a very patchy distribution can be expected, also at quite small scales. This has been demonstrated by dye experiments (e.g. Kullenberg 1969, Weidemann, ed. 1973).

DEPTH PENETRATION

Waste with an average density considerably higher than sea water will sink when dumped, and some of the spreading mechanisms occurring in this case will be discussed here.

Settling and flocculation: Not much is known about the settling velocity of the variety of particulate matter occurring in a sewage field. The settling velocity for single spherical particles calculated by Stokes formula can at best give a rough estimate. Apart from the shape of the particles the flocculation process will complicate matters considerably. Crickmore (1971) found by means of laboratory studies that the settling velocity increased by a factor of ten when going from a fully dispersed state to a flocculated state. It is very difficult to study this process in the field. In a quiet fjord Jerlov and Kullenberg (1954) deduced a settling velocity of about 1 m/hour for dredged mud from a series of observations using a transparency meter. This value agrees well with the results obtained by Crickmore (1971). In the wind-influenced surface layer the vertical mixing due to the turbulence will usually be larger by about an order of magnitude. But below a marked pycnocline layer or in deeper layers of a fjord or enclosed sea the turbulent mixing can be very weak implying that the settling velocity can influence the vertical spread considerably. This in turn means that different fractions of the waste will become separated.

Buoyancy spread: The initial buoyancy of waste with a noticeably higher density than sea water will effectuate a vertical penetration, in particular when dumped from an almost stationary vessel over a short period of time. The lumps of solid contained in the waste wil disintegrate, partly at least, when falling through the water and part of the solids will become suspended in the water. During the fall sea water is entrained into the waste cloud and the excess buoyancy is gradually neutralized.

The depth of penetration may be estimated by modelling the falling waste as a reversed plume, for a continuous source, or as a reversed thermal, i.e. a single blob of buoyancy, in the case of an almost momentaneous release. Both these phenomena have been much studied in atmospheric applications (see e.g. Turner 1973 for a review). It seems possible to apply some of the results to the present problem. We are then considering the initial stages of the spreading when the turbulence in the water can be neglected.

In the case of a thermal in a uniformly stratified environment, ($d\rho/dz \equiv$ constant $\neq 0$), similarity solutions yield the following expression for the maximum depth of penetration:

$$z_{max} = 1.5 \cdot (\alpha k)^{-3/4} \cdot \left(\frac{k \cdot F_*}{N^2}\right)^{1/4} \qquad \text{with } N^2 = \frac{g}{\rho}\frac{d\rho}{dz} \qquad (3)$$

where

$$F_* = V_o \cdot \frac{g\Delta\rho_o}{\rho}$$

is the initial buoyancy released at time t=0. $V_o$ is the initial volume of the dumped material, $\alpha$ is the entrainment coefficient and k is a numerical constant. The value $z_{max}$ should give the final depth of the cloud, but possibly the cloud will oscillate around the final depth due to the over-shooting effect.

In the case of a plume we have the following expression

$$z_{max} = 1.3 \cdot \alpha^{-\frac{1}{2}} \cdot \left(\frac{F_o^*}{N^3}\right)^{1/4}$$

where $N = \left(\frac{g}{\rho} \cdot \frac{d\rho}{dz}\right)^{\frac{1}{2}}$ and $F_o^* = \frac{V_o}{t_o} \cdot \frac{g \Delta \rho_o}{\rho}$.

$F_o^*$ is the buoyancy released per unit time at the source, $V_o$ is the volume of waste released over the time $t_o$, $\Delta\rho_o$ is the initial density difference, and $\rho$ is the density of the sea water at the source; $\alpha$ is the entrainment coefficient.

The entrainment coefficient has been determined by laboratory experiments and by observations on smoke plumes in the atmosphere. The published values are in the range 0.1-0.6. It is, however, quite possible that the entrainment in our case will be different because of the presence of lumps of solids. In 1963 a number of experimental sewage sludge dumpings were carried out near Landsort in the Baltic. The suspension of the sludge was observed from the dumping ship by means of water samples, and from a separate ship by means of an in situ transparency meter. The results were reported by B. Kullenberg (1964). Based on the observed concentration distributions he could calculate that the waste would reach a maximum depth of about 27 m beneath the point of injection. Using the following numbers: $V_o$=330 $m^3$, $\bar{t}_o$=75 minutes, $\Delta\rho_o$=26 $kg/m^3$, $\rho$ =1005 $kg/m^3$ in combination with $z_{max}$=27 m, we find

$\alpha$ (plume) $\simeq$ 0.1

$\alpha$ (thermal) $\simeq$ 0.5, assuming k = 3.

The value of k has been taken from the original work by Morton, Taylor and Turner (1956).

The waste cloud should probably be regarded as a combination of a plume and a thermal in this case. When prolonged dumping is carried out with a heaving ship the plume approximation is most appropriate with $\alpha$=0.1-0.2. In the case of a short-time release the thermal approximation should be used with $0.3 \lesssim \alpha \lesssim 0.5$.

The radius r of the plume or the thermal at a depth z can be estimated by the formula $r \simeq \alpha \cdot z$.

We are now in a position to estimate the maximum depth the waste will reach in a given dumping operation, under the assumption that the stratification in the water is approximately linear and that the environmental turbulence can be neglected. Around $z_{max}$ the plume or thermal will settle and spread out horizontally. The subsequent dispersion is dominated by the environmental turbulence.

The waste can become trapped in a pycnocline layer at a depth less than $z_{max}$. A falling cloud can collapse in the pycnocline layer. This process and its influence on the subsequent dispersion has not been subject to research to any extent. Clearly it is important to know if the waste is going to be trapped in a pycnocline layer. Preliminary laboratory experiments suggest that this will often be the case. But this part of the problem needs more research, and more experimental studies of dumping operations in the field with a view to determine the relevance of the plume or thermal concepts are desirable.

The vertical concentration distribution in the contaminated water column appears to be more difficult to predict. A theoretical expression may be obtained by using the plume or thermal concept combined with other assumptions. This distribution seems, however, to be too steep in the sense that the concentration increase is too rapid compared with the Baltic observations referred to earlier. It is clearly important to be able to predict the initial vertical concentration distribution since this will have a great influence on the subsequent dispersion.

The contaminated water contains an excess amount of suspended matter and will accordingly sink to its appropriate density level. The depth of this level can be calculated from a knowledge of the amount of solids contained in the waste material as well as the amount of waste contained per unit volume of sea water, and the vertical distribution in the un-contaminated water column. As a result of the processes the waste will become distributed in layers in the water column, and these layers will be subject to the turbulent dispersion determined by the dynamical conditions in the water, here called the subsequent dispersion. Part of the suspended matter can become trapped in strong density gradient layers and remain there for considerable periods of time.

The above discussion primarily applies to the particle fraction of the waste. Doubtless some separation can be expected between the liquid and the particle fractions. Considering the initial dilutions which can be obtained if desired it appears reasonable to assume that in most cases the liquid fraction after the initial stage will behave as a passive contaminant.

SUBSEQUENT DISPERSION

We will consider some aspects of the subsequent dispersion in sub-surface layers. The influence of the suspended matter originating from the waste on the dynamical conditions in the water can in most cases be neglected. The effect on the natural turbulence may be estimated theoretically (see e.g. Monin and Yaglom 1971, p. 412). The influence can become important only in cases of very weak turbulence.

As long as the waste material can be regarded as a passive contaminant there are simplified models available for estimating the dispersion (e.g. Carter and Okubo 1965, Okubo 1971, Kullenberg 1972, Callaway 1974, Munro 1974). The use of these models requires a knowledge of the mixing rates as well as the environmental conditions in general. Our knowledge of the sub-surface mixing rates at various scales in the ocean is very meagre. The available experimental evidence shows, however, that the vertical density and current distributions, the steady and oscillating current components, and the vertical gradients are decisive for the mixing. It is also quite clear that the mixing can be very weak in stratified conditions, considerably weaker than in the near-surface layers. Internal layers of passive contaminants can survive for long periods of time (e.g. Kullenberg 1973). This fact shows that the initial dilution is very important: when a high degree of dispersion is desirable the disposal technique should be adjusted to yield high initial dilution. On the other hand it appears to be quite possible to design the disposal technique and chose the dumping ground so that the waste is retained in a relatively limited area. This will depend very much upon the nature of the waste.

It should be stressed that the models available for predicting the dispersion are very simplified and can only give relatively crude predictions of the average dispersion. It is clear that the dispersion in the ocean is scale-dependent, but no single law can be expected to cover the whole range of scales occurring in practice (e.g. Talbot 1974, Kullenberg 1974). Since the natural conditions in many areas vary very much even at intermediate scales, order of kilometres, large variations in the dispersion conditions will also occur at these scales. The importance of the space and time fluctuations of the environmental conditions must be emphasized. Their profound influence on the biological conditions has been demonstrated (e.g. Platt 1972). The importance of using a three-dimensional approach to the dispersion in the sea should also be emphasized. The effects of the vertical processes must be included in the models and purely horizontal models cannot be expected to give reliable results. Finally, the necessity of considering these aspects in any observational programme aiming at elucidating the dispersion characteristics in an area should be pointed out.

## TRANSPORT ALONG THE BOTTOM

In many shallow water areas a large part of the material released during a dumping operation will penetrate directly to the bottom. The question then arises if the waste will remain at the site, be transported along the bottom, or become suspended. This will depend mainly on the bottom conditions, such as topography and currents, but also on the cohesiveness of the material. In the case of non-cohesive material we have a fair knowledge of the requirements for resuspension or transport along the bottom, but for cohesive material our present knowledge seems inadequate.

From the bottom conditions much information can be obtained about the transporting capacity of the currents. A bottom with coarse material indicates an area of strong bottom currents where fine grained material will be removed, whereas a bottom covered with fine grained material shows that the bottom currents are weak. The bottom friction velocity is defined as $u_* = \sqrt{\tau_b/\rho}$ where $\tau_b$ is the bottom stress and $\rho$ the water density. In the open ocean existing observations show that $u_*$ is low, in the range 0.02-0.4 cm/sec. These values are lower than most critical friction velocities for transportation of non-cohesive sediments.

In shallow waters considerably higher friction velocities can occur, and it is well-known that resuspension occurs in many such areas, sometimes on a seasonal basis. The concentration profiles of suspended matter close to the bottom can be easily observed by optical techniques. From the form of the concentration profile much information can be obtained about the transporting conditions in the boundary layer (Jerlov 1958, Rode 1973). It seems desirable that such observations are carried out in an area before marine dumping is initiated there.

REFERENCES

BOWDEN, K.F. (1965). Horizontal mixing in the sea due to a shearing current. J. Fluid Mech. 21, 83-95.

BOWDEN, K.F., KRANEL, D.P., and LEWIS, R.E. (1973). Some features of turbulent diffusion from a continuous source of sea. Paper presented at the 2:nd IUGG-IUTAM Symposium, Charlottesville 1973. In Adv. Geophys. 18 (in press).

CALLAWAY, R.J. (1974). Subsurface horizontal dispersion of pollutants in open coastal waters. In International Symposium on Discharge of Sewage from Sea Outfalls, London 1974, paper no. 30.

CARTER, H.H., and OKUBO, A. (1965). A study of the physical processes of movement and dispersion in the Cape Kennedy area. Chesapeake Bay Inst., Johns Hopkins University, Final Rep. 150 + 12 pp.

CRICKMORE, M.J. (1972). Initial behaviour of sludge. In Out of sight out of mind. Rep. of Working Party on Sludge Disposal in Liverpool Bay, Vol. 2, H.M. Stationary Office, 45-54.

JERLOV, N.G. (1958). Distribution of suspended material in the Adriatic Sea. Arch. Oceanog. Limnol., 11, 227-250.

JERLOV, N.G., and KULLENBERG, B. (1954). Undersökning rörande spridning och avsättning av i vattnet suspenderat slam vid utstjälpning av mudder i Byfjorden våren 1953 (with English summary). Sv. Geol. Unders. ser. C., no. 537, 48(2), 25 pp.

JOSEPH, J., and SENDNER, H. (1958). Über die horizontale Diffusion im Meere. Dt. Hydrogr. Z. 11, 2, 49-77.

KETCHUM, B.H., and FORD, W.L. (1952). Rate of dispersion in the wake of a barge at sea. Trans. AGU 33(5), p. 680.

KULLENBERG, B. (1964). Experimental sewage dumping in the Baltic 8-12 July, 1963 (in Swedish). Techn. Rep. Oceanographic Institute, Göteborg.

KULLENBERG, G.E.B. (1969). Measurements of horizontal and vertical diffusion in coastal waters. Kungl. Vetenskaps o. Vitterhets-Samhället, Acta Geophysica 2, 52 pp.

KULLENBERG, G.E.B. (1971). Vertical diffusion in shallow waters. Tellus 23, 129-135.

KULLENBERG, G.E.B. (1972). Apparent horizontal diffusion in stratified vertical shear flow. Tellus 24, 17-28.

KULLENBERG, G.E.B. (1973). Small-scale vertical mixing in relation to the temperature structure. Paper presented at the 2:nd IUGG-IUTAM Symposium, Charlottesville 1973. In Adv. Geophys. 18 (in press).

KULLENBERG, G.E.B. (1974). Effects of environmental factors, part 1. In International Symposium on Discharge of Sewage from Sea Outfalls, London 1974, paper no. 33.

MONIN, A.S., and YAGLOM, A.M. Statistical Fluid Mechanics: Mechanics of Turbulence. MIT Press, Cambridge, Mass. 1971.

MORTON, B.R., TAYLOR, G., and TURNER, J.S. (1956). Turbulent gravitational convection from maintained and instantaneous sources. Proc. Roy. Soc. A 234, 1-23.

MUNRO, D. (1974). Observed and predicted caliform distributions near a sea outfall. In International Symposium on Discharge of Sewage from Sea Outfalls, London 1974, paper no. 35.

OKUBO, A. (1971). Horizontal and Vertical Mixing in the Sea. In Impingement of Man on the Oceans, ed. D. Hood, J. Wiley and Sons.

PLATT, T. (1972). Local phytoplankton abundance and turbulence. Deep-Sea Res. 19, 183-187.

PORTMANN, J.E., and WILSON, K.W. (1973). Disposal of wastes at sea I. Factors to be considered in assessing the suitability of wastes for disposal. ICES, C.M. 1973/E:13 (Mimeo).

RODHE, J. (1973). Sediment transport and accumulation at the Skagerrak-Kattegatt border. Rep. 8, Inst. of Oceanography, University of Gothenburg.

ROLFE, M.S. (1973). Disposal of wastes at sea II. Factors to be considered in the selection of a dumping ground. ICES, C.M. 1973/E:14.

TALBOT, J.W. (1974). Interpretation of diffusion data. In International Symposium on Discharge of Sewage from Sea Outfalls, London 1974, paper no. 32.

TALBOT, J.W., and TALBOT, G.A. (1974). Diffusion in shallow seas and in English coastal and estuarine waters. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. 167 (in press).

TURNER, J.S. Buoyancy effects in fluids. Cambridge University Press, 366 pp, 1973.

WEIDEMANN, H. (ed.) (1973). The ICES diffusion experiment RHENO 1965. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. 163, 111 pp.