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This report contains results of work carried out
for the Hampton Roads Sanitation District Commission.
It does not constitute final publication.

W. J. Hargis, Jr.
Director

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Studies of turbulent diffusion in estuarine and inshore waters have given recent impetus to the development of a superior technique for tagging water masses and detecting the decrease in concentration of the tag through time. Independent research by scientists of the Japanese Governmental Agencies (1958) and the Chesapeake Bay Institute (Pritchard and Carpenter, 1960) led to the selection of rhodamine-B dye, an organic pigment, as a tagging agent, and to the development of fluorescence analysis as a detecting technique. The fluorescence spectrum of rhodamine-B has a maximum at 575 millimicrons and use of a Turner Model III fluorometer permits detection to 0.02 - 0.004 ppb. A review of the technique and its limitations was presented by Pritchard and Carpenter (1960). Studies by the Virginia Institute of Marine Science have utilized their experimental techniques.

Recent attempts to develop usable theoretical relationships for horizontal diffusion in oceanic waters have been made by Joseph and Sendner (1958, 1962), Ozmidov (1958), and Schönfeld (1959, 1962). The results of dye studies offer experimental verification of certain features of the theoretical equations (Pritchard and Carpenter, 1960; Okubo, 1962). Okubo (1962) has made a comprehensive analysis of the recent theoretical treatments of diffusion in the sea and of the results of experimental studies. He proposes a solution to the diffusion equations (1962, p. 56) that involves an "energy-dissipation" parameter having the dimensions $cm^{2/3}$/sec.

On August 1, 1962, between 0800 and 1400 hours, personnel of the Virginia Institute of Marine Science and the U. S. Coast and Geodetic Survey initiated, maintained, and monitored a continuous release of dye from a point approximately 800 meters off Cape Henry, Virginia (Fig. 1). The rate of release of rhodamine-B dye was 0.7 g/sec and the vehicle solution was adjusted to the density and temperature of the surrounding water (1.01 g/cc and 25°C, respectively). Release was from a point source at approximately 4 meters depth. In addition, a small number of surface and bottom drifters were introduced at the point of dye release (Fig. 1) to gain a crude measure of neighbor diffusion, in the event that the dye study should fail in some respect.

Wind, current, and wave data for portions of the release period are shown in Figure 1. The average current velocity, U, integrated along the axis of the dye plume, was 0.30 m/sec (0.58 kn) during the period of monitoring (1130 - 1230 hours) upon which the results below are based.

Neighbor diffusivity, $F(\ell)$, was calculated from returns of neutrally-buoyed drift bottles. $F(\ell)$ had a minimum value of 316 cm^2/sec and the coefficient e^3, in $F(\ell) = e\ell^{4/3}$, had the minimum value 0.062. This last value was calculated using Stommel's (1949) expression

$$F\left[\frac{\overline{(\ell_1 + \ell_0)}}{2}\right] = \frac{\overline{(\ell_1 - \ell_0)}^2}{2T}$$

for the reduction of the experimental observations, where ℓ_0 is initial neighbor separation (cm), ℓ_1 is separation after time T (sec), and the bars denote averages. The minimum value of e^3 falls (Table 1) within a range of values (0.006 - 0.08) that have been determined for other oceanic areas subject to tidal currents of variable strength. A calculation that allows for the turning of the drifters as they enter the longshore-current system shows that a maximum value for e^3 would not exceed 0.075.

Additional diffusion values were calculated from measurements of dye concentration along the axis of the steady-state plume (Fig. 1). A log-log plot (Fig. 2) of a "concentration ratio," $c \cdot M^{-1} \cdot D$ versus x, for values of x between 800 and 3800 meters, fits an x^{-1} relationship where c equals peak dye concentration, M equals rate of dye discharge (g/sec), D equals layer depth (meters) and x equals distance in meters along the axis of the plume. Thus, there was a decrease in dye concentration downstream from the discharge point proportional to the minus one power of the distance.

Table 1

Comparison of Neighbor Diffusivities Observed at Various Places
(Compiled from Pearson, 1956, table 10)

Place of Observation	Ocean conditions: Depth (meters)	Ocean conditions: Wind - current	Observed movement of	Initial neighbor separation ℓ, in cm	$F(\ell)$ cm^2/sec	e[3] in $F(\ell)=e\ell^{4/3}$
Loch Long, Scotland[1]	~2	Wind slight	Parsnips	187.7	84.3	0.0799
Loch Long, Scotland[1]	~2	Wind slight	Parsnips	26.7	6.4	0.0800
Virginia Beach, Virginia (this report)	4-6	Wind 3-6 kn Current 0.6 kn	Drift Bottles	150 cm	316-336	0.062 to 0.075
Vineyard Sound[2]	~25	Strong tidal current	Dye patches	9,000	2,400[4]	0.0132[4]
Near Woods Hole	~25	Strong tidal current	Dye patches	1,800	120[4]	0.0056[4]
Near Woods Hole	~25	Strong tidal current	Single dye spot	290 dia	50	0.0259
Vineyard Sound, off Falmouth Beach[2]	4-10	Very strong tidal current[5]	Mimeo paper	430	92	0.0284
Vineyard Sound, off Falmouth Beach[2]	4-10	Very strong tidal current[5]	Mimeo paper	77	10.4	0.0318
Near Cataract Hill, Bermuda[2]	~2,000		Mimeo paper	795	337	0.0457
Near Cataract Hill, Bermuda[2]	~2,000		Mimeo paper	103	36	0.0751

NOTES:
1 Richardson and Stommel (1948)
2 Stommel (1949)
3 Computed from data supplied to Pearson (1956)
4 Computed by Pearson (1956) from ordinary diffusivity, k
5 Scour of bottom visible from air

Calculation of the so-called "diffusion velocity" yielded a value of 2×10^{-3} m/sec. This value was computed from a relationship proposed by Schonfeld (1959) and expressed by Okubo (1962) as:

$$\bar{S}(x,y) = \frac{m/U}{\pi} \quad \frac{\omega\, x/U}{\omega^2 (x/U)^2 + y^2}$$

where $\bar{S}(x,y)$ equals the mean concentration at some point (x,y) in the plume, x being in the direction along the axis of the plume and y the direction perpendicular to the axis of the plume, m equals the number of particles released per unit time, U equals the mean flow, and ω equals the "diffusion velocity". When solving for ω, $\bar{S}$ (x) is expressed as the concentration ratio (mentioned above), in order to correct for depth-dependent variations in dye concentration along the axis of the plume. The approximate value for diffusion velocity (2×10^{-3} m/sec) found in this study has been found also by Pritchard and Carpenter (1960) in some of their experiments with continuous dye releases in waters influenced by currents.

Finally, a semi-log plot (Fig. 3) of the lateral distribution of dye concentration is presented for a transect (Fig. 1) across the plume, 1,695 meters downstream from the release point. A drop of one order of magnitude of dye concentration in 150 meters distance perpendicular to the plume was found.

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