CHAPTER 35
SUBMARINE WASTE DISPOSAL INSTALLATIONS

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The underlying philosophy of submarine waste disposal is economic disposal of waste without any significant adverse effect on the receiving water that would impair its beneficial use.

INTRODUCTION

A submarine outfall dispersal system is an integral part of any waste treatment facility discharging into the marine environment. Th design of the treatment facility as well as the submarine outfall installation is dependent upon the beneficial uses of the receiving water. the corresponding water quality criteria deemed necessary to protect the water use, and the waste assimilating or dissipational characteristics of the receiving waters.

The economic and technical factors related to the design and performance of waste treatment installations are familiar to most sanitary engineers. However, the quantitative resolution of the waste assimilating or dispersal characteristics of receiving waters is not well understood generally, and the problem is even more complex when dealing with coastal or nearshore marine waters. The principa reason for the complexity in the marine environment is that the waste assimilating or dispersal characteristics of coastal waters depends upon numerous physical oceanographic factors such as wind wave, sw littoral currents, variable water mass circulation systems, density gradients, upwelling, etc. in addition to the conventional physical, chemical and biological characteristics common to the aquatic environment.

FUNCTION

The obvious function of a submarine waste disposal installation is to convey a waste, treated to a suitable degree, to a point of final disposal where the effect of the waste on the receiving water is minimal even at the point of initial mixing as well as in the general area. While it may be desirable on a theoretical basis to treat a waste to a degree that even in the outfall pipe or in the area of initial mixing at the diffuser the waste has no significant effect on the receiving water; this may be unattainable from a technical viewpoint and is generally economically prohibitive. The point of final discharge must be selected on the basis of overall suitability with respect to the problem of rapid and thorough initial mixing of the waste with the receiving water and to prevent the occurrence of excessive concentrations of waste in the critical areas as a result of the subsequent transport and dispersion of the waste-sea water mixture.

RATIONAL DESIGN CONSIDERATIONS

The rational design of a submarine waste dispersion system entails consideration of a multiplicity of factors. Table 1 presents an outline-summary of the principal factors that should be evaluated.

TABLE 1

FACTORS TO BE EVALUATED IN DESIGN OF SUBMARINE WASTE DISPERSION SYSTEMS

I. Beneficial Uses of Receiving Water
   1. Bathing
   2. Marine recreation and/or working environment
   3. Fishery - propagation, migration, food organisms, etc.
   4. Shellfishery - propagation, harvesting, etc.
   5. Other marine plants, animals, i.e. kelp, etc.
   6. Industrial or commercial uses - cooling water, etc.
   7. Waste disposal
   8. Other

II. Water Quality Considerations to Protect Beneficial Uses
   1. Public Health
      a. coliform
      b. other
   2. Fishery and Shellfishery
      a. toxic substances
      b. antagonistic substances
      c. stimulants, fertilizers
      d. oxygen depressants
      e. settleable debris
      f. turbidity - suspended solids
   3. Nuisance
      a. grease and oil films
      b. floating debris
      c. settleable debris
      d. odors

TABLE 1 (cont)

4. Aesthetic
   a. sleek areas
   b. floating debris
   c. turbidity - suspended debris
   d. plankton blooms
   e. colors
   f. other

III. Oceanographic Characteristics of Site
   1. General nearshore circulation system
   2. Current structure
      a. surface and subsurface currents
      b. strength and direction as a function of time (ie current rose)
      c. effect of wind
         wave
         tide
         littoral drift
   3. Eddy diffusivity or dispersion characteristics
   4. Density structure, salinity-temperature-depth relationshi
   5. Submarine topography
   6. Submarine geology

IV. Waste Dispersion Considerations
   1. Initial mixing process - diffuser
      a. jet mixing
      b. buoyancy forces and induced mixing
      c. interference between jets
      d. possible effect of thermoclines or density gradien to throttle rise of waste plume
      e. diffuser orientation
   2. Dispersion plume and trajectory
      a. current rose
      b. eddy diffusion relationships
      c. rational dispersion equations for waste concentra
         1. no decay, ie dilution only
         2. decay or dieaway operative
            a. bacteria - coliform
            b. radioisotope
            c. other (BOD) etc.

V. Economic Analyses
   1. Types of treatment, effluents, and cost in varying combinations with
   2. Length, depth, cost of outfall systems and associated wa dispersal and assimilating characteristics

BENEFICIAL USES - WATER QUALITY CRITERIA

One of the fundamental requirements in the development of a marine waste disposal system is determination of the beneficial uses of the waters which are to be protected. Once this is done, suitable water quality criteria may be established to protect these uses and also provide a basis for evaluating adherence or compliance to the criteria. In some areas, there may be limited information on precise water quality standards for a respective use; however, for the most part reasonable criteria or standards can be established.

OCEANOGRAPHIC FACTORS

Oceanographic investigations of potential outfall sites are necessary to select the site having the most favorable characteristics with respect to outfall and diffuser location. It is necessary to know the general overall water mass circulation characteristics with respect to each potential site.

Current resolution - The current structure with respect to both depth and time must be studied with development of a statistically significant current rose as the ultimate objective. Sufficient studies must be conducted to provide an adequate sample of the variable currents that may exist at a particular location. Moreover, it is generally desirable to develop sufficient data so that at least a rough resolution of the effect of wind, wave, swell and tides can be made.

Current studies have been conducted using drogues of free floats, current meters, and drift cards consisting of small weighted plastic envelopes(4,14,18). Work is currently in progress on the adaptation of existing continuous recording current meters as well as the development of recording or transmitting current monitoring systems (2)(6).

If it is possible to show a fair degree of correlation between wind and current strength and direction, it is possible to employ this relationship to construct a "synthetic" current rose based on extended wind observations. This is of considerable practical importance because of the general availability of wind data and the relative ease and economy of collecting wind data as compared to current data. It should be noted that if such correlations exist, they generally apply only to the surface water layers.

Figure 1 presents a typical current rose - a plot of current direction, strength and percent (of time) occurrence for a given location. From the current rose, one can estimate the time of travel of waste material to the critical location. If data are available on

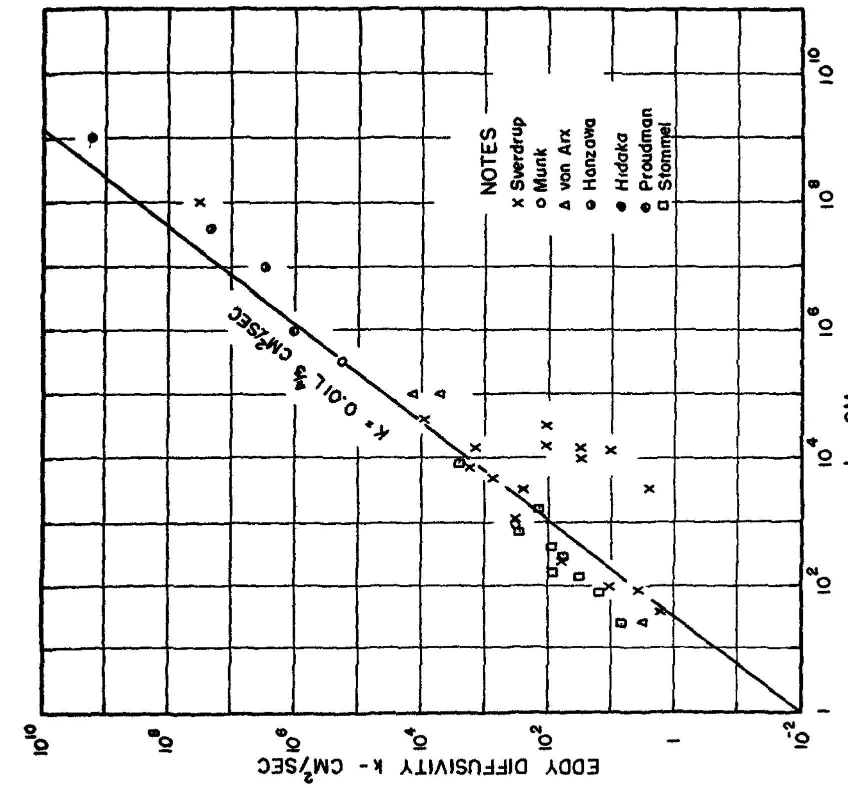

Fig. 2. Variation in eddy diffusivity, k, and scale of diffusion phenomena

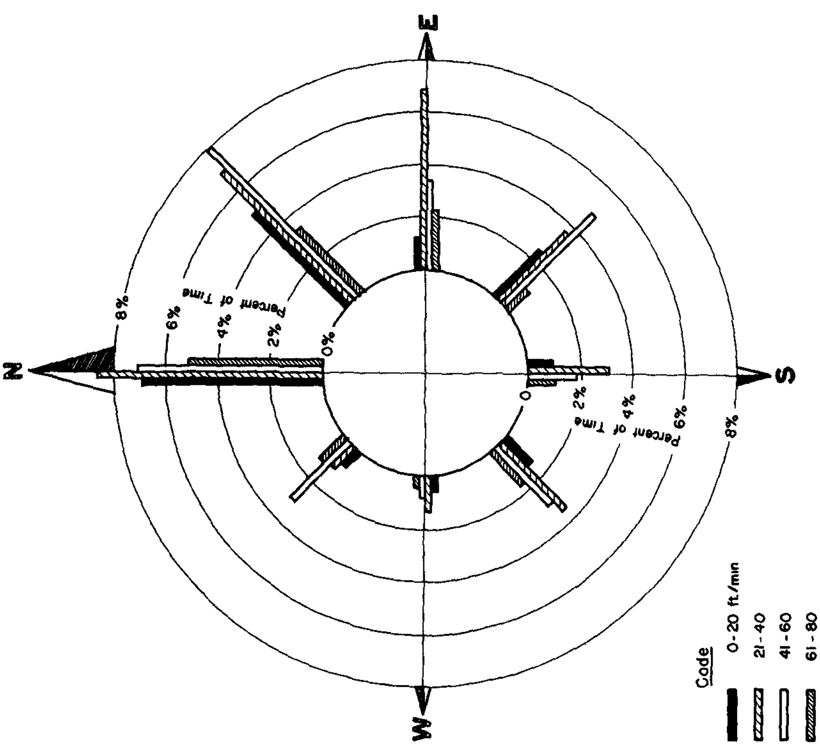

Fig. 1. Typical current rose

the decay or dieaway reaction kinetics of the waste, quantitative estimates can be made of the effect of decay during the time of travel to the critical location. Also, it permits prediction of the probability of occurrence of a given concentration of waste at any point.

Eddy diffusivity - Evaluation of the magnitude of the coefficient of eddy diffusivity for the receiving water is necessary if quantitative consideration is to be given the effect of eddy diffusion or dispersion in reducing the concentration of waste in the waste-sea water plume. Measurement of eddy diffusivity can be accomplished most easily by the use of dye tracers such as sodium fluoroscein. Chemical tracers such as iron salts (9) and radioisotopes (7) have been used, but are generally more complex in handling and analysis.

Various investigators have observed that the magnitude of the eddy diffusivity coefficient in the ocean has been dependent upon the scale of observation employed (8)(11). Richardson and others (17)(19) have postulated theoretically that the magnitude of eddy diffisuvity is proportional to the four thirds power of the scale of the phenomena or $k = \epsilon \ell^{4/3}$. Other investigators have confirmed this by measurement of the phenomena in the ocean. Figure 2 presents field values reported by many investigators plotted to show the relationship between eddy diffusivity, k, and the scale of the diffusion phenomena observed (8)(11).

Density-temperature structure - The density or temperature-depth character of an outfall site is an important characteristics of its suitability for waste dispersion. If there is a marked density or temperature gradient at some depth below the surface, this density gradient will aid in preventing the waste-sea water mixture from rising to the surface of the sea. In fact, the density gradient acts similar to an inversion layer in the atmosphere and tends to "throttle" the waste-sea water mixture below it. This is true if sufficient jet mixing and gravitational diffusion is effected before the waste-sea water mixture reaches the density gradient region: or, in other words, the buoyancy forces due to differences in density have been reduced to a negligible degree. If possible, it is desirable to keep the waste-sea water mixture from reaching the surface of the sea because it is in the surface layers where the most rapid transport occurs. Similarly, material that might accumulate in the surface film is transported at very high velocities induced by the wind compared to the water mass immediately beneath the surface.

In determining the density-depth characteristics of a given site, the bathythermograph (BT) is used most frequently. BT traces are made at each station and the temperature depth relationships as

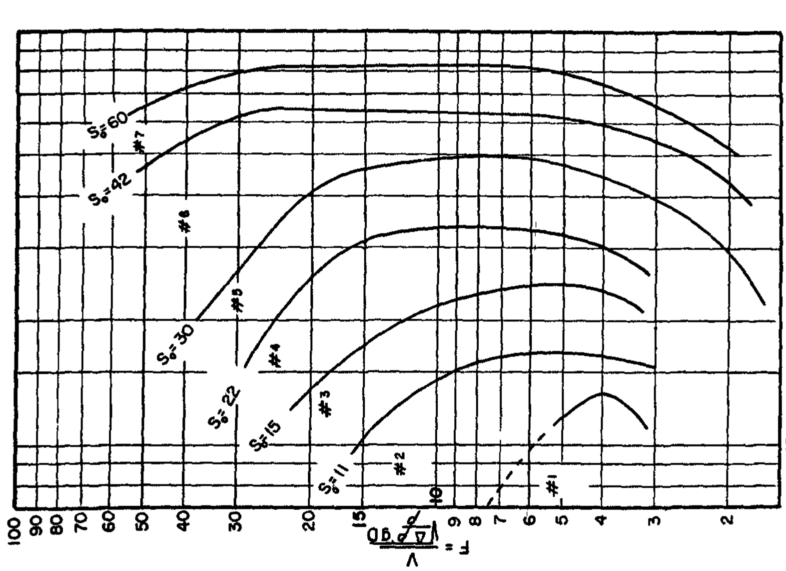

Fig. 4. Dimensionless plot of variables affecting dilution, So. based on Rawn and Palmer data for hori-

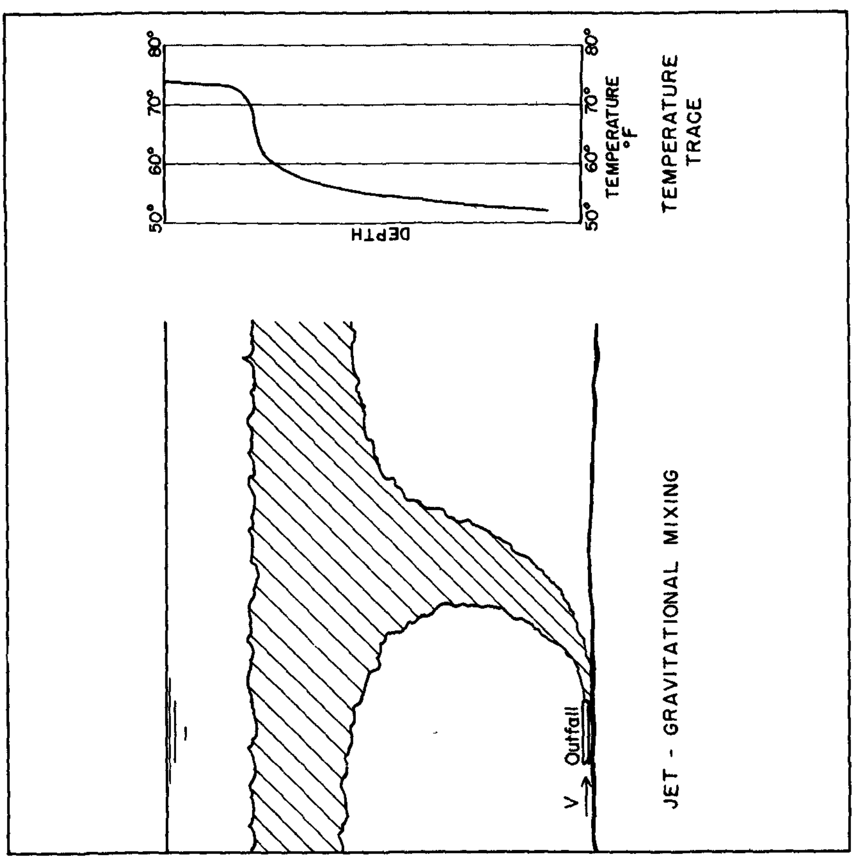

Fig. 3. Initial mixing - density considerations

measured by a rapid temperature-depth response circuit are traced on a suitable slide. The presence of a marked density gradient is easily detected and recorded at the depth encountered. BT traces are adequate for indicating density gradients in water where no significant salinity gradient exists. However, if the outfall site is subject to considerable upwelling of deep ocean waters so that both a temperature and salinity gradient are present, it is necessary to quantitatively measure the salinity as well as temperature to properly determine the density gradient.

Figure 3 presents a sketch of a typical temperature-depth trace with a bathythermograph as well as the effect such a density gradient may have on the gravitational diffusion of waste rising from a submerged jet.

Submarine topography and geology - Submarine topography may vary widely for submarine disposal installations. Ideally what is desired is a rather uniform sloping bottom to a considerable depth within reasonable distance from shore. While there is no minimum acceptable length or depth of outfall, it would appear that for most effective initial mixing and diffusion, a depth of 200 feet or greater is desirable for large outfall installations. Also, it is desirable that the bottom topography be relatively flat in the vicinity of the diffuser installation to minimize hydraulic flow distribution problems with a multi-port diffuser.

Bottom geology is an important consideration in the selection of the outfall site. Obviously fault zones and relatively unstable bottoms are to be avoided.

WASTE DISPERSION ANALYSIS

There are essentially two major fundamental aspects of the dispersion problem. The first is concerned with the mixing and dilution of the waste in the immediate proximity of the discharge point. The second is associated with the ultimate disposition of the waste-sea water mass or the direction of movement and concentration of waste in the waste-sea water dispersion plume.

Jet mixing - gravitational diffusion - The fluid mechanics of a single port discharging into a body of water with a density different than that of the jet is complex. The mixing phenomenon is a combination of mixing resulting from jet action, ie the kinetic energy of the jet, and mixing or diffusion resulting from the gravitational or buoyancy forces due to differences in density between the waste and sea water.

Rawn and Palmer (15) have studied the problem of dilution in rising jet in large scale experiments and reported the following expression:

$$S_o - 1 = \frac{0.5(L + 3)^{2.35}}{Q^{0.61}}$$

where S_o = dilution at the head of rising column

L = centerline length of rising column in ft

Q = flow per jet in gallons per minute

More recently, Rawn, Bowerman, and Brooks (16) have re-examine the original Rawn-Palmer data based on dimensional analysis and Froude law relationships. Figure 4 presents their dimensionless pl of dilution, S_o, in terms of Froude number $F = \frac{V}{\sqrt{\frac{\Delta p}{\rho} gD}}$ and y/D, t ratio of depth to diameter of the jet. The use of the figure is obvioı For a given Froude number, F, and the ratio of depth over outlet to outlet diameter, the intersection of the appropriate corrodinates is noted and the dilution, S_o, may be estimated. Rawn, Bowerman, a Brooks cite the need for caution in arriving at precise values of S_o from Figure 4 because the curves represent group averages and we not precisely defined.

Albertson (1) and Cooley and Harris (5) have developed ex perimentally similar equations for dilution in a jet. Cooley and Harris concluded that the average dilution in a jet could be express as follows:

$$S_o = \frac{L}{3 D_o}$$

where

S_o = average dilution in jet ($Q_{jet-total}/Q_{jet}$)

L = length of axis of jet trajectory in feet

D_o = diameter of outlet, ft

The preceding equations and others (11) permit estimation o dilution of the waste in the jet mixing-gravitational diffusion plum Analysis of these expressions points up the obvious desirability of viding up a given flow and single jet into a number of smaller flow and jets such as in a multi-port diffuser.

In dispersing a given flow into the water mass passing over a multi-port diffuser, the preceding expressions imply a "new" mixing-water supply and no interference between jets. However, the latter may not be attainable practically, and the amount of "new water" passing over the diffuser may limit the maximum dilution possible. Obviously, the maximum dilution of waste immediately over a diffuser, assuming perfect mixing, is the total "new" water supply ($Q_n = Vld$) divided by the waste flow, Q_w. Therefore:

$$S_o = \frac{Vld}{Q_w}$$

where

S_o = average dilution of waste

V = average velocity of "new" water flow past diffuser, ft/sec

l = length of diffuser, ft

d = effective water depth over diffuser, ft.

Q_w = waste flow, ft^3/sec

The above is simply a statement of continuity and represents the maximum dilution attainable at the source with perfect mixing - the obvious objective of a multi-port diffuser.

Eddy diffusion - Once the waste discharged through a submarine outfall is effectively mixed with sea water in the immediate proximity of the outlet, what then happens to the waste-sea water mass. Because the initial mixing and dilution achieved by the diffuser section generally does not dilute the waste to a harmless level at the outlet, it is necessary that subsequent dilution processes must be considered.

Most outfall location and design has been based on judgment influenced by past experience and float studies with the objective of keeping the fresh waste away from the shore for a minimum period of time. It is hoped that during this time, sufficient dilution and bacterial (waste) decay will occur so that the water reaching the shoreline will not exceed permissible waste concentration or bacterial standards for the beneficial uses of the area.

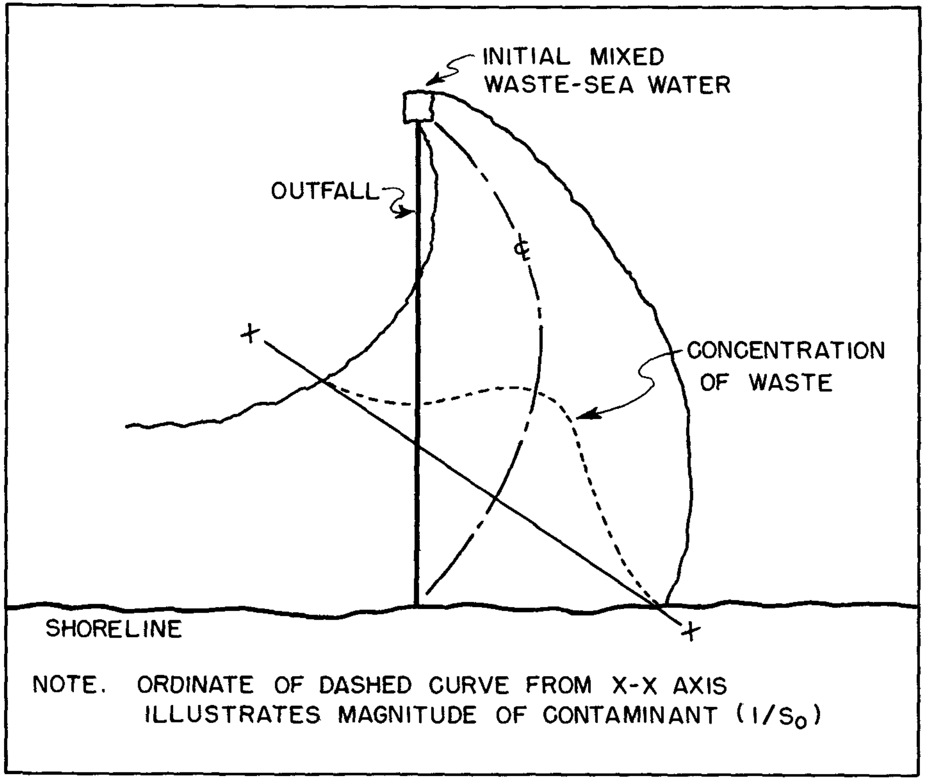

Fig. 5. Idealized trajectory of waste-sea water mass showing effect of current and horizontal diffusion

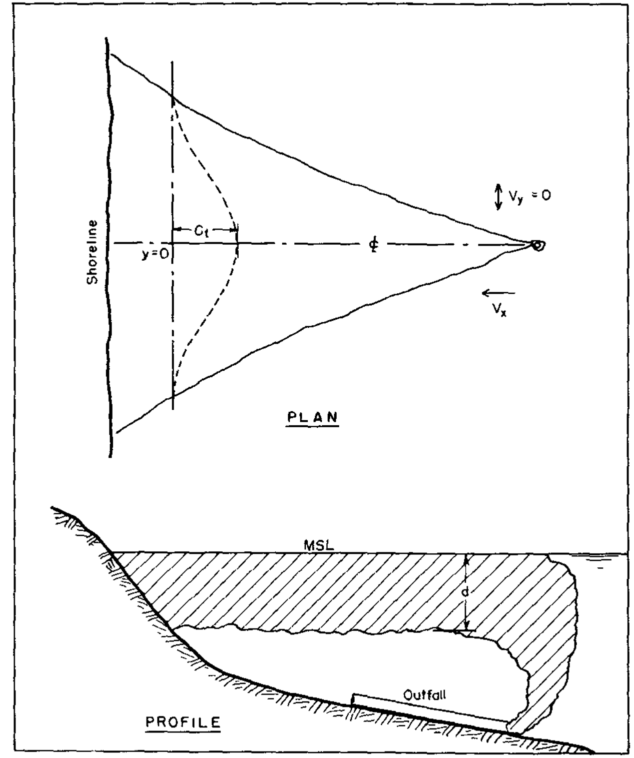

Fig. 6. Definition sketch for dispersion equations

There are numerous factors affecting the transport and dispersion of a waste-sea water mixture. General oceanographic factors such as periodic and non-periodic currents, wind currents, mass transport by waves, etc. have been reviewed by Pearson (11).

Lateral dispersion or horizontal diffusion of the waste-sea water mass occurs whether the current is such that it carries the waste away in a single direction or whether it is transported in an irregular pattern. By definition, lateral dispersion is intended to mean the dispersion of the waste-sea water mixture in a direction normal to the principal movement (advection axis) of the water mass.

Classically the current systems in nearshore waters have been assumed primarily to be rotational in character due to tidal currents (14). Figure 5 depicts an idealized trajectory of a waste-sea water mass may be likened to a plume of smoke emitted from a stack or point source. The plume follows the general direction of the current and the lateral width of the plume as it develops is a function of time and the turbulent characteristics of the receiving water (ie coefficient of eddy diffusivity).

Eddy diffusion in the ocean can be mathematically described by the Fickian diffusion formulation as follows:

$$\frac{\partial c}{\partial t} = k \frac{\partial^2 c}{\partial x^2}$$

In eddy diffusion vernacular, the diffusion constant, k, has been called the coefficient of eddy diffusivity. However, as previously pointed out, k, or the coefficient of eddy diffusivity appears to be a function of the scale of the phenomena.

The principal problem in ocean disposal of wastes is the prediction of the waste concentration at any fixed point with respect to the source. It is possible to compute this concentration if the appropriate differential equation considering continuity and boundary conditions is solved. Of particular interest in sewage dispersion is the effect of time on bacteria or coliform content of the sewage-sea water mixture. Inasmuch as this may be expressed as a decay function, it also can be included in the basic differential equation. Numerous investigators such as Ketchum and Ford (9), Munk, Ewing and Revelle (10), Pearson (11)(12) Pearson and Gram (13), Brooks (3) and others have reported solutions to the diffusion equation. Most have employed an assumed constant eddy diffusion coefficient; however, Brooks has proposed an approximate solution to the variable (function of scale, ie time) coefficient of eddy diffusivity.

Figure 6 reports an idealized definition sketch for the solution of the diffusion equation. A point source is assumed, steady unidirectional current in the direction of the shore, uniform mixing of the waste over a depth, d, and continuous uniform flow from the source. Obviously, no provision is made for return of water seaward which mus and does occur, hence the definition sketch is idealized.

A solution to the diffusion equation (point source) in terms of the minimum dilution of the waste along the axis of the waste-sea water is as follows:

$$S_o = \frac{2.35d\sqrt{kV_x \chi}}{Q}$$

where S_o = minimum dilution along axis of waste plume at distance χ from source

d = assumed vertical mixing depth, feet

k = eddy diffusivity, ft^2/sec

χ = distance from source, feet

V_x = average velocity of water mass, ft/sec

Q = waste discharge, MGD

Including the decay function for bacterial dieaway, and expressi the waste concentration in terms of coliform concentration, the above expression becomes:

$$MPN = \frac{0.438\ Q\ C_o}{d\sqrt{kV_x \chi}\ e^{(ax/V_x)}}$$

where MPN = most probable number of organisms per ml
C_o = concentration of organisms in waste, MPN/ml
a = bacterial dieaway (decay) constant, 1/sec

Similar expressions have been developed for a line source.

Brooks (3) has reported the following solution to the diffusion equation for a line source:

$$\frac{C_o}{C_{max}} = \frac{10^{\frac{t}{T}}}{\text{erf}\left(\frac{1.23}{\sqrt{\left(\frac{8C_1 t}{b^{2/3}} + 1\right)^3 - 1}}\right)}$$

where C_o = initial coliform concentration

C_m = maximum coliform concentration at time, t

t = time of travel

T = time required for 90% coliform dieaway (T-90)

C_1 = constant of proportionality ($k = C_1 l^{4/3}$) based on eddy diffusivity a function of scale ($C_1 \approx 1.84\ ft^{2/3}/hr$

b = initial width of sewage field

The significant feature of Brook's equation is that it attempts to include the effect of a variable eddy diffusion coefficient. The previously cited expressions assume a constant coefficient of eddy diffusivity with selection of the appropriate value based on a representative scale of the overall diffusion phenomenon.

Diffuser orientation - As cited previously, the magnitude of the coefficient of eddy diffusivity varies as the four-thirds power of the scale of the phenomena (ie approximately as the four-thirds power of the neighbor or particle separation in the waste plume). The advantage of dispersing the sewage over as wide an area as possible, normal to the major set of the current, rather than parallel to it, is obvious. Not only is the initial dilution of the waste increased but for a given initial dilution of the waste, the waste-sea water mass having the greatest scale normal to the major current will disperse laterally at the greatest rate; hence, effecting maximum dilution of the waste. Figure 7 shows an idealized trajectory of a waste-sea water mass with respect to the orientation of the diffuser section and the relative con-

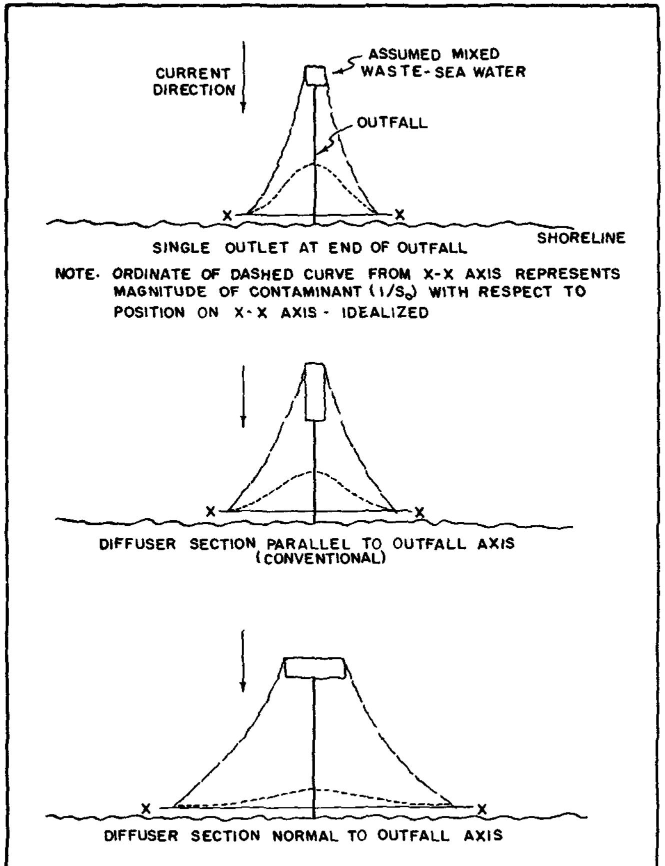

Fig. 7. Idealized representation of effect of horizontal diffusion and diffuser ori-

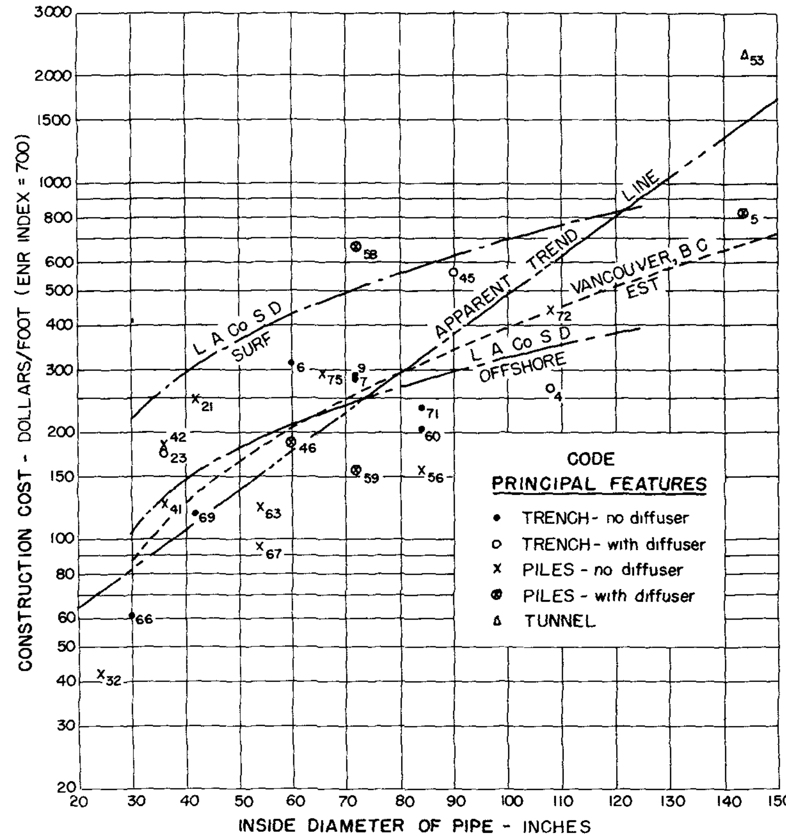

Fig. 8. Construction costs of reinforced concrete submarine outfalls

centrations of waste in the waste-sea water plume. It is apparent that the most effective orientation of a diffuser system in outfall design would be essentially normal to the axis of the so-called "critical" onshore current. In many cases this would result in the diffuser being parallel or nearly parallel to shore.

ECONOMIC CONSIDERATIONS

The design of a waste treatment plant and submarine outfall installation should be based on an analysis of all factors including economic, for all possible treatment - outfall systems. Basically, the best solution is the most economic combination of degree of waste treatment and outfall length that will produce the desired receiving water conditions. It is obvious that the difference in annual cost between varying degrees of waste treatment can be used to construct a longer outfall for the plant with the lesser degree of treatment. If the lesser degree of treatment and longer outfall is more economic than a higher degree of treatment and a short outfall; providing both alternates produce equivalent receiving water conditions at the critical point, obviously the former combination is preferred. All economic comparisons must be based on equivalent receiving water conditions or effects in the areas to be protected. Nomographic bases for economic analyses of degree of treatment and outfall length have been reported by Pearson (11). The cost of submarine outfalls is variable because of gross differences in surf and bottom condition, type of construction, anchorage, and method of construction. Figure 8 reports the unit construction costs of several large reinforced concrete submarine outfalls adjusted to an ENR Index of 700 and the relationship between unit cost and diameter of the pipe. Figure 9 presents a similar plot of unit cost versus pipe diameter for cast iron submarine outfalls.

EXISTING INSTALLATIONS

There are over 125 California coastal communities, including eleven of the thirteen largest cities, that dispose of their sewage effluent (and in some cases sewage sludge) through submarine outfalls. In addition there are a large number of industrial submarine outfall installations. The characteristics of these installations vary from relatively small (12 inch diameter) conventional pipelines to large (12 foot diameter, 5 miles long) specially designed submarine outfall installations (11).

The largest submarine outfall installation in the United States is currently under construction at the Hyperion plant for the City of Los Angeles. The effluent outfall includes a 12 foot I.D. reinforced con-

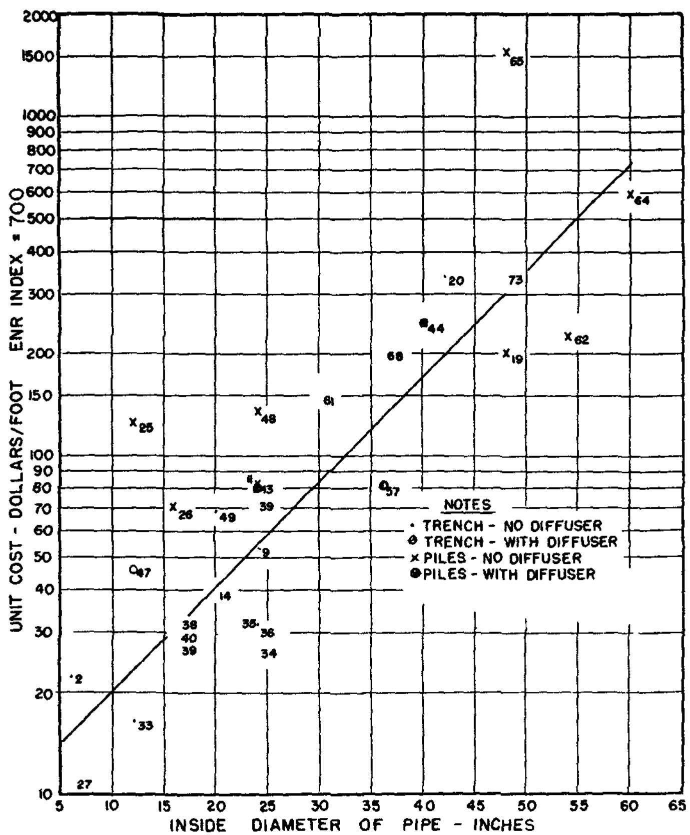

Fig. 9. Construction cost of cast iron submarine outfalls

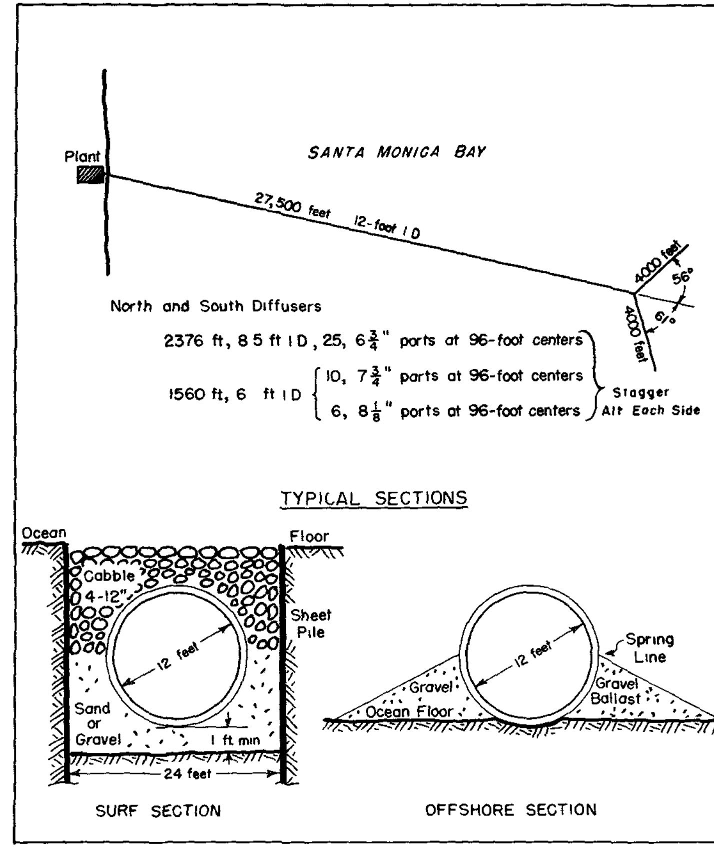

Fig. 10. City of Los Angeles effluent line

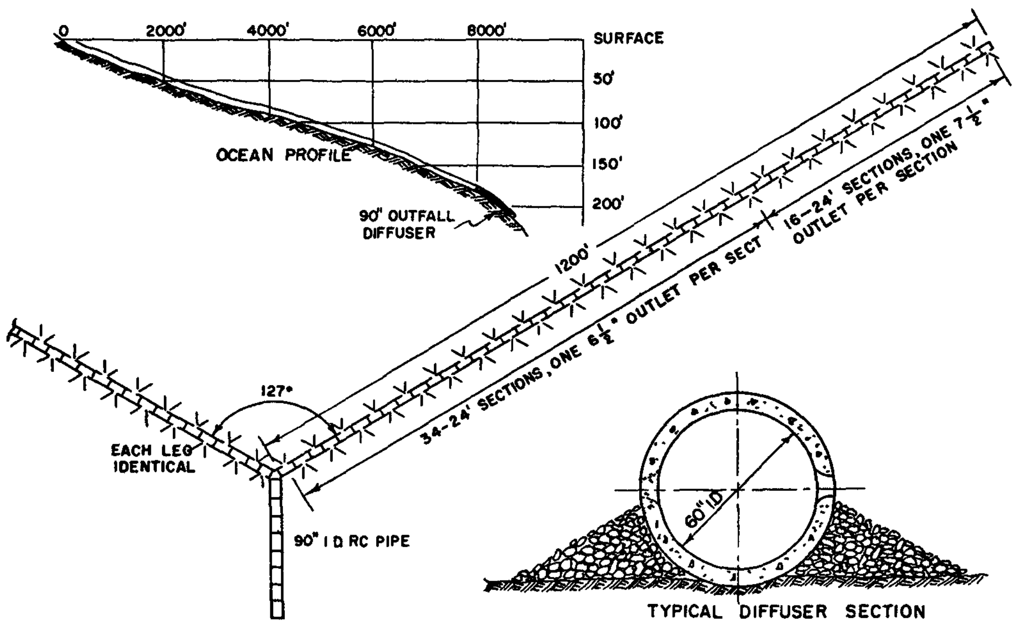

Fig. 11. Diffuser for 90 inch diameter outfall Los Angeles County Sanitation Districts No. 3

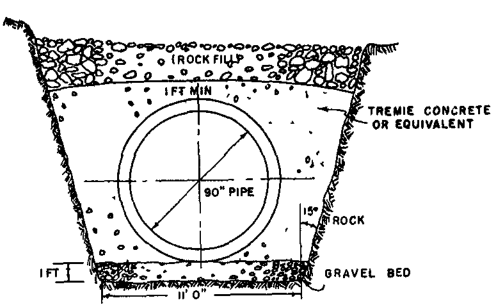

Fig. 12. Surf section, rock trench anchorage
Los Angeles County Sanitation Districts No. 3

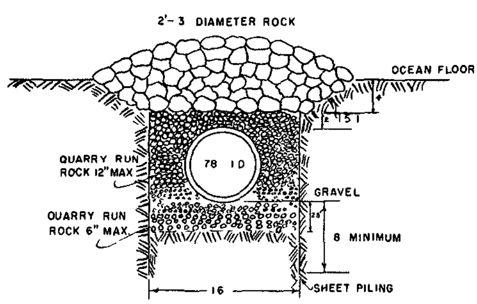

Fig. 13. Surf section anchorage
Orange County Sanitation District, Calif. (1953)

crete pipe extending 5 miles offshore and submerged at the diffuser in 192 feet of water. The diffuser consists of two branches forming a 120° wye, each leg approximately 4000 ft. long and containing approximately 82 ports varying from 6-3/4 to 8-1/8 inches in diameter. Figu 10 presents a schematic view of the Hyperion, City of Los Angeles effluent line currently under construction as well as typical cross-sectic of the surf and offshore sections showing the method of construction ar type of anchorage employed.

Figure 11 presents a schematic view of the recently completed 90 inch diameter outfall line (No. 3) for the Los Angeles County Sanitation Districts.

Figure 12 and 13 show the type of construction employed in the surf zone for Whites Point Outfall No. 3 and the Orange County Sanitation Districts outfall, respectively. This type of construction is typical of that employed to protect the pipe in the surf zone.

Details of other outfalls in California, as well as in other sections of the United States are presented in a report by Pearson (11) to the California State Water Pollution Control Board.

SUMMARY AND CONCLUSIONS

The role and function of a submarine waste disposal installatior as a component of overall waste treatment and disposal systems is reviewed in detail. It is necessary to resolve the beneficial uses of the receiving water, the areas involved, and the appropriate water qualit criteria to protect the uses. Moreover, water quality criteria are necessary so that it is possible to quantitatively assay the performanc of waste treatment and facilities in protecting the uses.

Consideration is given the significant oceanographic characteristics affecting the design of a submarine outfall dispersal system. The practical evaluation and importance of nearshore circulation systems, current structure, density-temperature structure, and the coefficient of eddy diffusivity in the design of submarine dispersion systems are discussed and quantitated.

Quantitative estimation of the concentration of waste in waste-sea water dispersion plumes is presented on a rational basis. The problem of initial mixing in the proximity of the diffuser is reviewed and a basis for estimating initial dilution is outlined. A definition sketch of the waste-sea water dispersion plume and solutions to the diffusion equation are presented. In this manner, a rational estimati of the concentration of waste (dilution or bacterial concentration) can be made if reasonable estimates of water mass velocities, mixing depths, eddy diffusivity, bacterial concentrations and dieaway or decay reaction kinetics are available.

Cost data on submarine outfalls are presented as well as details of the physical characteristics of some of the larger submarine waste disposal installations in California.

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