U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
SYSTEMS DEVELOPMENT OFFICE
TECHNIQUES DEVELOPMENT LABORATORY

TDL Office Note 78-1

TECHNIQUES FOR FORECASTING TRAJECTORIES AND
FATES OF OCEAN OIL SPILLS

Celso S. Barrientos and Kurt W. Hess

September 1978

FOREWORD

This Note deals with estimates of the location and concentration (or thickness) of oil spilled on the open sea. We want to answer the question, "what happens to the oil spilled on the ocean?" Because the behavior of oil on the sea is so complex, and not entirely understood, we present an overview of the entire problem in some detail. Also included is a summary of the knowledge required to make a simple forecast of the movement and approximate area covered by a range of volumes of spilled oil. Forecasts of many chemical changes are specifically excluded.

The Note may be quite lengthly for its intended readers, the marine forecasters. Therefore, we have included an Appendix which describes specific steps in making an oil spill forecast. This Appendix, along with the appropriate figures, provides a convenient source for operational forecasting. The entire Note is useful, however, for understanding the nature of the oil spill problem.

TECHNIQUES FOR FORECASTING TRAJECTORIES AND FATES OF OCEAN OIL SPILLS

Contents

Tables

Figures

1. Relationship between oil specific gravity (ratio of oil density to sea water density) and American Petroleum Institute (API) density degrees.

2. Graph of volatility (volatile fraction) of oil vs. its specific gravity.

3. A schematic representation of the spreading forces.

4. The size (diameter) of an oil slick as a function of time for 10,000 ton spill, from Fay (1969).

5. East coast wind roses and semipermanent surface currents for January (n mi per day) as shown in the U.S. Navy Pilot Charts of the Defense Mapping Agency, Hydrographic Office, Washington, D.C.

6. West coast wind roses and semipermanent surface currents for January (n mi per day) as shown in the U.S. Navy Pilot Charts of the Defense Mapping Agency, Hydrographic Office, Washington, D.C.

7. Graphs of oil slick diameter vs. time for calm sea spread, for various values of the spreading force, sigma (dyne/cm).

8. Same as Fig. 7 except for different values of sigma.

9. NWS coastal wind forecast locations on the East coast of the U.S.

10. NWS coastal wind forecast locations on the West coast of the U.S.

11. A series of diagrams showing the outline development and subsequent break-up of an oil slick (from Jeffery, 1973).

12. Sample graphical calculation of an oil spill trajectory with a 30 kt wind, a 0.5 kt tidal current, a 0.5 kt semipermanent current, and an 80% developed sea (see Appendix).

13. Sample graphical calculation of an oil spill trajectory with a 20 kt wind, a 0.5 kt tidal current, a 0.5 kt semipermanent current, and a 50% developed sea (see Appendix).

TECHNIQUES FOR FORECASTING TRAJECTORIES AND FATES
OF OCEAN OIL SPILLS

Celso S. Barrientos and Kurt W. Hess

1. INTRODUCTION

The demand for energy and raw materials in the United States continues
to increase. Petroleum and its byproducts are the main source of energy
and materials. This ever-increasing demand has led to a substantial increase
in the scale of production and transportation of oil. Subsequently, this
led to the increase in the level of pollution by oil, especially in the
marine environment where much of the production and transportation are going
on.

Oil pollution in the ocean, coastal, and inland waters is largely
due to natural seepage, continuous seepage during production, loading and
unloading operations in port areas, the input of industrial wastes, tanker
cleaning discharge while on the open sea, and to a lesser extent from major
disasters in marine transportation and offshore production. Disasters occur
in a more concentrated and spectacular form, often causing severe and notice-
able environmental problems. Although disastrous spills have caused dispro-
portionately large amounts of public attention, they only account for a small
percentage of the oil input in the marine environment. Based on estimates
of Farrington (1977) for the U.S., only 4% of petroleum hydrocarbon input
to the marine environment is due to accidents, while the largest input is
river runoff, about 35%. Worldwide, the percentages are 6% and 26% for
accidents and river runoff respectively. Thus, the extent of oil pollution
in the marine environment is much greater than that caused by the much-
publisized major accidents. Oil is being added to the marine environment
in such large quantities that the marine ecosystems cannot react efficiently.

The most noticeable damage to the marine environment occurs in the coastal
areas. Wildlife and sea life are very susceptible to accidental oil spills.
Esthetic damage to the shorelines is generally severe. The populace is heavily
affected from the loss of recreational areas, coastal usage, and food sources.
Therefore, an immediate remedy to combat oil pollution is vitally needed.

Contingency plans to prevent damage by oil pollution have been devised.
There is an urgent need to develop methods of forecasting movements and fates
of the oil pollution. To take action during an oil spill emergency the behavior
of the pollutant has to be known. In case of an oil spill, possible actions
are warning, cleaning, preventing, and planning. All these actions can be
accomplished only with viable methods to predict the oil movement.

This Note was initiated by the request of the NWS Western Region. They
suggested that the Department of Commerce, as a primary agency of the National
Response Team, has primary responsibility in an oil spill event to promote
effective operation of the National Oil and Hazardous Substances Pollution
Contingency Plan. In this plan the Department, through NOAA, provides support

with respect to marine environmental data, living marine resources, and current and predicted meteorological, hydrologic, and oceanographic conditions for the high seas, coastal, and inland waters, including tides and currents for coastal and territorial waters.

Responsibility of NWS with respect to meteorological and oceanic factors can be met with expertise from forecasters at the Weather Service Forecast Offices (WSFO's). However, techniques for prediction related to oil spills are needed. Technical guidance is needed to gather and to provide the best information with respect to oil spill operations.

In this Note we will first discuss the behavior of oil spilled in the marine environment. Then we will deal with some of the methods used to assess quantitatively the processes involved. Finally, we will treat the forecasting of oil spill trajectories in the ocean. We believe a review of the processes involved in the complex behavior of oil spill will be a helpful background in our discussion. There are four broad types of processes that affect spilled oil. These are (1) weathering, (2) spreading, (3) diffusion, and (4) advection. These processes are sometimes interactive. They are acting all the time, but some are dominant depending on the time and size of the spill, and the characteristics of the environment.

Weathering is a set of processes related to the physical characteristics of the oil. These include evaporation, coagulation, sedimentation, dissolution, emulsification, and microbial degradation, although evaporation is probably most important. Some of the weathering processes are dependent on physical variables of the environment, e.g., evaporation is a function of temperature and wind speed. Weathering processes are ongoing at various stages of the spilled oil; some are more dominant than others at those stages.

Spreading refers to the physical expansion of the size of the spill due to mechanical forces. There are two spreading forces, gravity and surface tension forces, and two retarding forces, inertia and viscous forces. The gravity force is dependent on the thickness, the inertial force is a function of acceleration, and surface tension and viscous forces are determined by the physical properties of the oil. There are three spreading regimes depending on which of the spreading forces are dominant. These are gravity-inertia, gravity-viscous, and surface tension-viscous. The spreading regimes are dependent on the time from when the oil was spilled, as well as the volume of oil.

Diffusion is the process by which the size of the spill grows by random motion of the oil. We refer here to turbulent diffusion, which is several orders of magnitude larger than molecular diffusion. Diffusion is usually handled by the gradient method with eddy diffusion coefficients. There are estimates of diffusion coefficients for spreading of dyes and other conservative substances in water, although the diffusion coefficient for oil is not well known. Another complexity is whether the oil behaves similarly to dye.

Advection refers to the advective movement of oil as the spill is being carried by water and wind. When moved by water, we refer to it as motion due to currents and when by wind we refer to it as wind drift. Water currents are induced by density differences, winds, waves, and tides. Wind drift may

include action of the wind directly on the oil. The advection is the actual vector sum of the current drift and wind drift. When oil is spilled, a certain time will be reached when the advective component is probably the most dominant part of the dispersal of oil in the water.

The greatest environmental problem in forecasting oil spill trajectories is in the prediction of the advection. It is both an oceanic and a meteorological problem. Motions in both the atmosphere and the ocean must be known over a wide range of time scales. The presence of interfacial phenomena (waves) and oil slick modification of the interface add to the complexity of the problem.

This note will cover a detailed outline of the above four major processes. We will discuss previous work in various areas, evaluate the applicability of methods and techniques, and we will make some suggestions for possible tools in actually forecasting oil spill trajectories in a practical situation in the National Weather Service Forecast Offices.

A review and evaluation of basic techniques for predicting the behavior of surface oil slicks has been prepared by Stolzenbach, et al. (1977) for NOAA's deepwater ports assessment. The review is a comprehensive study of the existing techniques and gives good insight to this very complex problem. Fallah and Stark (1976) have prepared a bibliography on oil spills. The paper covers all aspects of the oil spill, such as modeling, observations, experiments, and processes. The Oceanographic Institute of Washington (1977) has compiled a summary of the modeling methods for predicting oil spill movement. The summary describes 17 models and for each includes assumptions, parameters and constants, data requirements, validity, and critique. More information on oil spills can be obtained in these three review publications.

2. PETROLEUM AND THE PROCESSES AFFECTING SPILLED OIL

An understanding of the physical nature of petroleum will be helpful in forecasting the eventual fate of the oil. Lighter components, such as gasoline, will most likely evaporate, whereas the heavier components, such as lubricating oil and fuel oils, will be around for significant periods of time. Some of the terminology will help familiarize the forecaster with the types of petroleum products likely to be encountered. This is especially important given the large number of such products, and the general lack of a uniform classification system. See also Curl and O'Donnell (1977).

The mechanisms of oil dispersal in the marine environment will be discussed in some detail. Emphasis will be placed on development of forecast techniques and well-known relationships. Extensive theoretical arguments will be avoided. From this, a clearer picture of the fate of oil on the sea should evolve.

A. The Nature of Petroleum and Spilled Oil

The fate of petroleum on the sea depends greatly upon the physical and chemical properties of the oil. Therefore, these properties must be determined for the forecasting process. The oil density will determine whether sinking

will occur, and will influence spreading. Viscosity is generally related to density. The final stage of spreading is primarily by surface tension. Evaporation of the lighter fractions can be determined by the boiling point. Molecular weights are useful in determining the properties of mixtures of individual oils.

Petroleum is composed mainly of hydrocarbons, with at most a few percent being elements like sulphur, oxygen, and nitrogen. The number of pure hydrocarbon compounds runs into the thousands, and specific properties of each have not been tabulated. The two structural classes of hydrocarbons, aliphatic (chained) and aromatic (ringed) compounds, are well represented. Of the first, the paraffin series (alkanes, methane hydrocarbons), C_nH_{2n+2}, is of the greatest importance. These hydrocarbons with carbon number (n) up to 4 are called "natural gas," 5 to 8 the light and heavy gasolines, 9 to 13 the lubricating oils, and n greater than 14, paraffin wax. The alkenes, C_nH_{2n}, (olefines) may not occur naturally, but can be found in significant quantities in distillates as the result of the cracking process. Cycloparaffins (the napthanes, cyclopropane, cyclobutane), also C_nH_{2n}, have a cyclic structure.

Of the aromatics there are the benzenes (C_nH_{2n-6}) and homologues (toluene, xylene), dicyclic aromatics (napthalenes), tricyclic (anthracenes), and polycyclic (pyrenes). Also there are combinations of aromatics and cycloparaffins, the napthenoaromatics (indanes, indenes). Structures for some hydrocarbons appear in Table 1.

The boiling point is an important physical property of the hydrocarbons. Differences in boiling point between various crude oil hydrocarbons are useful in separating the oil into fractions with individual characteristics suited to specific uses as fuels or lubricants. During the refining process, crude oil is separated into what is termed "cuts" of different boiling ranges. These ranges vary widely depending on the nature of the crude oil which itself varies depending on the origin. Table 2 shows petroleum classification by its distillate fractions which generally follow the order of the molecular weights.

Petroleum density, ρ (mass/volume), varies from 0.6 gm/cc for the lightest paraffins to 1.1 or higher for asphaltic components; most crude oils range 0.8 to 1.0 gm/cc. Specific gravity (s.g.) is the ratio of oil density to the density of fresh water, and is used in the American Petroleum Institute (API) scale of density degrees.

$$API \text{ density degrees} = (141.5/s.g.) - 131.5$$

API density can be converted to specific gravity by Fig. 1.

Viscosity, μ, is a measure of resistance to flow and has the units of poise (=1 gm/cm-sec), or Saybolt universal seconds. Kinematic viscosity, $\nu=\mu/\rho$, varies from about 0.3 stokes (cm^2/sec) for hexane to around 3000 for some Venezuelan crudes. Viscosity varies approximately with density and with temperature.

4

Lighter fractions evaporate quickly, depending upon boiling point. Virtually all components which boil under 270°C will be lost after 2 days, while those which boil above 400°C will remain for weeks. An approximate portion of total volatiles based on density is given in Fig. 2.

Surface tension, σ(dynes/cm), is measured between oil and air (σ_{oa}), and oil and water (σ_{ow}). The difference between σ_{aw} (73 dyne/cm) and the sum of σ_{oa} and σ_{ow} is known as the spreading pressure. Although the spreading pressure may occasionally be negative, in most cases a value of 20 dyne/cm may be assumed.

Another important quantity is the melting or pour point. This is easy to obtain for some specific hydrocarbons, but less so for mixtures. If oil is spilled upon a sea at a temperature below the melting point, the oil will congeal and harden, and spreading will be severely limited. We must assume that oil spilled will have a low melting point, and be liquid on the sea.

Typical properties of petroleum products and crude oils are summarized in Tables 3 and 4. Also, Table 5 shows the typical volumes of petroleum oils transported by water in the Seattle, WA region. These show the relative likelihood of products being spilled on the sea from shipping accidents.

B. Weathering

Weathering is a term applied to the effected changes caused by environmental conditions on spilled oil. Weathering includes evaporation, emulsification, dissolution, sedimentation, and microbial degradation. These processes will cause changes to the spilled oil dependent on the physical environmental conditions. The changes are functions of the physical properties of the oil and the reactions are mostly chemical. There is an extensive body of literature on oil weathering produced by oil chemists. However most of the experiments were conducted in the laboratory and applicability to field situations is open to question.

Evaporation

For meteorologists and oceanographers, evaporation is probably the easiest weathering process to comprehend. We know for example that the biggest interchange of energy from sea to air occurs through the evaporation process, i.e., water vapor loss from the sea surface. Similarly, evaporation of spilled oil into the atmosphere occurs through the same process. Since evaporation is the transfer of liquid to gas and subsequent mixing with the atmosphere, we know logically that the lighter constituents of the oil will evaporate first. Initially, the evaporation is at a fast rate, then decreasing as the process continues until all the constituents subject to evaporation are gone. Evaporation alters the damage that may be caused by an oil spill. As the process continues, the toxicity of the oil is decreased and the harmful effect to neuston is reduced, although harm to benthos may be increased. After the oil evaporates, it will mix with a bigger volume of the air result-

ing in lower concentration. Additionally, the atmosphere acts efficiently to distribute the components. For some oils, evaporation will leave a residue which is denser than sea water and the oil will sink.

Evaporation will depend on the concentration, so that

$$E = K_E(W,T,p,h)C \qquad (1)$$

where E = Evaporation rate (mass/sec-area),
K_E = exchange coefficient,
C = oil concentration,
W = wind speed,
T = air temperature,
p = partial pressure of hydrocarbons, and
h = oil film thickness.

Evaporation generally depends on the vertical gradient of an oil constituent concentration; Eq. (1) is a simplification of the physical relationship, with evaporation being proportional to the bulk oil concentration at the surface. The constant K_E combines many environmental factors, such as air speed, air temperature, sea state, and sea temperature, with physical and chemical properties of the oil.

In a number of simulated oil spills, Kreider (1971) found that the lighter components of petroleum evaporated rapidly. Virtually all of the hydrocarbons up to and including C_{12} were completely lost after 24 hours. C_{14} was completely gone after 7 days, and C_{15} after 15 days. The rate of loss was however, more rapid for thinner films than the 0.5 mm thickness for which the above rates apply.

The calculation of the evaporation rate is amenable to approximation and can be checked against data in the literature. We believe evaporation can be the best estimate of the weathering processes.

Emulsification

Emulsification is another of the important weathering processes acting on the oil spill. However, it is probably the least understood. Emulsification refers to the process when water is trapped in oil, forming lumps. Emulsion forms with a semi-solid, grease-like consistency, and has been nicknamed "chocolate mousse" because it resembles the dessert in appearance.

When emulsions form, other processes are also affected, e.g., the evaporation process may either increase or decrease depending on the size of the surface area. Emulsification might enhance sedimentation after the evaporation of volatile components in the later history of the spill.

Present models do not take emulsification into account. To do so means the onset of emulsification process plus the details of the process itself have to be predicted. For example, the percentage of water actually trapped in the emulsion has to be known. This percentage is greatly variable and will depend on the chemical properties of the oil and environmental conditions.

Dissolution

Dissolution is the opposite of evaporation. It is the rate by which oil is going down into the water column and it will depend on the vertical exchange at the oil-water interface. In contrast to evaporation, it is the heavier components of the oil that will separate from the oil mixture and dissolve into the water. The dissolution process is very important because the amount that dissolves into the water and reaches the deeper part may be harmful to organisms. Dissolution is slower than evaporation and may be neglected in practical models of surface slicks. However, it should be included in a form essentially identical to evaporation in a mass balance study.

Sinking and Sedimentation

Oil sinks and reaches the bottom by various ways. The simplest way is gravity-induced descent. This happens when the oil becomes more dense than the water. This can occur after other weathering processes have been acting on the oil. Another way is for the oil to absorb particulate matter in the water and become denser. In shallow coastal areas and estuaries, sinking of the oil because of physical contact with the bottom is also likely.

There have been some cases of oil spills where the oil sank after a couple of days. However in most cases only a small percent of the volume of the oil spill actually sinks to the bottom.

Data on sinking and sedimentation is virtually nonexistent. Most of the studies have been done by introducing massive doses of particles (e.g. sand) to remove the oil as a means of cleaning. After the oil is settled on the bottom, it may again resurface depending on the turbulence and bottom currents.

Microbial Degradation and Oxidation

Even if the other processes cease acting on the oil, micro-organisms continue to attack the oil to reduce the concentration. When oil is spilled, bacteria begin eating the oil. Some organisms are very efficient, and can produce CO_2 and O_2 from the oil. Organisms act on the lighter nonaromatic constituents first. Microbial reaction therefore proceeds like evaporation. The resulting oil concentration has higher density and more aromatics. This process enhances emulsification and sedimentation.

Microbial reaction to the oil is rather slow, on the order of 1% to 2% of the total rate of degradation, although it continues to act on the oil. It is a helpful process to the organisms and later the organisms will be utilized by the higher forms on the food web.

Microbial degradation is only one form of oxidation. Another is photochemical oxidation, which occurs in the presence of sunlight. The oil will also self-oxidize, using its own oxygen. Both these processes are usually slower than bio-oxidation.

C. Spreading

When oil is spilled, it is going to expand in area due to its having greater potential energy and to its other physical properties. We refer to this process as spreading. This is different from diffusion or advection of the oil by actual movement of the water surface. Spreading is occurring even if the sea is perfectly calm, i.e., no wind and waves. As a matter of fact, we can visualize the spreading process better by considering a calm ocean.

The earliest analysis by Fay (1969, 1971) of spreading was done for calm conditions. Spreading of oil on a calm sea is the consequence of the forces of gravity, surface tension, inertia, and viscous friction acting on the slick. A schematic representation of the forces is shown in Fig. 3. Each of these forces has a component in the horizontal direction which either accelerates or retards the spreading action.

Gravity and surface tension forces accelerate, while inertia and viscous forces retard. The gravity force is a result of the oil being slightly above the surface and having more potential energy. The magnitude of the gravity force is proportional to the thickness and gradient of the thickness of the oil film, and to the difference in density between water and oil.

Surface tension is the net of the water-air interfacial tension minus the sum of the oil-air and oil-water tensions. This difference between the surface tensions is called the spreading force. The magnitude of the spreading force is dependent only on the chemical properties of oil, while the magnitudes of the other spreading forces depend on the physical properties.

The inertial force is the result of the outward acceleration of the oil. The magnitude depends on the thickness and size of the slick and the difference in density between the water and the oil. The viscous force is due to the fact that the oil flows past the water. A boundary layer below the oil-water interface is created by friction. The magnitude of the viscous friction force is proportional to the boundary layer thickness and the viscosity of the water.

The schematic in Fig. 3 shows in symbolic forms the expressions for the magnitudes of the forces. The symbols are

$$\rho_w = \text{water density,}$$
$$\rho_o = \text{oil density,}$$
$$h = \text{oil thickness,}$$
$$g = \text{gravity,}$$
$$x = \text{horizontal coordinate,}$$
$$\sigma = \text{surface tension with subscripts for water, air,}$$
$$\text{and oil,}$$
$$u = \text{velocity along } x,$$
$$\delta = \text{boundary layer thickness,}$$
$$\nu = \text{viscosity of water, and}$$
$$t = \text{time.}$$

During different times in the spreading process, one accelerating and one retarding force play the dominant roles in balancing each other. The combinations of the dominant forces give rise to the three speading regimes. These regimes are, in order from the spill time, gravity-inertia, gravity-viscous, and surface tension-viscous. For the ideal conditons considered by Fay (1969), approximte expressions have been obtained for the size (diameter) of the spill ℓ, as a function of time t.

Fig. 4 shows the first spreading regime proceeding quickly, followed by a slowly spreading regime dominated by viscous forces, and finally the third regime in which the surface tension is effective in spreading the slick. We point out that this analysis is based on a calm sea. There are interactions between processes which we will mention later. A maximum area was estimated to be $A(m^2) = 10^5[Vol(m^3)]^{3/4}$, where m = meters.

D. Turbulent Diffusion

Turbulent diffusion will cause the oil slick to grow on a calm sea (no waves or mean currents). This horizontal diffusion is made up of two parts: the oil turbulent motion and the water turbulence. No data exist on the oil turbulent diffusion, which is very hard to isolate from the other spreading processes. We treat only turbulent diffusion and neglect molecular diffusion since turbulent diffusion is several orders of magnitude bigger than molecular.

Horizontal diffusion of oil due to turbulent water fluctuations is estimated by assuming that the oil will move exactly as the water surface. Estimates of eddy diffusion are by the tracer method. Usually dye or a marker that behaves exactly as the water particles is studied. Values of eddy diffusivity coefficients are estimated in this manner.

The extension of the dye tracer approach to an oil spill has not been demonstrated. We know that oil and dye do not behave the same. Dye behaves as a dynamically active agent, while oil is dynamically passive. Dye mixes freely with turbulent water and interchanges energy with the surrounding fluid. However, oil does not mix freely with water due to its bouyant nature and can only interchange energy through pressure fluctuations and shear at the oil-water interface. Whether these differences are significant, making the dye results inapplicable to oil, has not been determined. At any rate, estimates by the dye or marker approach are the only data available. Hopefully certain correlations can be applied in the future to correct the differences.

The horizontal diffusion of oil can be viewed as a classical diffusion problem. Let us neglect advection, then,

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial C}{\partial y}\right), \tag{2}$$

where C = concentration,

   K_x, K_y = eddy diffusivity,
   x, y = horizontal coordinates, and
   t = time.

Various solutions for Eq. (2) exist. It can also be solved numerically.

The major problem in Eq. (2) is the value of the exchange coefficients. These coefficients are functions of time and space. Even if we can extend the tracer result to the oil spill problem, we still do not have a good handle on the eddy exchange coefficients.

E. Advection

By advection we mean the movement of oil due to wind and water motion. Turbulent diffusion is also the result of random water movement but it is not included here. Advection includes wind drift, ocean currents, wave-induced currents, and tidal currents. We will discuss these currents in detail since for practical forecasting these are the processes for which we can make reasonable estimates. Additionally, advective currents are meteorological and oceanic problems, and are closer to our field of expertise.

Consider the case of wind-drifting oil on still water. Wind blowing on the water surface will drag the oil slick. The stress induced by the wind on the surface of the fluid is

$$\tau_a = \rho_a C_{Da} \vec{V} \left| \vec{V} \right| ,$$

where: τ_a = the stress from above,
ρ_a = air density,
$\vec{V}$ = wind speed, and
C_{Da} = drag coefficient.

We can do a similar formulation for the stress coming from the bottom of the oil layer

$$\tau_b = \rho_w C_{Dw} \vec{W} \left| \vec{W} \right| ,$$

where: τ_b = the stress from the bottom,
ρ_w = water density,
CD_w = drag coefficient, and
$\vec{W}$ = speed of the slick upon still water.

Then we assume that the two stresses are equal. We assume further that we are dealing in one dimension so the $\vec{V}$ and $\vec{W}$ can be replaced by V and W.

$$W = V \sqrt{\frac{\rho_a C_{Da}}{\rho_w C_{Dw}}} .$$

Since C_{Da} and C_{Dw} are the same, the wind factor is the square root of the ratio of the densities, or

$$W \simeq 0.03 \; V .$$

This is the famous and simplest 3% wind factor mentioned in various publications. It is very simple to use and has been shown to give a fairly good estimate of the movement of oil spill. As for the direction, the same direction as the wind is generally used. If a deflection angle is applied, it is to the right of wind up to about 15° maximum. The average deflection used is 5° - 10°. In shallow water on the continental shelf, 0° deflection angle should be used. Shallow water is 50 feet or less.

The classical Ekman solution for an infinite depth sea is

$$W = \frac{\tau_a}{(Af)^{\frac{1}{2}}},$$

where: A = vertical eddy viscosity, and

f = Coriolis parameter = $\pi/21600 \sin(\text{latitude})$.

The surface speed W is inclined 45° to the right of V. For the case of finite depth, W is a complicated function, and is deflected less than 45°. However, the uncertainties in estimating A prohibit the use of Ekman's approach at this time.

The oil slick is also advected by wave transport. However an analysis of how the oil is being advected by waves is based on many assumptions. If we assume a "no slip" condition, that is, the oil is carried by the surface water without slipping, then we can assume Stokes wave drift for the wave transport. The Stokes solution is for an inviscid fluid and relatively deep water and is a function of wave amplitude and period. To predict Stokes drift we should be able to predict the wave characteristics based on the knowledge of the surface wind ignoring contribution to drift from swell.

The simplest wave forecasting technique is that developed by Sverdrup and Munk and later modified by Bretschneider (1966) (SMB-method). This method gives significant wave height and period based on the speed, duration, and fetch of the wind. For a fully developed sea, Stokes solution yields a surface wave drift in deep water

$$\overline{U}_s = 0.02 \ V \ ,$$

i.e., 2% of the wind speed. How this should be combined with the 3% wind factor is not known. Some oil slicks have been observed to move higher than 5%, but it is not clear where to attribute the movement. There are other transport processes acting on the slick, and we are not certain how to isolate the various components.

Similar Stokes wave drift can be derived if we apply the spectrum method for wave forecasting. Using the Pierson-Moskowitz (1964) spectrum, we found

$$\overline{U}_s = 0.016 \ V.$$

Similarly using the Bretschneider (1966) spectrum,

$$\overline{U}_s = 0.027 \ V,$$

which is the same order of magnitude as the very simple SMB-method. The wind speed V is generally taken at the 10-meter level.

Schwartzberg (1971) has found, based on some empirical results, that an oil slick moves at about 56% of the speed of the current. However, this correction may not be true in general and we do not advocate applying it.

Currents are also generated by large scale meteorological systems and by tidal action. Semi-permanent large scale ocean circulations are examples of the first case. The coming and ebbing of tides cause tidal currents which are probably not significant in the deep ocean but may be significant on the shelf near the coast and near entrances to large bays and rivers. Tidal currents also average out when we consider a time interval more than one tidal cycle. Tidal current tables are useful.

Currents can also be density induced, e.g., geostrophic currents. To compute density induced currents, density measurements in three dimensions may be required. Density currents are significant in coastal areas when temperature and turbidity gradients are marked, and surface runoff is substantial.

For current observations we must rely on catalogued data, such as the U.S. Navy Pilot Charts (Figs. 5 and 6). Since our interest in oil slick modeling is the surface current, the problem is doubly difficult. For some situations, we can solve the dynamical equations to compute the current. Dynamic models can also be used to do diagnostic analysis (by interpolation procedures) of the current field. Since observations are very few or nearly nonexistent, diagnostic analysis is required for dynamic consistency of the initial field.

Our knowledge of the transport mechanisms of oil spill is far from complete. However, NWS forecasters have the best knowledge of the wind field. Once we know the wind, an estimate of the transport as 3-5% of the wind is a reasonable first-order approximation. Forecasting the movement of oil, therefore, is one result of a very important meteorological concern--prediction of the wind field.

3. FORECASTING TECHNIQUES

In Section 2, we reviewed the processes or combination of processes causing the oil spill to expand in size. These processes are acting in concert in an oil spill; however, some are more dominant than the others in various stages of the spill. Forecasting techniques used are strongly dependent on application. The forecast is also scale-dependent in both space and time. We will discuss applications to the open ocean only.

If the spill is very near the coast or inside bays or estuaries, then various complexities are added. Forecast techniques for these areas will be developed later.

The present state of the art in oil spill modeling can deal only with prediction of the edge of the spill. Although we presented four major process groups, they have not been tied together. There is as yet no simple model that considers all the processes. Our understanding of the physical and chemical processes in oil spill is limited. At best we can only make qualitative predictions.

The first object of the forecast is to predict the size, and if possible the form, the petroleum spill will have after a specified interval of time. The immediate fate of oil can be determined in large part by the physical and chemical properties as well as the size of the spill. Thus sinking, solidification, or evaporation are processes which can be forecast if specific gravity, pour point, and boiling point, respectively, are known. In the event they are not given to the forecaster, some approximations must be made to complete the forecast procedure.

If the oil does not rapidly disperse from the point of origin, the second object of the forecast is the location of the spill, so that its future position can be predicted.

A. Size of the Spill

The size or weight of the oil spill can roughly indicate how severe the damage. We follow the work of Beynon (1973) and designate as small any spill less than 10 tons, medium spill from 10 to 500, and large any spill greater than 500 tons (1 ton = 4.11 x 10^6 cm^3; 1 bbl = 42 gal = 350 lb = 0.175 ton). A small spill may spread out so rapidly that the oil is too thin to be visible within a few hours. A large spill will remain in the environment for a longer period of time.

It is also expedient to define, as best as possible, at what point the oil has disappeared. Visibility is a useful criterion, especially if the spill is to be monitored by aircraft. Table 6 summarizes oil industry work quoted by Hornstein (1973), so a criterion of minimum average thickness for the oil spill to be visible as a dark film is 0.0001 cm.

During the early minutes of the spill, the petroleum will spread outward as it is expanded by natural forces, providing it neither evaporates immediately or sinks. Concurrently the several phenomena known collectively as weathering will be present to change the properties of the oil. We assume that spreading follows Fay's (1969) determination of the observed surface tension-viscous regime law in cgs units

$$\ell = 10(\sigma^2 t^3/\rho_w^2 \, \nu)^{1/4},$$

where: ℓ = radius of the slick,
 σ = surface tension,
 t = time,
 ρ_w = water density, and
 ν = water kinematic viscosity.

In Figs. 7 and 8 a plot of ℓ(km) vs. time (days) is useful to estimate the slick size for various values of surface tension σ(dyne/cm). Occasionally σ will be negative; when this happens, the slick will grow slowly when it reaches the beginning of the surface tension-viscous regime. ℓ can then be estimated by taking its value from Fig. 7 or 8 and σ to be 1 dyne/cm.

Evaporation proceeds regularly until most or all of the volatile fraction has been lost. The density will increase, so the spreading will be affected.

After several days, evaporation will have ceased, and the long-term weathering processes (oxidation, dissolution) will become dominant. These processes are so slow in comparison with evaporation, that they will be neglected for

the present. The residual oil remaining may become inert, or become an emulsion (mousse) if it has an asphaltic base, or form waxy lumps if it has a paraffin base (Beynon, 1973).

The following steps are recommended to ascertain the state of the spilled oil due to weathering and spreading:

1. (a) Determine the size (mass) of the spill and the nature of the petroleum from on-the-scene reports, Coast Guard reports, etc.

   (b) Determine the properties of the petroleum necessary for estimating the fate: density (ρ), pour point, and surface tension (σ). Tables 2 and 3 may be helpful.

   (c) Approximate the radius of the spill from Fig. 7 and 8 (if $\sigma <$ 0, use $\sigma = 1$), using the present age of the spill, or maximum radius from Table 8, whichever is smaller.

2. If the petroleum is gasoline, naptha, or light distillates (API density greater than 55 or ρ less than 0.760), it will evporate rapidly, especially for a small spill. If the distance to the coast is greater than 60 n mi, go to step 6. Otherwise, the trajectory must be computed--proceed to step 5.

3. Having established a minimum thickness of 0.0001 cm, use Table 7 to estimate the time (days) required to reach minimum thickness. If less than a few days, and oil is more than 60 n mi from the coast, spill will disperse rapidly--go to step 6. Otherwise, trajectory must be computed--go to step 5.

4. We assume that 70% of the volatile fraction will evaporate in 5 days. With this evaporation, the density will increase, and sinking may occur. If ρ is initially greater than 1.024, sinking will be likely, so proceed to step 6. Compute the new weight, W*, of oil from the initial weight, W, from Table 9.

   With the new weight, W*, compute time to reach minimum thickness from Table 6. If less than a few days, and oil is greater than 60 n mi from the coast go to step 6. Otherwise, go to step 5.

5. Oil will remain on the sea for a considerable time, so a trajectory forecast must be made.

6. Oil should disappear rapidly. No further forecast necessary.

B. Forecasting of Slick Advection by Currents

We consider four advective currents:

(1) Tidal current
(2) Semipermanent current
(3) Wave-induced current
(4) Wind drift

14

Tidal current is induced by tide. We know very little about tidal currents in the open ocean because of lack of measurements. It is also very hard to separate from the other components of current. In bays and estuaries, more measurements are available because tidal circulation is very important to keep the inland waters clean (tidal flushing). Another method of estimating tidal current is by solving the dynamical equations. This procedure is again difficult to do for the open ocean because the other terms in the equations are also not known. In bays and estuaries, computations of tidal circulations have been done with fair amount of success. For forecasting oil spill trajectory, tidal current can be added on when there is enough information available. If no data are available we simply neglect it. Neglect of tidal current is probably not serious on the open ocean.

By semipermanent current we mean the current system induced by the large scale atmospheric circulation system, e.g., the Gulf stream. There are some good climatological measurements of these currents available in publications. Bishop (1976) used the current data for the Gulf Stream to simulate oil spill trajectories. We can use the Navy Pilot Charts for a good approximation of the surface semipermanent current (Figs. 5 and 6).

There is an ongoing controversy among dynamical oceanographers concerning wave-induced motion. The addition of oil spill on the water surface makes the problem even more difficult. What we need is a complete understanding of wave interaction with the presence of viscous fluid (the oil) on the top layer. The mechanism for the process is not yet formulated. For forecasting, we will assume Stokes drift is applicable, therefore we can estimate the wave-induced motion from the wind speed. Applying the SMB-method of wave forecasting, we obtain 2% of the surface wind as the magnitude of the wave motion. If the sea is fully developed, 2% of the surface wind speed can be used. If sea is not fully developed, reduce the percentage wind factor accordingly. Prediction of sea condition should be made at intervals of no more than 6 hours. Shorter intervals are preferable.

The last component of motion we want to discuss is wind drift. This has the largest contribution to the oil spill movement. We believe it is most important and that meteorologists can contribute heavily in forecasting. Before we can predict the wind drift, we have to predict the wind field first. From the wind speed, we take 3% as the wind drift component. As for the direction of the drift, we can leave it the same as the wind especially on shallow continental shelves or turn it to the right looking in the direction of flow, as much as 15°. We can take the forecast wind from the closest coastal forecast station (Figs. 9 and 10) or by computing gradient winds from surface isobars.

In summary, the total advective speed of the oil, OS, is

$$OS = TC + PC + WI + WD,$$

where   TC = tidal current,
        PC = semipermanent current,
        WI = wave induced transport, and
        WD = wind drift current.

If we have little information on tidal current and the climatology of semi-permanent current is not available, then we are left with just the wave induced current and the wind drift current. Since both WI and WD can be expressed in terms of the surface wind speed V, then the total oil speed is

$$OS = WI + WD$$
$$= 0.02V + 0.03V = 0.05V ,$$

i.e., the simplest expression for oil speed is 5% of the surface wind speed. PC, if known, can be added.

In forecasting oil spill trajectories, we can consider the center of mass of the spill or the boundary of the spill and advect accordingly. If the spill is small, considering the center of mass may be adequate. We advect by multiplying the speed, OS, by the time increment (3 hours) to get the incremental position change of the mass center. However, if the areal coverage of the spill is big, then the horizontal gradient of the wind may be so significant that it becomes necessary to consider more mass points (i.e. near one slick boundary). After properly advecting the spill, we can apply the spreading to get the total extent. A diagram of a typical small slick is shown in Fig. 11. It shows the outline of the slick and subsequent break-up into patches. Note the dense patches which may tend to remain long after the thinner areas have dissipated.

Let us consider an instantaneous point scource, e.g., a tanker blow-up. We will compute the observed wind field, then advect the oil spill according to the prediction in time. Forecasts should be made at a minimum of every 3 hours. Then we will construct trajectories for up to 36 hours, for example. It is preferable to use shorter time intervals in forecast computations so that the linear trajectory does not have to be extrapolated to longer time periods. After the advection is made, the shape of the spill can be modified according to the spreading. Some qualitative estimates of the weathering processes can also be included for determining the concentration.

4. SUMMARY

We are aware of the oil spill contamination problems. We want to have a means of combating oil spills to prevent the resultant damage and, if possible, to recover the oil. At this stage we don't have the tools and we don't understand the complete processes of oil spill behavior. However, the National Weather Service and other government offices must deal with the problem now.

We discussed four major classification of processes affecting oil spill. These are weathering, spreading, diffusion, and transport. The processes are interrelated; however, previous studies have only dealt with them independently.

During the early part of the spill, spreading is dominant. We can use Fay's (1969) theory and estimate the growth of the spill, and correct for some weathering processes, e.g., evaporation and sedimentation. In the future, we will add turbulent diffusion to the spreading.

A day or two after the spill, depending on the volume of the spill, the advective process becomes more significant in the increase of the spill size. Here we have four components in the procedure. These are (1) tidal currents from charts, (2) basic current data from charts based on semi-permanent currents, (3) wave induced current, and (4) wind drift. A simple vector addition of these four currents will give the net surface current. The slick can then be advected in the direction of this current a distance equal to the product of the speed of the current and the time of the calculation interval.

This method of estimating spill size and position with time is useful for preparing a forecast of the fate of the oil. An in-depth prediction of oil behavior is beyond the scope of this Note.

REFERENCES

Beynon, L. R., 1973: Codes of practice for dealing with oil spills at sea and on shore: a European view. _Proceedings of Joint Conference on Prevention Control of Oil Spills_, Washington, D.C., American Petroleum Institute, 617-626.

Bishop, J. M., 1976: Surface currents in the New York Bight as related to a simple oil trajectory model. _Preprints, Conference on Coastal Meteorology_, Virginia Beach, American Meteorological Society, 98-101.

Bretschneider, C. L., 1966: Wave generation by wind, deep and shallow water. _Estuary and Coastline Hydrodynamics_, Ippen, A.T. (Ed.) McGraw-Hill, Chapter 3.

Curl, H. Jr., and K. O'Donnell, 1977: Chemical and physical properties of refined petroleum products. _NOAA Technical Memorandum_ ERL MESA-17, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 31 pp.

Fallah, M. H., and R. M. Stark, 1976: Literature review: Movement of spilled oil at sea. _MTS Journal_, (10) No. 1, 3-18.

Farrington, J. W., 1977: The biogeochemistry of oil in the ocean. _Oceanus_, 20, 5-14.

Fay, J. A., 1969: The spread of oil slicks on a calm sea. _Oil on the Sea_, Hoult, D. P. (Ed.), Plenum Press, 53-63.

_____, 1971: Physical processes in the spread of oil on a water surface. _Proceedings of a Joint Conference on Prevention and Control of Oil Spills_, Washington, D.C., American Petroleum Institute, 463-467.

Frankenfeld, J. W., 1973: Factors governing the fate of oil at sea; variations in the amounts and types of dissolved or dispersed materials during the weathering process. <u>Proceedings of the Joint Conference on Prevention and Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 485-495.

Hornstein, B., 1973: The visibility of oil-water discharges. <u>Proceedings of Joint Conference on Prevention Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 91-99.

Jeffery, P. G., 1973: Large-scale experiments on the spreading of oil at sea and its disappearance by natural factors. <u>Proceedings of the Joint Conference on Prevention and Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 469-474.

Kreider, R. E., 1971: Identification of oil leaks and spills. <u>Proceedings of the Joint Conference on Prevention and Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 119-124.

Leotta, J. V., and A. J. Taylor, 1973: Coast Guard transfer monitoring program. <u>Proceedings of the Joint Conference on Prevention and Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 45-51.

Oceanographic Institute of Washington, 1977: Modeling methods for predicting oil spill movement, A report to the Oceanograhic Commission of Washington, 99 pp.

Pierson, W. J., and L. Moskowitz, 1964: A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii. <u>J. Geophys. Res.</u>, 69, 5181-5190.

Schwartzberg, H. G., 1971: The movement of oil spills. <u>Proceedings of Joint Conference on Prevention and Control of Oil Spills</u>, Washington, D.C., American Petroleum Institute, 489-494.

Stolzenbach, K. D., O. S. Madsen, E. E. Adams, A. M. Pollock, and C. K. Cooper, 1977: A review and evaluation of basic techniques for predicting the behavior of surface oil slicks. Report No. 222, MIT R. M. Parsons Laboratory for Water Resources and Hydrodynamics, A Sea Grant Report to EDS-NOAA, 319 pp.

APPENDIX

PRACTICAL METHODS FOR FORECASTING
THE FATE OF SPILLED OIL

This Appendix is for the operational forecaster, and it summarizes information in the main part of the Note. The Appendix will thus serve as a ready reference for the forecaster and the Note can be referred to when detailed information is required.

We divide forecasting an oil spill trajectory into two stages: the weathering and spreading stage, and the advection stage.

Here is the step-by-step procedure to forecast the oil spill trajectory.

A. Forecast of Oil Weathering and Spreading

The following steps are recommended to ascertain the state of the spilled oil due to weathering and spreading:

1. (a) Determine the size (mass) of the spill and the nature of the petroleum from the on-scene reports, Coast Guard reports, etc.

    (b) Determine the properties of the petroleum necessary for estimating the fate: density (ρ), and surface tension (σ). Tables 3 and 4 may be helpful.

    (c) Approximate the radius of the spill from (a) Fig. 7 or 8 (if $\sigma < 0$, use $\sigma = 1$), using the present age of the spill, or (b) the maximum radius from Table 8, whichever is smaller.

2. If the petroleum is gasoline, naptha, or light distillates (API greater than 55 or ρ less than 0.760), it will evaporate rapidly, especially for a small spill. If the distance to the coast is greater than 60 n. mi., go to step 6. Otherwise, the trajectory must be computed—proceed to step 5.

3. Having established a minimum thickness of 0.0001 cm, use Table 7 to find the time (days) required to reach minimum thickness. If the time is less than a few days and the oil is more than 60 n. mi. from the coast, the spill will disperse rapidly—go to step 6. Otherwise the trajectory must be computed—go to step 5.

4. We assume that 70% of the volatile fraction will evaporate in 5 days. With this evaporation, the density will increase, and sinking may occur. If ρ is initially greater than 1.024, sinking will be likely, so proceed to step 6. Compute the new weight, W*, of oil from the initial weight, W from Table 9.

5. Oil will remain on the sea for a considerable time, so a trajectory forecast must be made. Go to B.

6. Oil should disappear rapidly. No further forecast necessary.

B. Forecasting of Slick Advection

In forecasting oil spill speed vectors, we consider four components:

1. Tidal current (TC)
2. Semipermanent current (PC)
3. Wave induced advection (WI)
4. Wind drift (WD)

Here are the steps in determing the oil velocity vector.

1. Determine tidal current and semipermanent current from charts or tables, when available. Otherwise, TC and PC can be neglected. Note that water currents are referenced by the direction toward which they flow.

2. Determine the forecast mean wind speed and direction for the forecast interval. The forecast interval should not be more than 3 hours.

3. Compute the wave induced advection, WI. Determine if the sea is fully developed from the sea state report and other forecast considerations. If the sea is fully developed, WI=2% of the wind speed. If not, then WI=fraction of sea development x 2% x wind speed. The direction of wave-induced transport is the same as the direction of the wind.

4. Determine the wind drift component

    WD = 3% of the wind speed.

    Determine the direction of the wind drift in the following manner:

    a. In shallow water, (depth is 50 ft or less) use the same direction as the wind;

    b. In intermediate depth, (50 ft < depth < 300 ft) the direction of the drift is 10° to the right of the wind direction.

    c. In deep water, (depth greater than 300 ft) the drift direction is 15° to the right of the wind direction.

5. In summary, the total transport of the oil,

    OS = TC + PC + WI + WD.

All the components of current are vectors, thus the addition must be done vectorially.

Let us illustrate by an example. Fig. 12 is the graphical illustration of the procedure.

(1)   TC = 0.1 kt to the west (180°)   [Here we use mathematical coordinates, where East is 0°]

　　　 PC = 0.1 kt to the south (270°)

(2)   Wind speed/direction = 30 kt/315° [This is meteorological direction, where North is 360°]

(3)   Sea is 80% developed,

　　　 WI = 0.8 x 0.02 x 30.

　　　　 = 0.48 kt to the SE (135°)

(4)   Assume spill is in deep water (greater than 300 ft)

　　　 WD = 0.03 x 30.

　　　　 = 0.9 kt to 150°

(5)   Compute the vector sum

　　(a)   Find the summation along east latitude

$$\Sigma X = + 0.1 \cos 180° + 0.1 \cos 270°$$
$$+ 0.48 \cos 45° + 0.9 \cos 60°$$
$$= -0.1 + 0. + 0.34 + 0.45$$
$$= 0.69 \text{ kt to the E } (0°)$$

　　(b)   Find summation along north longitude

$$\Sigma Y = 0.1 \sin 180° + 0.1 \sin 270°$$
$$+ 0.48 \sin 215° + 0.9 \sin 300°$$
$$= 0. + (-0.1) + (-0.34) + (-0.78)$$
$$= -1.22 \text{ kt to the S } (270°)$$
$$OS = (\Sigma X)^2 + (\Sigma Y)^2 = 0.69^2 + 1.22^2$$
$$= 1.40 \text{ kt}$$

$$\text{Direction} = \arctan \frac{\Sigma\ Y}{\Sigma\ X} = \arctan \frac{-1.22}{0.69}$$

$$= -60.5° \text{ or } 150.5° \text{ meteorological direction}$$

between SE and SSE.

After 3 hours, the oil would have moved a little over 4 n mi (1.4 x 3 = 4.2 n mi). Then a new OS should be computed. The procedure can be done graphically as shown in Fig. 12.

Let us now consider that after 3 hours,

(a) the wind has become westerly and has slowed down to 20 kt,

(b) the tidal current has reversed,

(c) the sea is 50% developed, and

(d) the oil is now in shallow water.

The graphical determination of OS is shown in Fig. 13. It is approximately .87 kt moving toward 95° (east and slightly south).

Table 1. Structures of some common hydrocarbon compounds.

Paraffin (Saturated Hydrocarbon) Series

Name	Structure	Composition
Methane	H H C H H	CH_4
Ethane	H H H C C H H H	C_2H_6
Propane	H H H H C C C H H H H	C_3H_8
Butane	H H H H H C C C C H H H H H	C_4H_{10}
Pentane	etc.	C_5H_{12}
Hexane		C_6H_{14}
Heptane		C_7H_{16}
Octane		C_8H_{18}
Nonane		C_9H_{20}

Cyclic Petroleum Molecules
(From Frankenfeld, 1973)

	Molecular Formula	Typical Structure	Typical Name
1.	C_nH_{2n}		Cycloparaffins
2.	C_nH_{2n-2}		Cycloolefins
3.	C_nH_{2n-4}		Cyclodiolefins
4.	C_nH_{2n-6}		Alkyl Benzenes
5.	C_nH_{2n-8}		Indanes
6.	C_nH_{2n-10}		Indenes or Dinapthenobenzenes
7.	C_nH_{2n-12}		Naphthalenes
8.	C_nH_{2n-14}		Acenaphthenes
9.	C_nH_{2n-16}		Fluorenes
10.	C_nH_{2n-18}		Phenanthrenes
11.	C_nH_{2n-20}		Naphthenophenanthrenes
12.	C_nH_{2n-22}		Pyrenes

Table 2. Boiling Range of Petroleum Distillate Fractions.

Fraction	No. of Carbon Atoms	Approximate Boiling Range (°C)
Natural Gas	1-4	20
Napthas	5-7	20-100
Gasoline	6-12	40-200
Kerosene	12-15	175-275
Fuel Oil	15 and up	250-400
Lubricating Oil and Residuum	19 and up	Above 400

Table 3. Properties of Common Petroleum Products.

	Category	Specific Gravity	Viscosity Centistokes	Remarks
A1	Napthas, Light Gasoline	.6–.7	.5–2	100% evaporation within a few hours
A2	Gasolines	.6–.8	.5–2	Up to 100% evaporates within one day
A3	Kerosene	.8	1–2	100% evaporates within 1 to 10 days
A4	Fuel Oil			
	JP-5 Turbine	.811	1.59	
	Navy Distillate	.844	2.8	
	No. 2	.851	2.5	Pour Point, –15°F
	Marine Diesel	.853	3.9	
	No. 4	.905	26.4	
	No. 5	.925	74.9	
	Navy Special	.964	115	
	No. 6 or Bunker C	.942–1.05	2800 4250	Pour Point, 65°F
A5	Residuum			
	Lubricating Oil	.91–.93	20–200	
	Residual fuel	.95–.97	500–1000	
	Residue	.90–1.1	500–10,000	
B1	Light Crude	.80–.85	1–5	Pour Point, 10°F
B2	Medium	.85–.90	5–15	
	Prudhoe Bay	.895	6	Pour Point, 15°F
	Sadlerochit	.89	23–50	
	N. Calif. (Santa Barbara)	.88–.91	10–15	High Asphalt
	S. Calif. (Long Beach)	.85–.87	7	High Wax
B3	Heavy	.90–.95	15–100	Pour Point, 15°F
B4	Very Heavy	>.95	>100	

Table 4. Specification of crude oils, (from Benyon, 1973).

Category	Country	Type	Loading terminal	Density d15/4	Viscosity cSt 100°F	Pour point °F	Pour point °F residue 200°C	Distillation ASTM °C 20%	30%	40%
1. High wax content	Gabon	Gamba	Sette Cama	0.872	28.5	86	not	269	—	—
	Libya	Es Sider	Es Sider	0.841	5.7	48		152	200	253
	Libya	Libyan high pour	Ras Lanuf	0.846	12.7	70	relevant	187	244	—
	Libya	Sarir	Marra el Alariga	0.847	11.9	75		178	242	292
	Nigeria	Nigerian light	Bonny	0.844	3.59	70		157	203	246
	Egypt	El Morgan	Ras Shukhair	0.874	13.0	55		185	240	298
2. Moderate wax content	Qatar	Quatar	Umm Said	0.814	2.55	0	40/50	133	170	211
	Qatar	Quatar marine	Halul island	0.839	4.1	10	40	146	187	233
	USSR	Muhanovo		0.835	4.18	32	55	149	192	236
	USSR	Romashkinskaja	Novonossisk	0.859	6.9	25	40/45	159	210	265
	Algeria	Zarzaitine	La Skirra	0.816	4.56	5	40	143	183	234
	Libya	Brega	Marsa el Brega	0.824	3.6	0	45	142	186	237
	Libya	Zueitina	Zueitina	0.808	2.9	10	45	129	159	194
	Iran	Iranian light	Kharg island	0.854	6.6	25	50	157	206	257
	Iran	Iranian heavy	Kharg island	0.869	10.2	19	45	158	213	270
	Iraq	Northern Iraq	Tripolis/Banias	0.845	4.61	5	50	142	184	240
	Abu Dhabi	Abu Dhabi	Djebel Dhanna	0.830	3.42	0	40/45	143	181	223
	Abu Dhabi	Abu Dhabi-Zakum	Das island	0.825	2.9	5	45	124	166	212
	Abu Dhabi	Abu Dhabi-Umm Shaif	Das island	0.840	3.8	5	40/50	134	178	218
	Norway	Ekofisk		0.847	4.5	25	50	140	200	240
3. Low wax content	Algeria	Hassi Messaoud	Bougie	0.802	1.95	<−22	<40	118	148	181
	Algeria	Arzew	Arzew	0.809	2.4	<−22	<40	128	163	197
	Nigeria	Nigerian medium	Bonny	0.907	14.1	<−22	<40	251	275	300
	Nigeria	Nigerian export	Forcados	0.872	5.8	<−22	<40	189	228	268
	Kuwait	Kuwait	Mina al Aghmari	0.869	10.6	1	<40	164	218	282
	Saudi Arabia	Arabian light	Ras Tanura/Sidon	0.851	5.45	<−22	<40	159	205	258
	Saudi Arabia	Arabian medium	Ras Tanura/Sidon	0.874	9.7	5	<40	169	225	283
	Saudi Arabia	Arabian heavy	Ras Tanura/Sidon	0.887	19.1		<40	200	257	—
	Neutral Zone	Kafji	Ras el Kafji	0.888	18.1	<−22	<40	185	254	
	Iraq	Southern Iraq	Fao/Hohr al Amaya	0.847	5.78	9	<40	165	210	263
	Oman	Oman	Mina al Fahal	0.861	8.7	−17	<40	175	233	283
	Venezuela	Tia Juana medium	Puerto Miranda	0.900	16.8	<−22	<40	224	285	—
4. Very low wax highly viscous	Venezuela	Bacchaquero	Puerto Miranda	0.978	1280	5/19	—	—	—	—
	Venezuela	Tia Juana pes	Puerto Miranda	0.980	2983	27	—	—	—	—

Table 5. Petroleum products moved by water per month in the Seattle, WA region, (from Leotta and Taylor, 1973).

I.	**GASOLINE**		
	A.	Aviation Gas (two grades 100-130 and 115-145)	27,000 BBL
	B.	Regular and Premium grade Gasoline	456,715 BBL
II.	**KEROSENE**		
	A.	Jet-A Fuel	205,000
	B.	J.P.-4	335,000
	C.	J.P.-5	63,000
	D.	Kerosene	1,000
III.	**DIESEL**		
	A.	Diesel	178,000
	B.	Heating Fuel #1 (Stove Oil)	320,000
	C.	Heating Fuel #2 (Furnace Oil)	270,000
IV.	**HEAVY FUEL**		
	A.	Light Fuel Oil (P.S. 300, Bunker #5 is same thing)	155,000
	B.	Standard Fuel Oil (Bunker "C" & #6, P.S. 400 same thing)	328,000
V.	**CRUDE OILS**		
	A.	Light-end Crude	70,000
	B.	Full Body Crude	265,000
	C.	Unfinished Naptha Crude	18,000
	D.	Asphalt Crude	60,000
	E.	Asphalt	15,000
VI.	**OTHERS**		
	A.	Distillates (all grades)	30,000
	B.	Solvent – 345	1,600
	C.	Certex (wood treatment)	4,000
	D.	Starter Solvent	4,000
	E.	Lube Oils	8,000
	F.	Medium Aeromatic Oil (wood treatment)	800
	G.	Refineries (total all products)	1,300,000
VII.	**TOTAL**		4,100,715

Table 6. Oil Film Thickness vs. Visible Color (from Hornstein, 1973).

Appearance	Film Thickness				
	in.	cm	μ	nm	Angstrom
Barely visible under most favorable light conditions	1.5×10^{-6}	3.8×10^{-6}	3.8×10^{-2}	3.8×10^{1}	3.8×10^{2}
Visible as a silvery sheen on surface	3×10^{-6}	7.6×10^{-6}	7.6×10^{-2}	7.6×10^{1}	7.6×10^{2}
First trace of color may be observed	6×10^{-6}	1.5×10^{-5}	1.5×10^{-1}	1.5×10^{2}	1.5×10^{3}
Bright bands of color are visible	12×10^{-6}	3.1×10^{-5}	3.1×10^{-1}	3.1×10^{2}	3.1×10^{3}
Colors begin to turn dull	40×10^{-6}	1.0×10^{-4}	1.0	1.0×10^{3}	1.0×10^{4}
Colors are much darker	80×10^{-6}	2.0×10^{-4}	2.0	2.0×10^{3}	2.0×10^{4}

Note: 1 nanometer (nm) = 1×10^{-9} meter = 1×10^{-7} cm = 1×10^{-3} micron (μ)

Table 7. Days to reach average thickness of 0.000010 cm.

Weight (Tons)	Sigma (Dyne/cm) 1.	5.	10.	15.	20.	30.
1.	7.3	2.5	1.6	1.2	1.0	0.8
3.	15.2	5.2	3.3	2.5	2.1	1.6
10.	33.9	11.6	7.3	5.6	4.6	3.5
30.	70.5	24.1	15.2	11.6	9.6	7.3
100.	157.3	53.8	33.9	25.9	21.3	16.3
300.	327.2	111.9	70.5	53.8	44.4	33.9
1000	730.1	249.7	157.3	120.0	99.1	75.6
3000	1518.7	519.4	327.2	249.7	206.1	157.3
10000.	3388.9	1159.0	730.1	557.2	459.9	351.0
30000.	7049.3	2410.8	1518.7	1159.0	956.7	730.1

Days to reach average thickness of 0.000100 cm.

Weight (Tons)	1.	5.	10.	15.	20.	30.
1.	1.6	0.5	0.3	0.3	0.2	0.2
3.	3.3	1.1	0.7	0.5	0.4	0.3
10.	7.3	2.5	1.6	1.2	1.0	0.8
30	15.2	5.2	3.3	2.5	2.1	1.6
100.	33.9	11.6	7.3	5.6	4.6	3.5
300.	70.5	24.1	15.2	11.6	9.6	7.3
1000	157.3	53.8	33.9	25.9	21.3	16.3
3000	327.2	111.9	70.5	53.8	44.4	33.9
10000.	730.1	249.7	157.3	120.0	99.1	75.6
30000.	1518.7	519.4	327.2	249.7	206.1	157.3

Table 8. Maximum radius of oil slick spread by weight.

Weight (tons)	Maximum Radius (km)
1	0.3
3	0.4
10	0.7
30	1.1
100	1.7
300	2.6
1000	4.0
3000	6.1
10000	9.5
30000	14.4

1 ton	= 2000 lbs.
	= 6.3 barrels
	= 267 gallons

1 gallon	= 7.5 lbs.

1 barrel	= 42 gallons
	= 315 lbs.

Table 9. Ratio of final weight of oil to initial weight after five days of evaporation.

Specific Gravity	Ratio of Final to Initial Weight
≤ 0.76	0.00
0.78	0.37
0.80	0.44
0.82	0.47
0.84	0.51
0.86	0.68
0.88	0.74
0.90	0.79
0.92	0.84
0.94	0.89
0.96	0.92
0.98	0.94
≥ 1.00	0.97
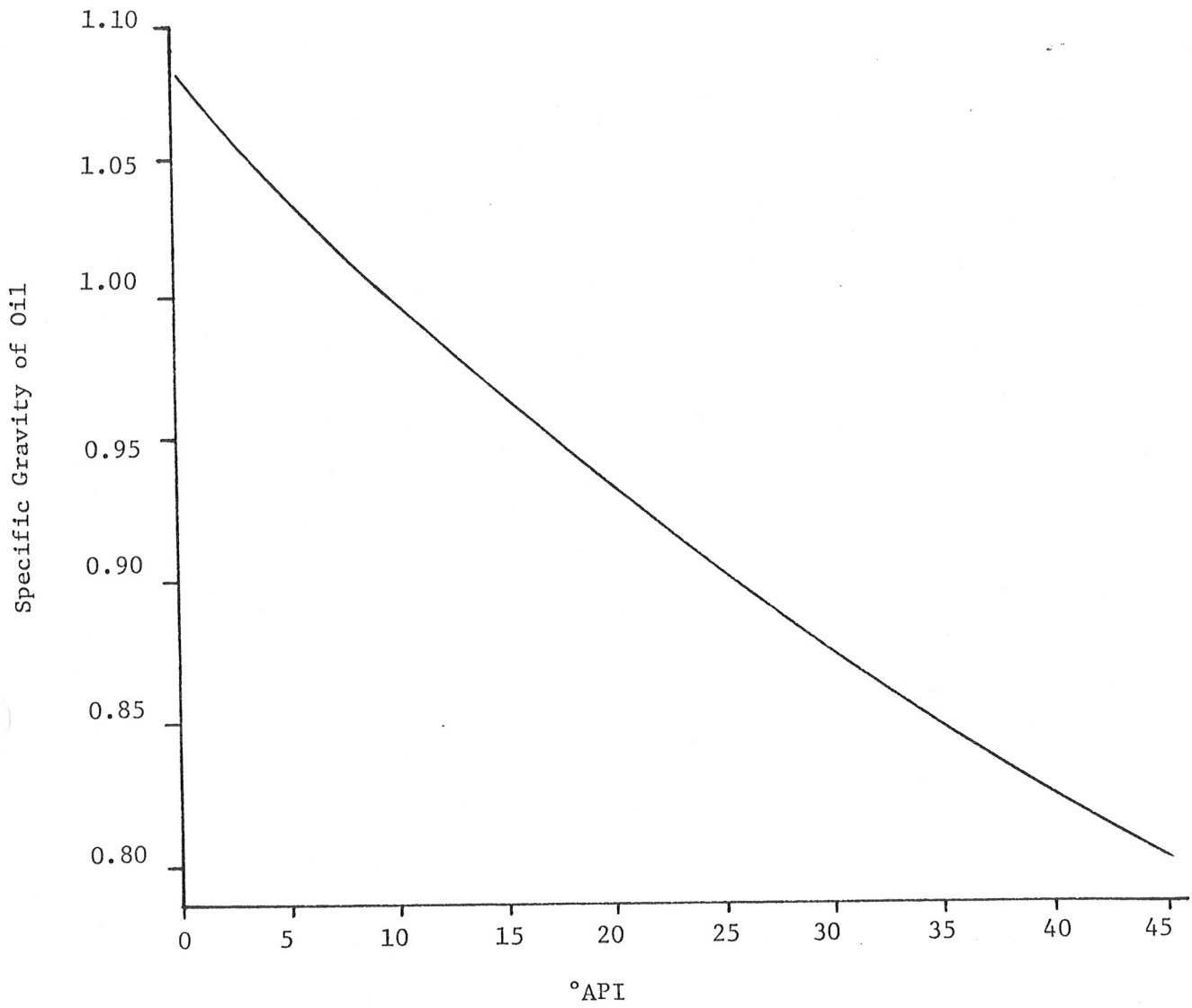
Figure 1. Relationships between oil specific gravity (ratio of oil density to sea water density) and American Petroleum Institute (API) density degrees.
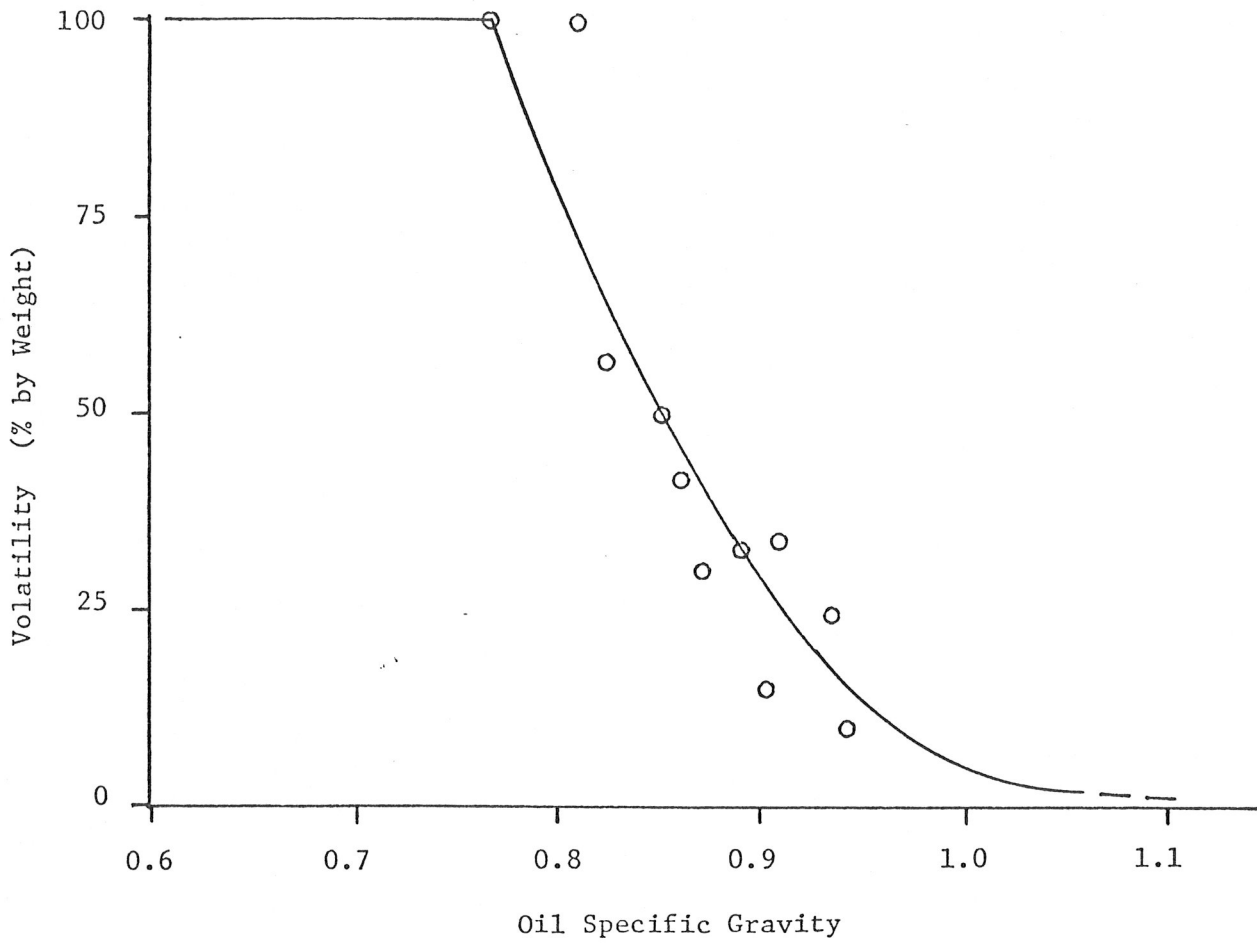
Figure 2. Graph of volatility (volatile fraction) of oil versus its specific gravity.
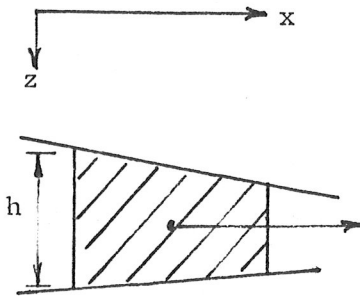
Gravity Force

$$(\rho_w - \rho_o) \ gh \ \frac{\partial h}{\partial x}$$
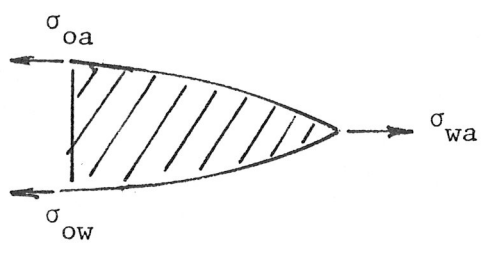
Surface Tension Force

$$\sigma = \sigma_{wa} - (\sigma_{oa} - \sigma_{ow})$$
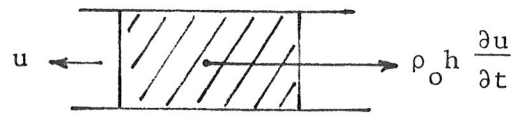
Inertia Force

$$\rho_o h \ \frac{\partial u}{\partial t}$$
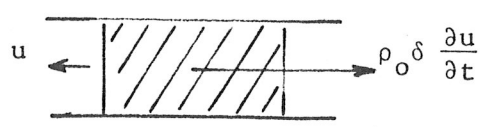
Viscous Friction Force

$$\rho_o \delta \ \frac{\partial u}{\partial t}$$

Figure 3. A schematic representation of the spreading forces.
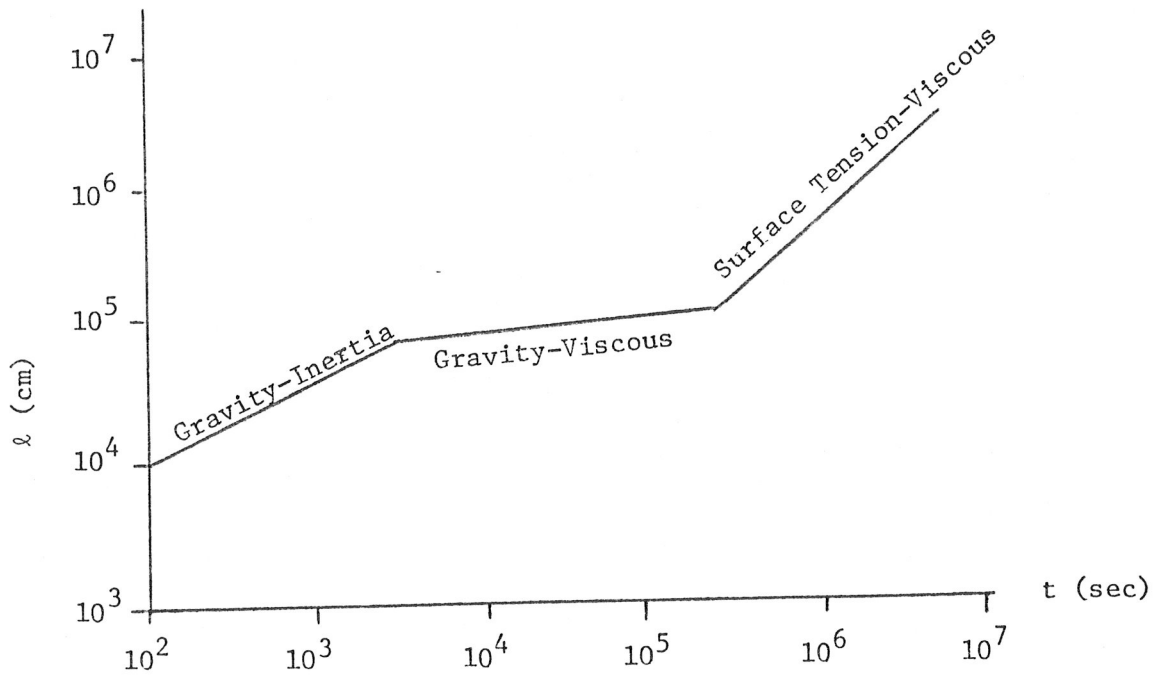
Figure 4. The size (diameter) of an oil slick as a function of time for a 10,000 ton spill, from Fay (1969).
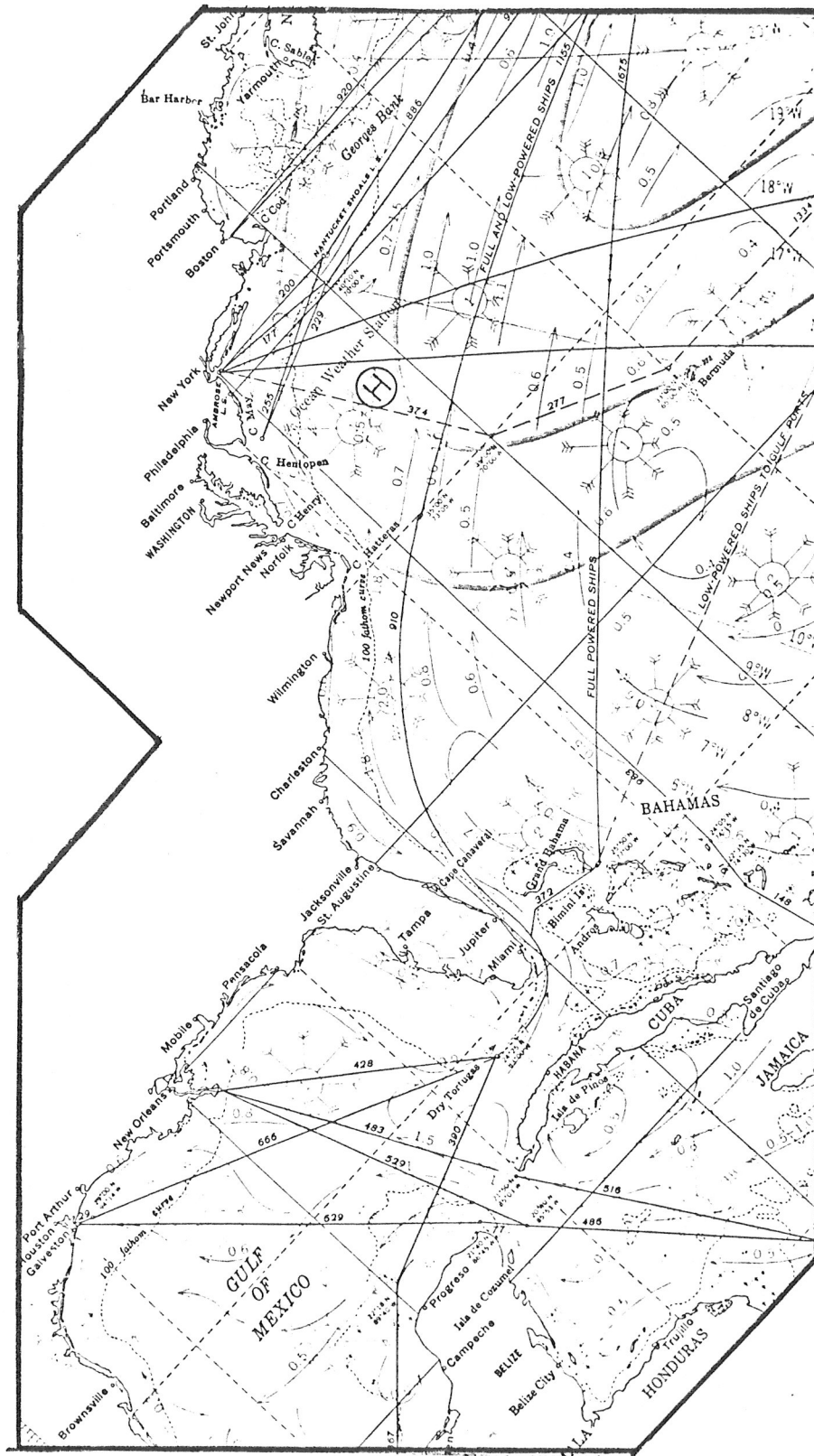
Figure 5. East coast wind roses and semipermanent surface currents for January (n mi per day) as shown in the U.S. Navy Pilot Charts of the Defense Mapping Agency, Hydrographic Office, Washington, D.C.
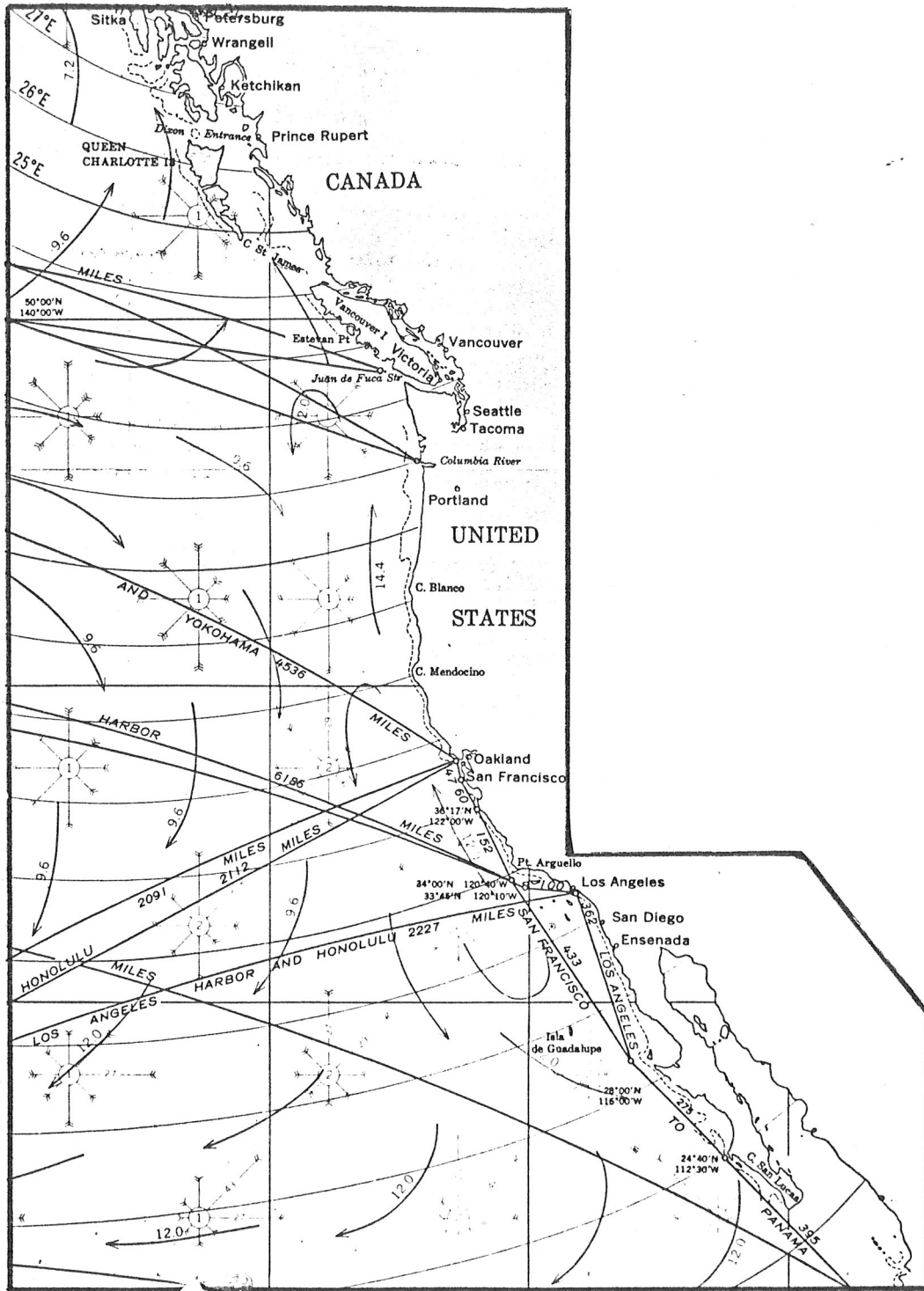
Figure 6. West Coast wind roses and semipermanent surface currents for January (n mi per day) as shown in the U.S. Navy Pilot Charts of the Defense Mapping Agency, Hydrographic Office, Washington, D.C.
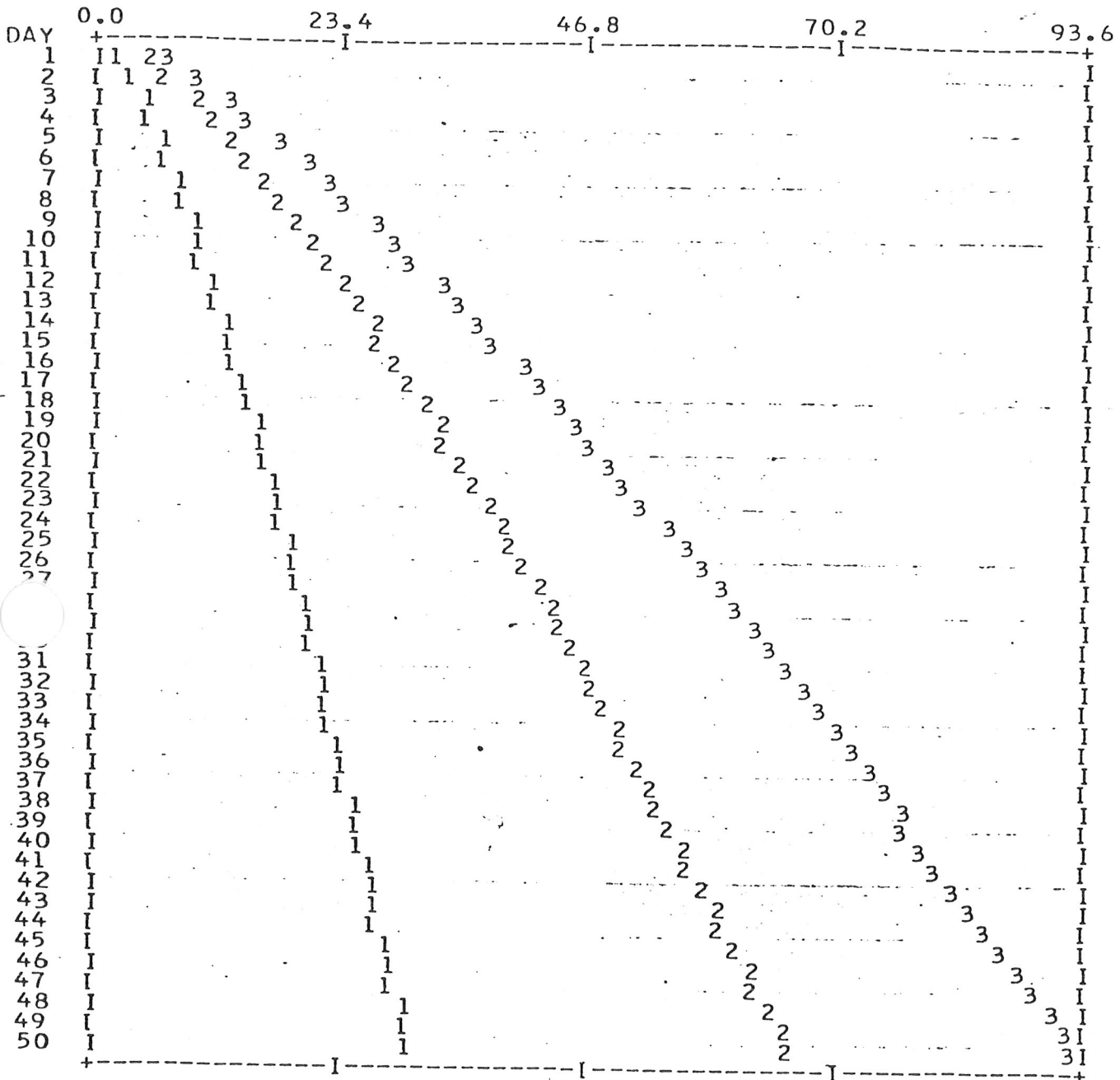
Figure 7. Graph of oil slick diameter vs time for calm sea spread, for various values of the spreading force, sigma (dyne/cm).

Figure 8. Same as Fig. 6 except for different values of sigma.

LOCATION OF FORECAST POINTS
(LIGHT SHIPS) USED IN THE
DEVELOPMENT OF OFFSHORE
WIND FORECASTS
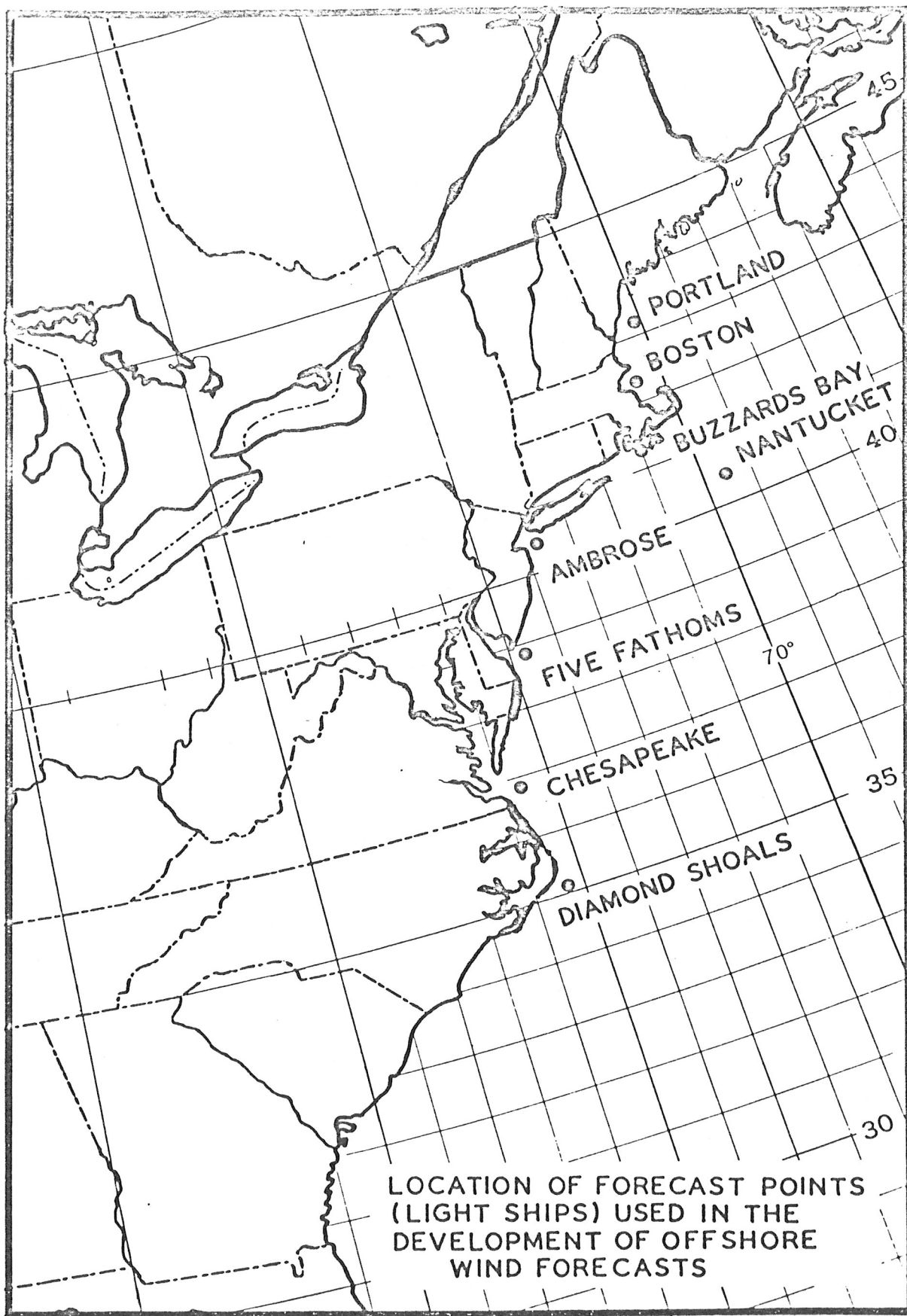
Figure 9. NWS coastal wind forecast locations on the east coast of the U.S.

QUILLAYUTE

COLUMBIA RIVER

45

NEWPORT

BLUNTS REEF

40°

SAN FRANCISCO

35°

PIEDRAS BLANCAS

130

120

FORECAST POINTS FOR WEST COAST
COASTAL WIND FORECASTS
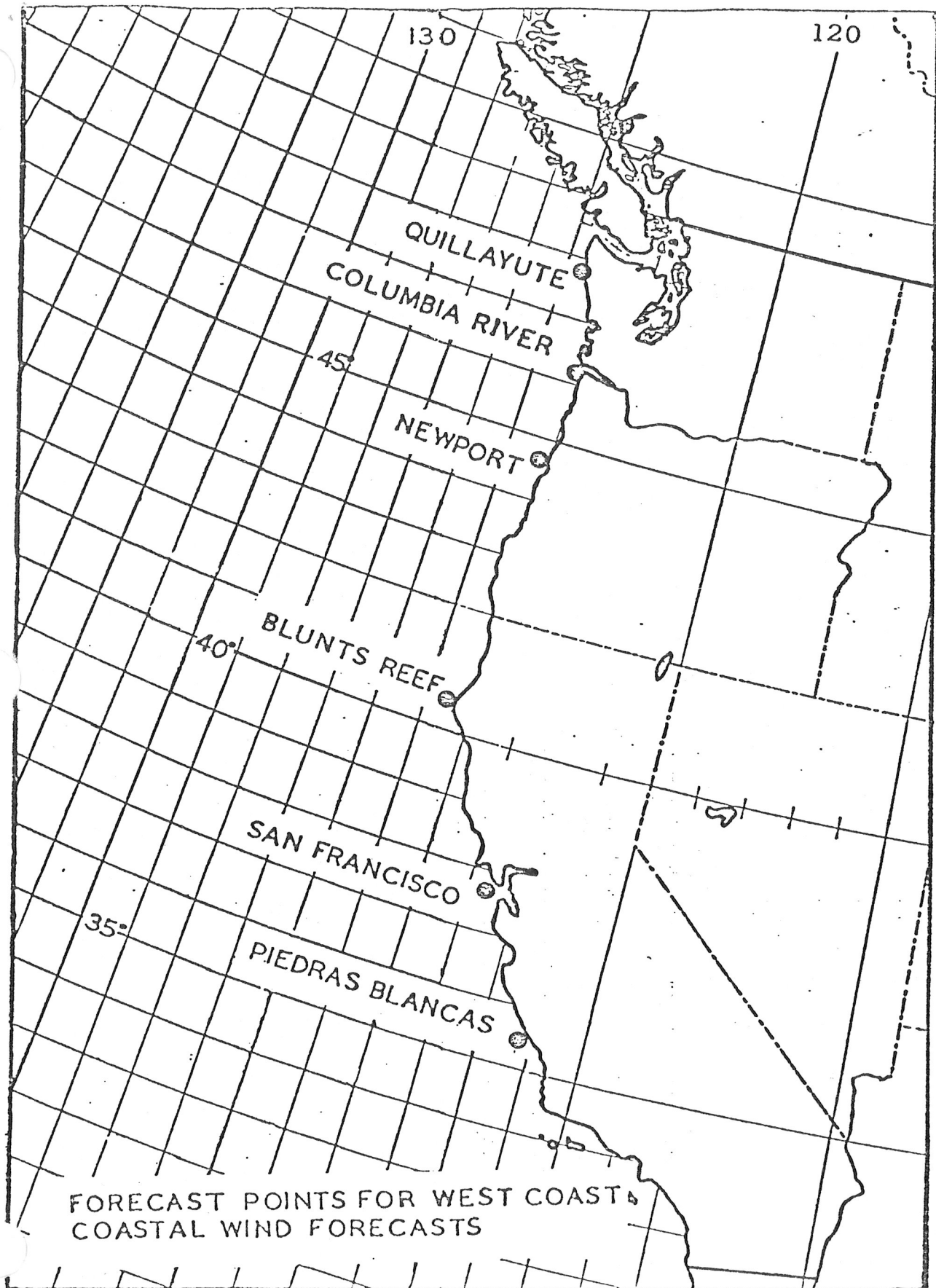
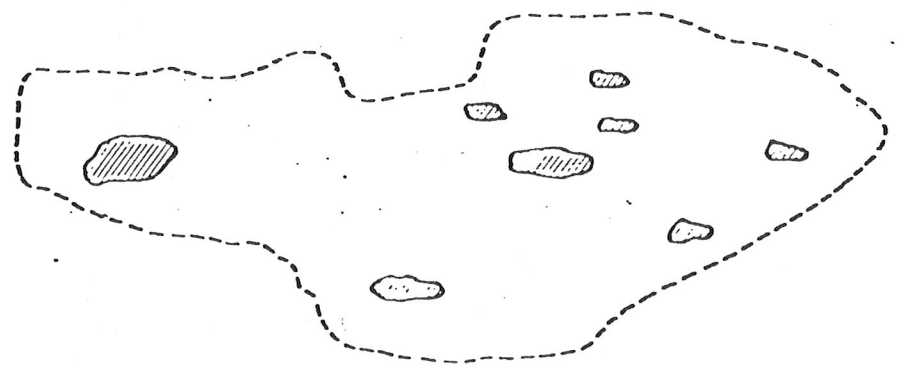Figure 10. NWS coastal wind forecast locations on the west coast of the U.S.
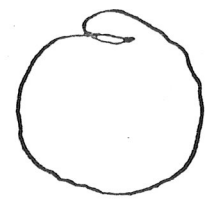
O min   4 min   22 min   42 min   2h
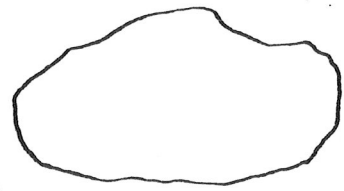
7h   2 days
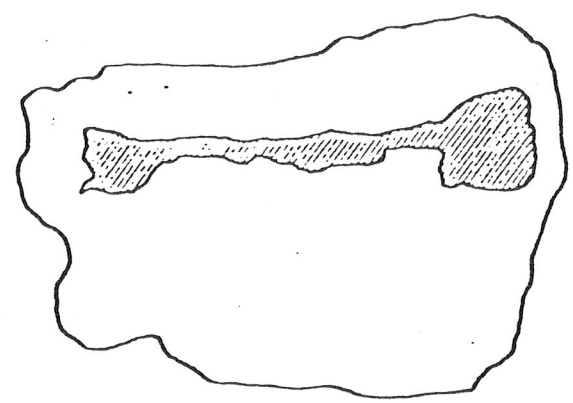
2½ days

PATCHES OF
THICKER OIL

4 days

Figure 11. A series of diagrams showing the outline development and
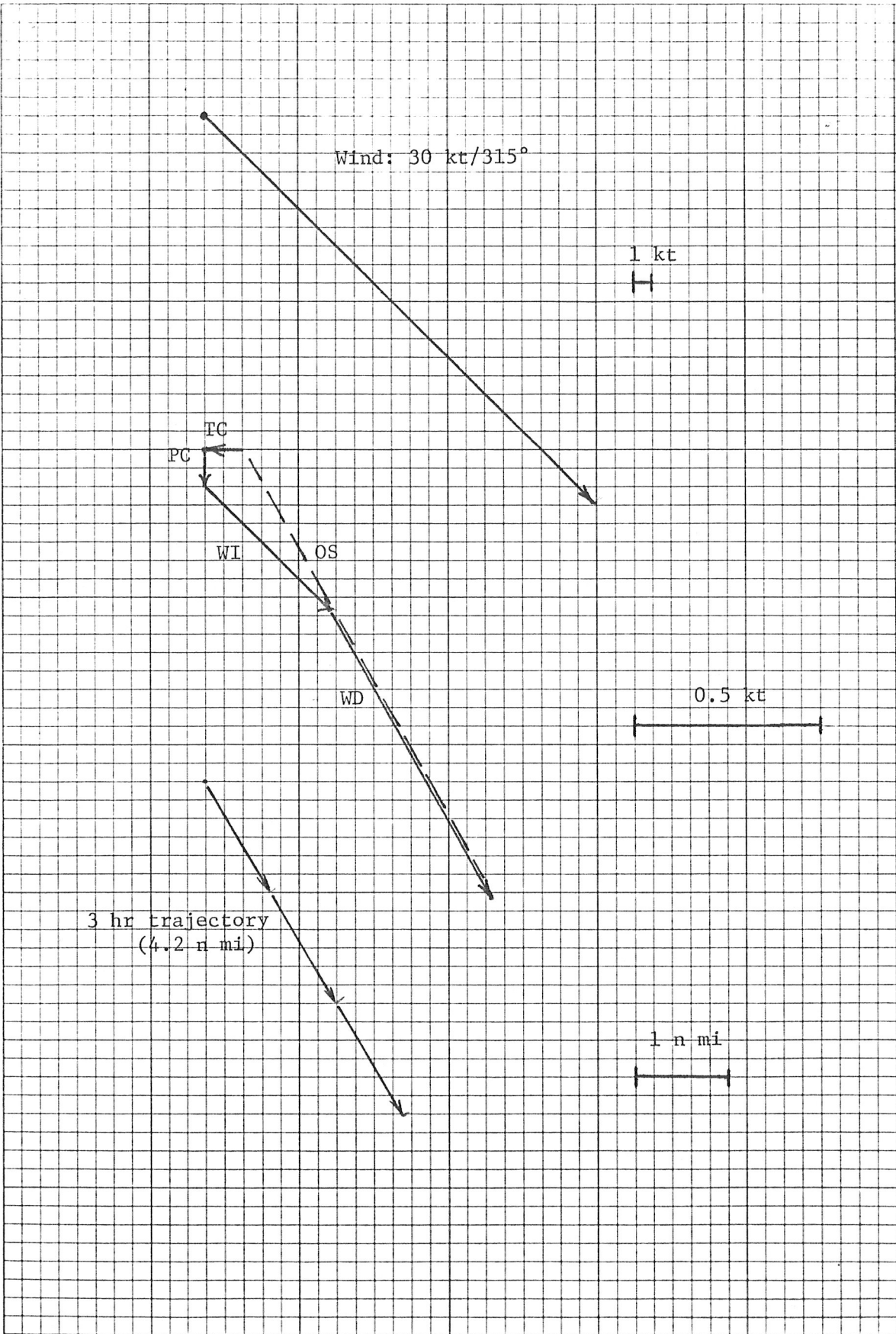subsequent break-up of an oil slick (from Jeffery, 1973).

42

Figure 12. Sample graphical calculation of an oil spill trajectory with a 30 kt wind, a 0.5 kt tidal current, a 0.5 kt semipermanent current, and an 80% developed sea (see Appendix).
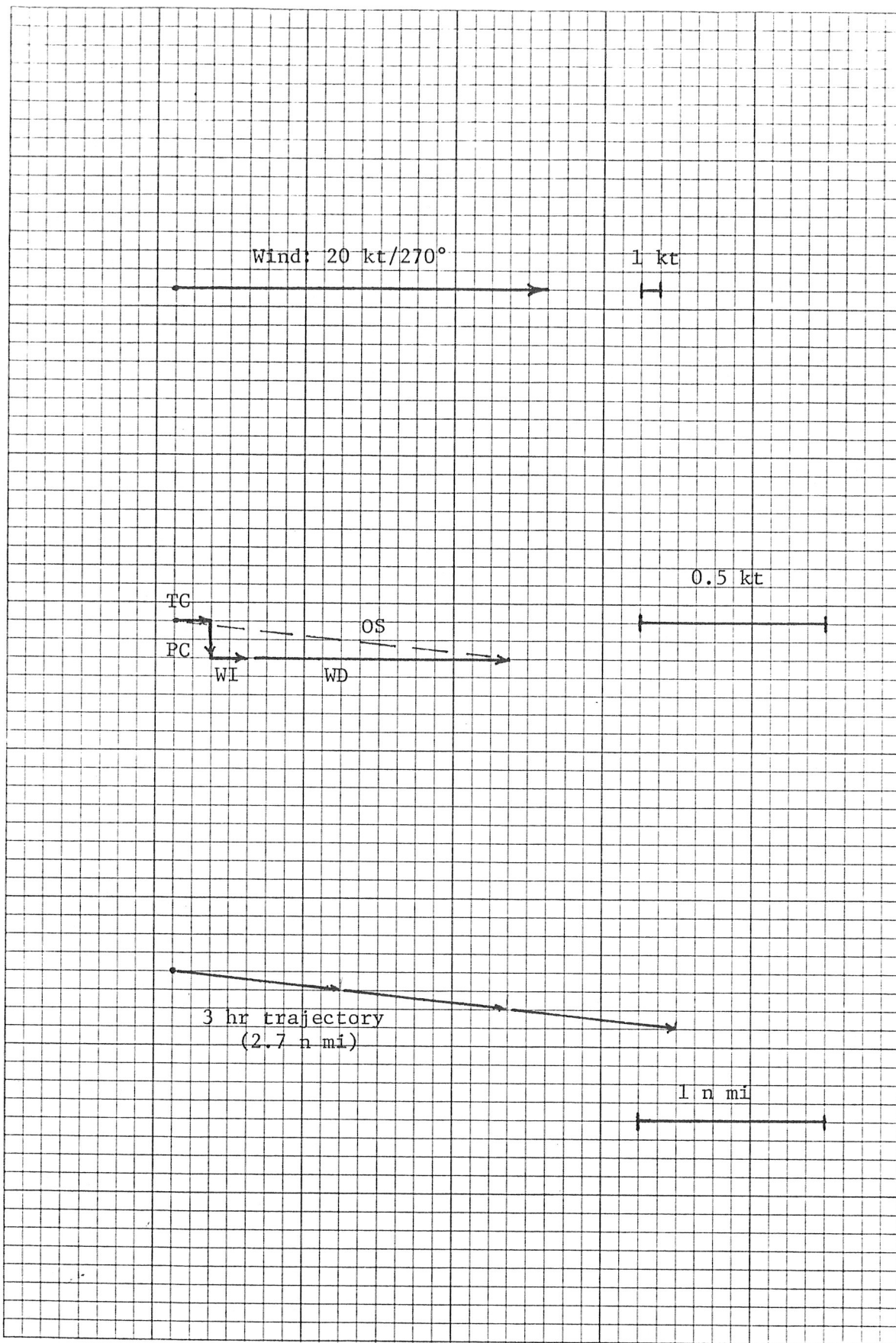
43

Figure 13. Sample graphical calculation of an oil spill trajectory with a 20 kt wind, a 0.5 kt tidal current, a 0.5 kt semipermanent current, and a 50% developed sea (see Appendix).