CHAPTER 151

ENVIRONMENTAL ANALYSIS FOR BAHAMAS SUPERTANKER PORT

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ABSTRACT

From the point of view of the Bahamian environment, the most favorable locations for a supertanker port are 1) the western margin of the Great Bahama Bank, 2) the western shores of Grand Bahama Island and 3) the western margin of Little Bahama Bank. A port in any of these areas would a) usually be located down-wind and down-current of the majority of Bahamian islands and shallows, b) be located adjacent to boundary currents, expecially the Florida Current, that would tend to carry large accidental oil spills away from coastal areas and into the North Atlantic, c) be located where wave energies would be relatively low, and d) be positioned close to sea-lanes, obviating supertanker penetration of the central Bahamas.

A site 30 miles east of Freeport, Grand Bahama Island, was chosen for construction of a sea-island supertanker bunker. Six controlled spills (270 U.S. gals. each) of crude and two spills of naptha were made at the sea-island site during the windiest month (February). Slick spreading rates are presented. Cumene and all lower-boiling aromatics disappeared within the first 90 minutes after a crude-oil spill; a majority of toxic fractions (BP < 220°C) disappeared within 3 to 8 hours. Slick-drift roses for extreme-wind-persistence and strongest-coastal-current conditions indicate the environmental suitability of the site for capture and cleanup of small spills (< 1000 gals.).

INTRODUCTION

From the standpoint of environmental hazards, the Bahama Islands have advantages over many other potential sites for supertanker ports along the Atlantic seaboard of North America. Threats to shipping, to oil-storage, or to oil-transfer operations from fog, snow, ice, or earthquakes are minimal or non-existent. Hurricanes are the only significant natural hazard, and ship captains and superport managers can take advance precautions for them.

In 1971, the Bahamian Government decided to consider development of a bulk terminal which could handle super-sized ships, including tankers. The author was requested to make a general environmental analysis of the Bahamian archipelago with a view to identifying coastal reaches that would be suitable for location of the superport. Figure 1 indicates the value of a general analysis. The broad interplay of winds, waves, and ocean currents can be considered. For example, from the point of view of the Bahamian environment, the most favorahle locations for a superport are 1) the western margin of the Great Bahama Bank, 2) the western shores of Grand Bahama Island, and 3) the western margin of Little Bahama Bank. Accidental oil spills would tend to move away from ports located in these areas of the archipelago and the port sites themselves would be near deep-water sea lanes, protected from North Atlantic swell.

LARGE TO CATASTROPHIC-SIZED SPILLS

The size of an oil spill is defined here as "large" if it is greater than 500 tons (10^5 Imp. Gallons). A spill greater than 30,000 tons will be

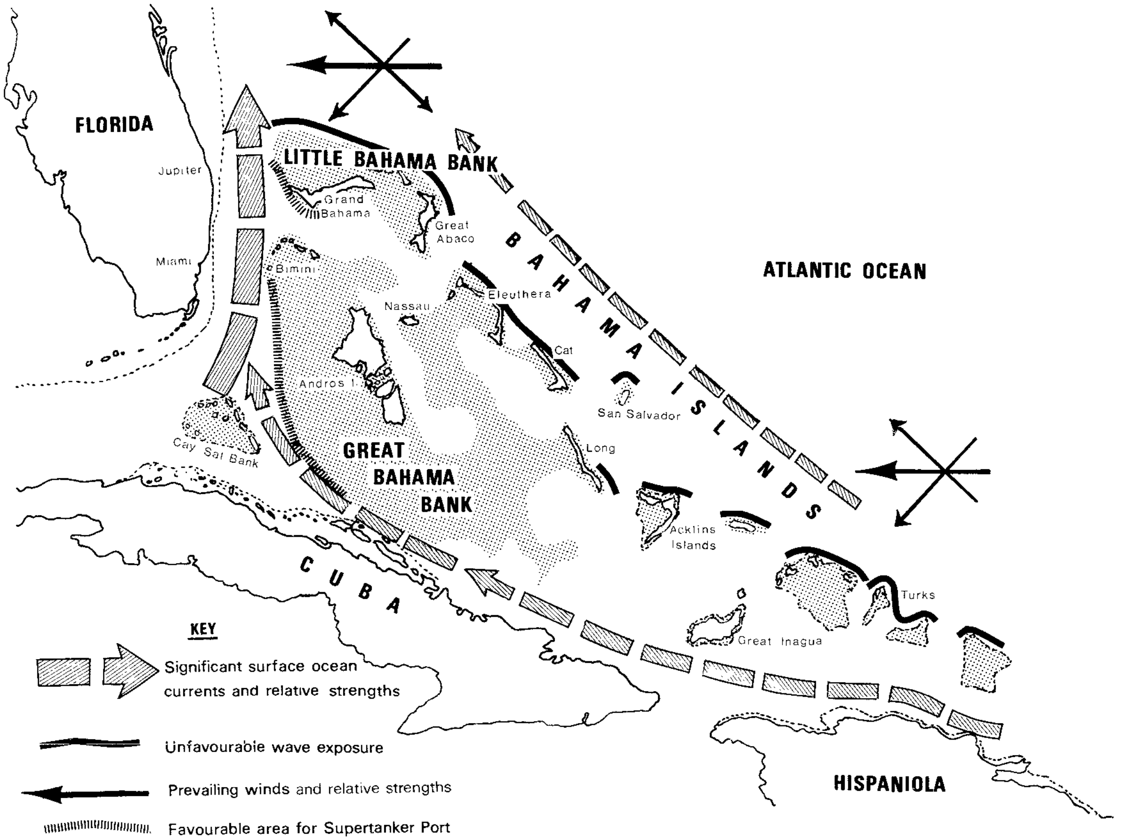

Fig. 1. Summary of winds, waves, and ocean currents and environmentally favorable areas for siting a supertanker terminal in the Bahamas.

assumed to be of "catastrophic" proportions. On March 7, 1968, the General Colocotronis ran aground on a reef about 1000 m offshore of the eastern shore of Eleuthera Island (Fig. 1) and lost about 2,500 to 3,000 tons of Venezuelan crude into the sea. This was the only large spill to occur in Bahamian waters and the spill was located adjacent to a boundary current (Fig. 1). Unfortunately no useful data were obtained on the trajectory of, or chemical changes in, this large spill. Furthermore, very little can be said about the physical fate of oil slicks from large or catastrophic spills in the Bahamas until more is known about the surface ocean currents. This deficiency in environmental information is encountered all too often. With the exception of the Tongue of the Ocean and Northwest Providence Channel, data on inter-island or inter-bank currents in the Bahamas are quite scanty. It is likewise almost impossible to make meaningful analyses of the chemical fate of large oil spills. In the analysis below for medium-sized spills, however, the outlook is better.

MEDIUM SIZED SPILLS

Grand Bahama Island (Fig. 1) was eventually selected as the best of the environmentally-favorable areas for the superport. It then became necessary to make smaller-scale wind, wave, and ocean-current analyses for several potential port sites on the southern and western shores of Grand Bahama Island and to obtain a general idea of the motion of medium-sized oil spills at each site. Medium-sized spills result from the rupture of storage tanks on land or from the rupture of ship hulls during groundings or in collisions with other ships. During such events only limited quantities of oil are lost. A spill is medium-sized (1) if it is between 10 and 500 tons, or about 2 x 10^3 to 10^5 Imperial Gallons. Its probability of occurrence is considerably greater than a large or catastrophic spill.

It is important to be able to estimate the response to wind stress of slicks from medium-sized spills. In a study of oil-slick motion at the entrance to Chesapeake Bay (2), it was found that wind has a measurable effect upon the movement of small slicks only when the wind speed exceeds about 7 knots (3.6 m s^{-1}). Below this threshold value slick motion can be assumed to be due entirely to ocean-surface currents. Above the 7-knot threshold, the relative wind factor increases gradually so that for a 20-knot wind ($\approx$10 m s^{-1}) a small-sized oil slick moves at approximately 2.0 percent of the wind speed, and in the direction in which the wind is blowing. It was assumed that oil slicks from medium-sized spills would obey the same relationship (Fig. 2) as that found for slicks from small (10 - 240 Imp. Gal.) spills.

The advection of slicks from medium-sized spills can be estimated by the construction of monthly slick-drift roses for a potential port site. This involves summation of current and wind-transport vectors, the wind-transport vector being taken as a percentage of the wind speed, as just mentioned. For Grand Bahama Island the wind vectors used in monthly rose constructions were those corresponding to extreme-wind-persistence values found in compilation of one year's wind data obtained at the Freeport meterological station. The nearshore-current values used for the current vectors were determined from an analysis of U.S. Navy and Nova University current-meter records from the Northwest Providence Channel (Fig. 1). Maximum expectable current velocities were used because an environmental impact analysis of oil spills should be based upon the most vigorous conditions to be expected along the coastal reach under consideration.

Monthly vectors for extreme wind persistence and strongest ocean currents were determined, added, and the net vectors plotted for each of 16 points of the compass. The ends of the vectors were then connected by straight lines. The final result was a "rose" (compare Fig. 3) that showed the extreme limits of potential slick motion that could be expected from small and medium-sized spills originating at a

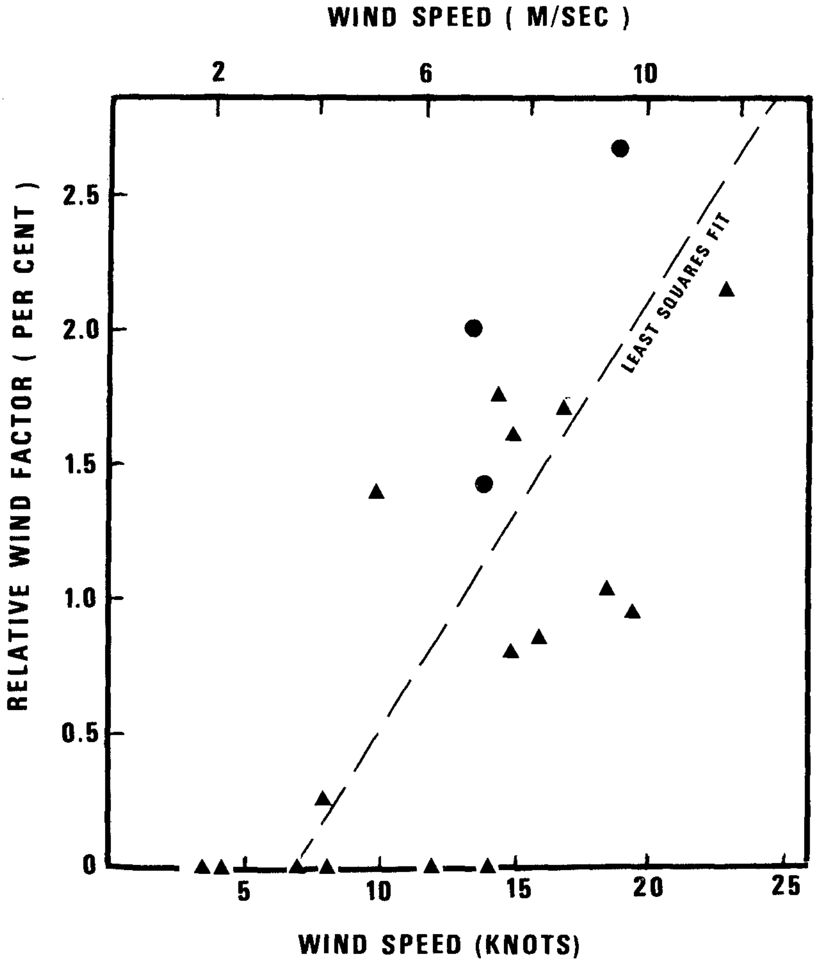

Fig. 2. Slickdrift wind factor versus wind speed. The wind factor does not include slick motion due to local surface currents. Triangles indicate values from Chesapeake Bay (3). Dots are values from the Bahamas.

given point during a given month.

If a medium-sized spill were to occur at the 100-ft. depth contour off Gold Rock Creek (Fig. 3), for example, the crude-oil slick would usually move in response to the net westward flux of surface water in the Northwest Providence Channel. As the slick spread, it would tend to move westward along the south shore of Grand Bahama Island and, although the slick might be blown about during a several-day period by the passage of frontal winds in the late fall or winter months, it would eventually enter the Florida Current. Following that, the slick would be transported by the Gulf Stream into the North Atlantic. It is quite unlikely that easterly winds of sufficient strength and persistence would ever develop which could overcome the transport vector of the Gulf Stream and blow a slick as far west as the shores of the eastern United States.

The adoption of a model for slick spreading for a medium-sized spill poses difficulties. Theoretically at least, oil spreading should be due to hydrostatic forces derived from density differences and at a certain point in spreading history the forces of interfacial tension should determine the final stages of configuration. This will lead to an upper limit in the diameter of a slick. Fay (3) developed a slick-spreading model in which he identified three successive stages in spreading that are governed by the dominsnt retarding force that operates to impede spreading in each stage. Because crude oils are complex, however, and different components have differing solubilities and spreading rates, Fay's simple model breaks down in nature. These observations led Blokker (4) to propose an empirical relationship based upon the assumption that the spreading rate decreases exponentially with the reduction of slick thickness:

$$Krt = \frac{\pi(r_t^3 - r_o^3)\ dw}{3\ V\ (dw-do)\ do} \qquad (1)$$

where Kr is a constant (the "Blokker constant") for a given oil, r_o and r_t are the radius (cm) of the slick initially and after time t sec, t is the spreading time (sec), V is the volume of oil in the slick (cm^3), and dw and do are the density (gcm^{-3}) of the sea water and the oil, respectively.

Several of the assumptions of this spreading model, such as the assumption that the oil spreads uniformly and becomes a circular patch, do not apply in practice, as will be expanded upon in the section on "small-spill analysis" below. Jeffery (5), however, made a controlled, medium-sized spill of 120 tons of light Iranian crude in the North Atlantic and followed the slick for four days. He found that Blokker constants calculated from the observed maximum slick dimension ranged between 109 and 360, with an average value of 216. Jeffery regarded the value of 216 as a reasonable approximation for a spreading constant for the four-day period, after which time the slick rapidly disappeared. At no point during the four-day interval did Jeffery find evidence for a change in spreading mechanism as described by Fay's model.

In the case of the advection and spreading analysis for the Grand Bahama sites, the author used a Blokker constant of 240 to project the maximum dimensions of slicks of Persian Gulf crude, from hypothetical 400-ton spills, and for time intervals of drift corresponding to the lengths of each of the 16 spokes of each slick-drift rose (cf. Fig. 3). The slick-transport and slick-spreading data formed the basis for an assessment of the physical environmental vulnerability of each projected port site to medium-sized spills of Persian Gulf crude oil, the type of petroleum which the superport was to handle.

A determination of the chemical fate of medium-sized crude-oil spills is more problematical than determination of their physical fate. One model for

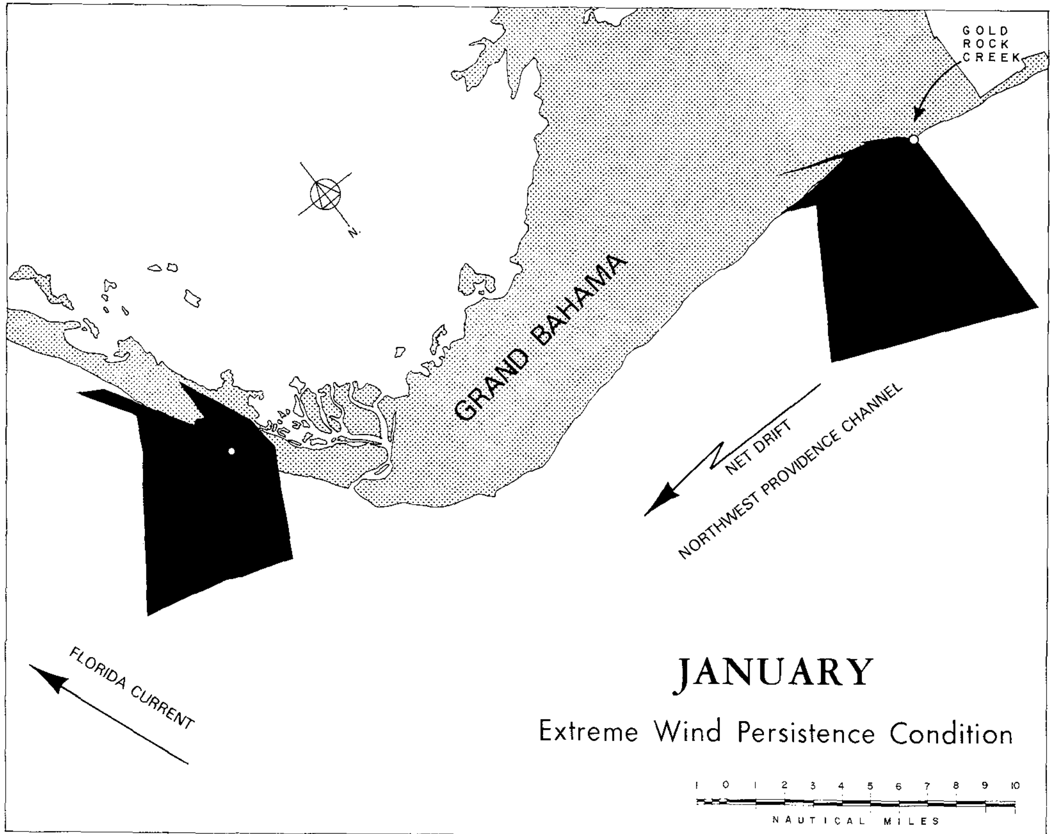

Fig. 3. Slick-drift roses for two supertanker port sites on Grand Bahama Island. Limits of a given rose correspond to predicted drift positions of leading edge of a hypothetical slick. An estimate of slick spreading does not enter into computation of these roses.

chemical fate is Moore's (6) first-order model which approximates the rates of evaporation, dissolution, and biological degradation of six oil fractions. The basic equation for each oil fraction is given by

$$\frac{dc}{dt} = (K_e + K_d + K_b)\ C \qquad (2)$$

where C is the concentration and K_e, K_d, and K_b are the evaporation, dissolution, and biological decay coefficients, respectively. The solution to this equation is

$$C = C_o e\ -(K_e + K_d + K_b)t \qquad (3)$$

where C is the concentration of a particular fraction after some exposure period t in days and C_0 is the initial concentration. Biological decay is of no consequence in analysis of the chemical fate of medium-sized spills. A list of the six fractions and of approximate values of the coefficients K_e and K_d are given in James, et al. (7). The values are approximate because they will depend upon temperature and oil-film thickness.

The transfer rates given by James, et al. can be used to make rough predictions of the toxicity of oil-fouled water at the shoreline following arrival of a slick borne by an onshore wind (of 10 knots) and associated current. The current vector is actually of most importance because dissolved components will move with the water column. (The minimum possible spill-site-to-land distance that will be travelled by the dissolved components will depend upon the grounding depth of the particular fully-loaded supertanker which might be involved in an accident). If one assumes that the depth to the thermocline off Grand Bahama Island is 10 m, the concentration of the water soluble fractions of the oil below the sea surface (C at a depth z) can be estimated (7) by

$$C = C_s \exp\left(-\frac{z^2}{50}\right) \qquad (4)$$

where z is the depth in meters. The use of equations 3 and 4 resulted in conservative estimates of the toxicity of oil-fouled nearshore waters following medium-sized spills of Persian Gulf crude at the potential port sites on Grand Bahama Island. C_s in equation 4 is the surface concentration (7,p.137).

SMALL-SIZED SPILLS

Analysis of the prediction of slick drift, slick spreading, and slick aging for medium-sized spills led to the approval of two possible superport sites and on March 6, 1972, the Prime Minister of the Bahamas announced that a supertanker port would be constructed about 30 miles east of Freeport, Grand Bahama Island. In early 1973 it became known that the proposed superport would be located slightly east of South Riding Point (Fig. 4) and that a sea-island, oil-transfer structure would be built 3,600 feet offshore in water about 100 feet deep. The Bahamian Government then indicated its desire for additional information on the fate of small spills that commonly occur during oil-transfer operations at a sea-island. This necessitated the release of five controlled spills (275 U.S. gallons, or $1.04m^3$, each) of oil (8) at the sea-island site under a variety of wind and nearshore-current conditions. The releases were made in February, 1973, because February is usually the windiest month in the northwestern Bahamas. The oil slicks were tracked and sampled from ships. Surface-current drogues were tracked by radar to determine the nearshore current field. The Canada Center for Remote Sensing photographed the slicks from aircraft in connection with their sensor-development program. Analysis of the field measurements permitted:

1) the calculation of slick-spreading rates,
2) determination of the rates of chemical aging of the slicks, and
3) construction of precise slick-drift roses for the sea-island site.

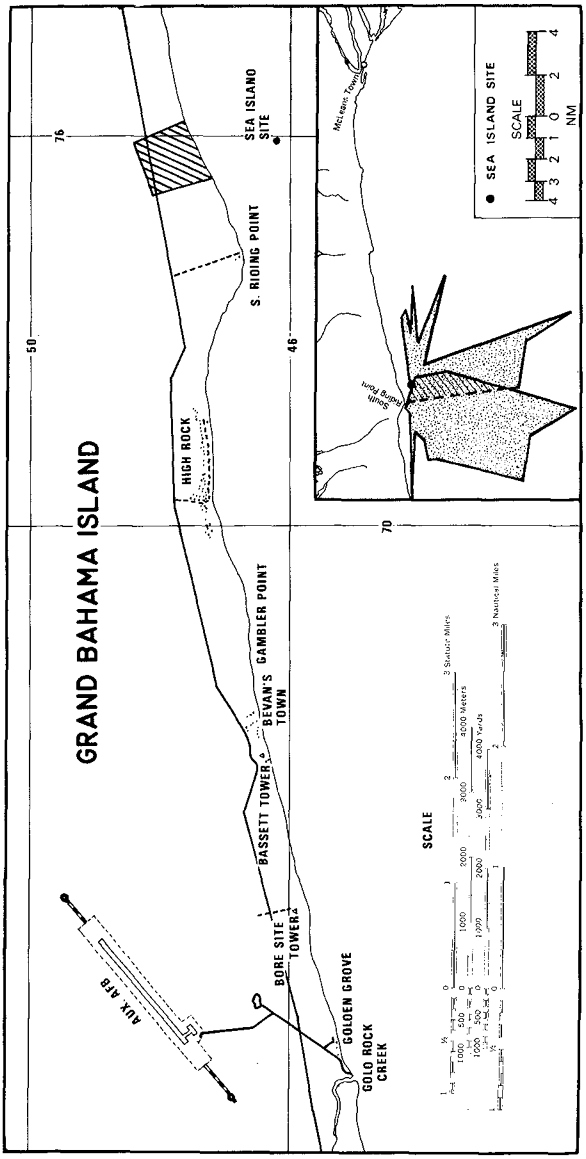

Fig. 4. Location of the sea-island supertanker bunker off South Riding Point, Grand Bahama Island. Shaded pattern indicates storage tank site. Inset shows slick-drift roses for January, in which data for extreme-wind-persistence conditions are combined with nearshore-current data for west-setting (left-hand rose) and east-setting currents.

A typical slick trajectory is shown in Figure 5 and slick-spreading data are plotted in Figure 6. Bien (9) analyzed slick spreading by planimetering slick areas as seen on 9 x 9-inch aerial Ektachrome photographs and produced a graph similar to Figure 7. This graph shows clearly that there is a decrease in the rate of change in area of an oil slick as a function of increasing wind speed. When the current vector is not dominant relative to the wind vector, and is not markedly off-angle to the wind vector, oil slicks align themselves with their long axes parallel to the mean wind direction. Heavier components of the slicks are transported toward the downwind (leading) edges.

It is probable that Langmuir circulation (10) plays an important role in limiting the spreading of slicks in directions perpendicular to their long axes. Langmuir circulation sweeps organic matter in sea-surface films together along the lines of convergence of convection cells whose long axes parallel the wind direction. This action is quite evident in air photos of crude-oil slicks under wind speeds of moderate strength and it effectively reduces the rate of horizontal spreading. The vigor of the Langmuir circulation increases as the wind speed increases and may lead to entrainment of slick material where water sinks in a convergence zone. Whatever the nature of the complex factors which enter into slick spreading, it is important that empirical data such as those of Figure 7 be used in conjunction with spreading models, such as those of Fay (3) and Blokker (4) mentioned earlier.

The chemical fate of the small spills was studied rather carefully because water-soluble aromatic and aliphatic hydrocarbons may have sub-lethal effects on marine organisms at concentrations of 10-100 ppb, lethal toxicity at 0.1-1.0 ppm for most larval stages, and lethal effects at 1-100 ppm for most adult organisms (7). The rates of disappearance of specific aromatic and aliphatic components of five crude-oil slicks were studied (11) because the lower-boiling fractions contain almost all of the lethal components of the slicks.

Previous investigations of the aging of crude-oil slicks have demonstrated that all of the lower-boiling components evaporate and dissolve within a few hours of oil spillage. The five Bahamian spills were studied for the "disappearance" (evaporation plus dissolution) of the aromatic and aliphatic components shown on Figure 8. Ten gallons of crude oil were replaced with technical grade cumene, to act as a tracer and internal standard, in each 275-gallon spill. Wind speeds ranged from calm to 18 mph (with gusts to 22 mph) and sea-surface conditions ranged between calm with gentle swell to extensively whitecap covered. Water temperature was essentially constant at 23.6°C. Air temperature ranged between 20.5 and 24.0°C and relative humidity between 60 and 79%. Details of the field and laboratory procedures are presented elsewhere (11). Sampling of crude oil was confined to the thickest oil pools of each slick.

Of particular interest in interpreting the experimental results are the relative disappearance rates of cumene and nonane. These hydrocarbons have very similar vapour pressures (cumene 4.2 and nonane 3.9 mm Hg at 23.6°C); thus, their evaporation characteristics will be similar. Cumene is, however, considerably more soluble in water (50 vs. 0.22 mg/l). A comparison of the relative rates of loss of these hydrocarbons may yield information on the contributions of evaporation and dissolution as mechanisms for the removal of specific hydrocarbons from oil spills.

Analysis (11) suggests that in each spill there was dissolution of about 2 kg of cumene. If this was into a water column 1 m deep and over an area of 10^4 to $10^5 m^2$, the aqueous cumene concentration would be in the range of 0.2 to 0.02 mg/l. Water samples taken from under the spill identified cumene

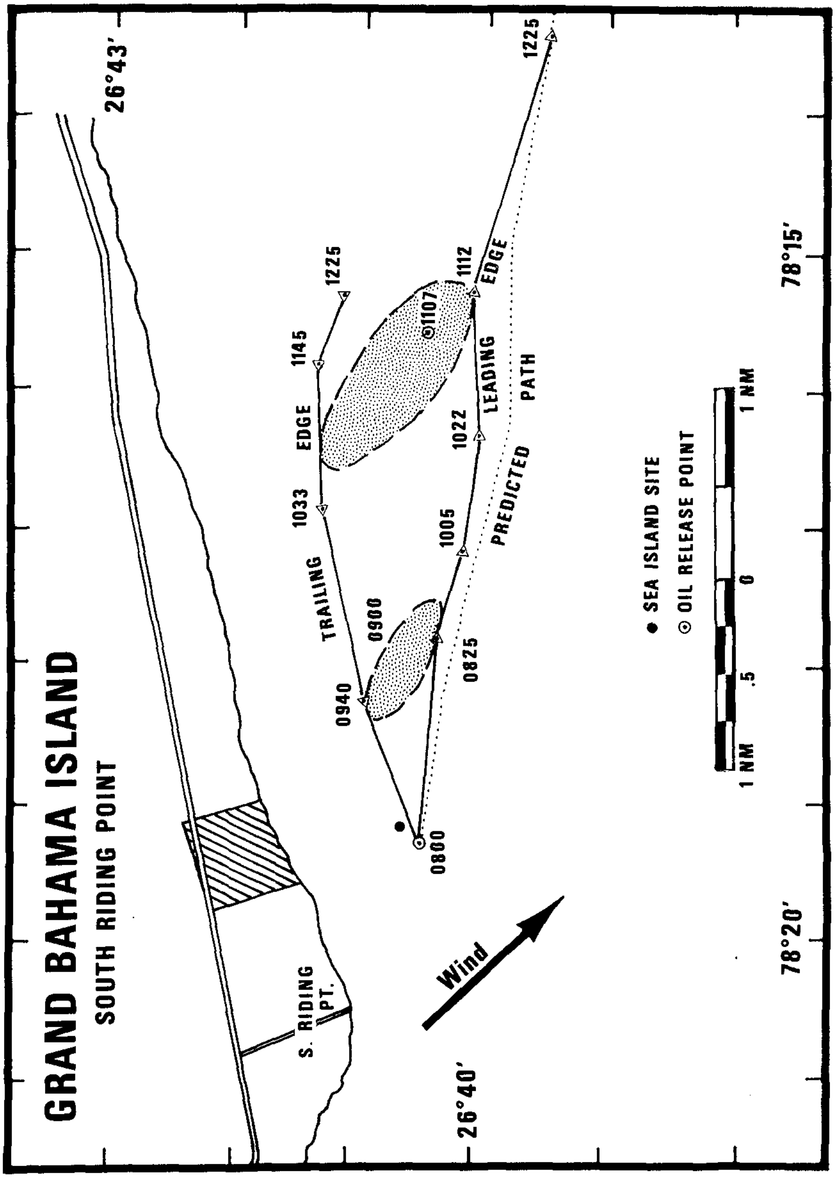

Fig. 5. Positions of leading and trailing edges of the 270-gallon (U.S.) slick of February 16, 1973, and predicted slick trajectory. Slick outlines are approximate only. Times given are in hours (EST).

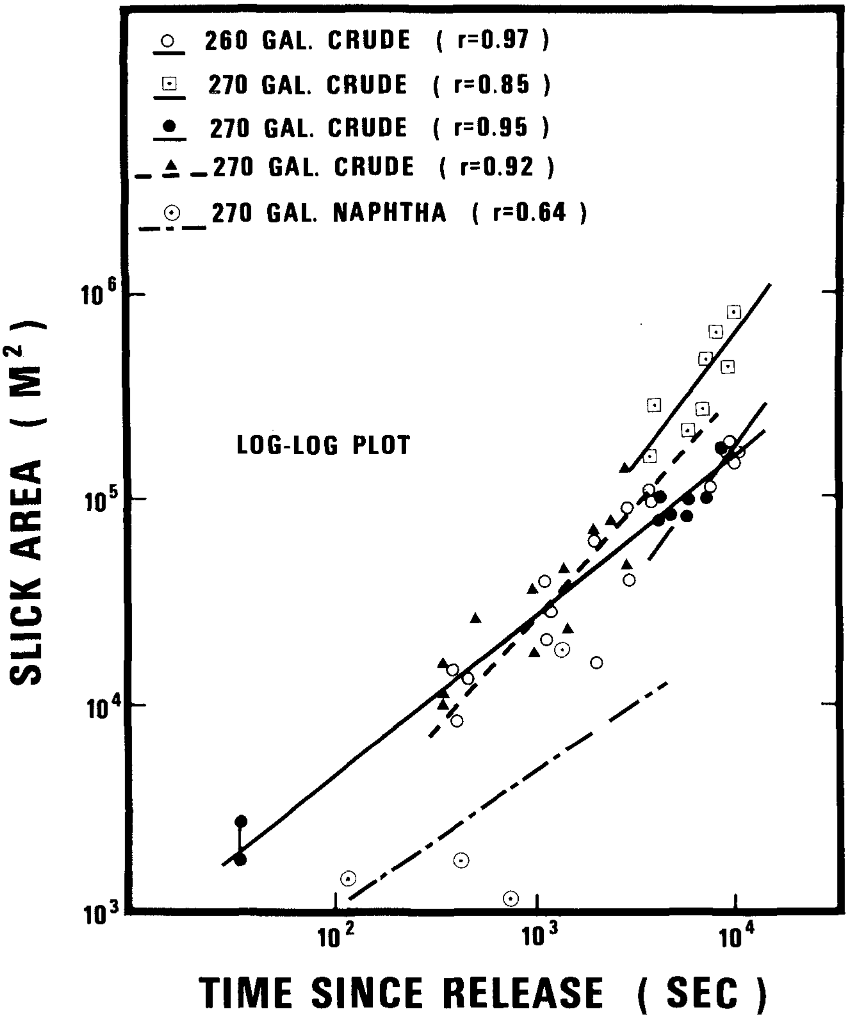

Fig. 6. Slick area as a function of time for 4 South Louisiana crude-oil spills off S. Riding Point, Bahamas during February, 1973.

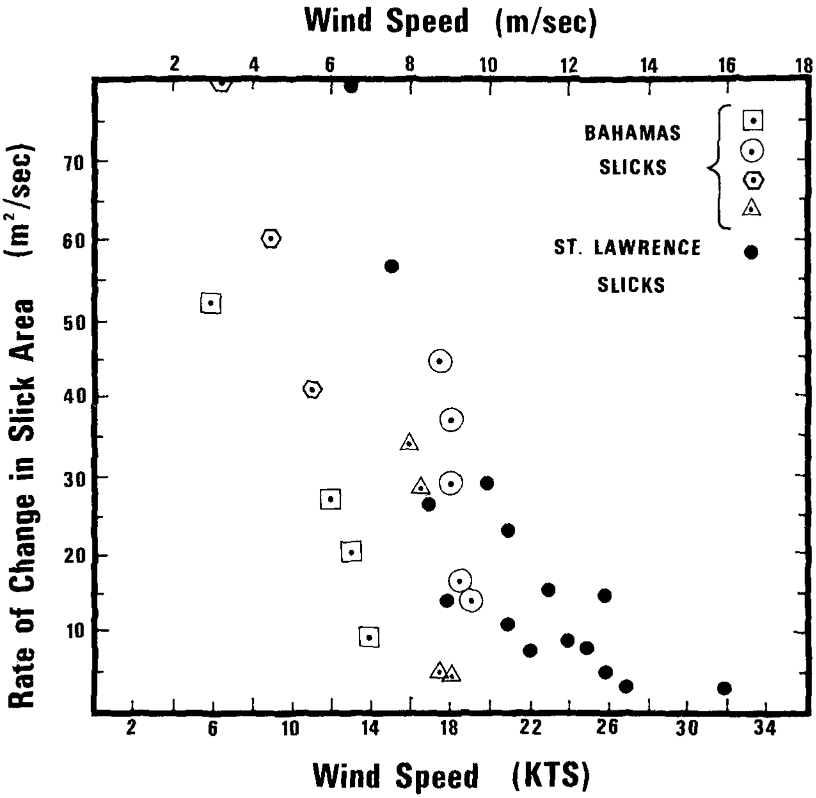

Fig. 7. The rate of change in slick area as a function of wind speed (over short intervals during the period 10^2 to 10^4 seconds after release).

as being present at concentrations below 1 mg/l, the analytical technique being insufficiently sensitive to give quantitative results. In two samples no cumene was detected and in two samples cumene was detected at concentrations in the range 0.1 to 1.0 mg/l. The biological implications of such concentrations are that only organisms which are in close proximity to the spill for an extended time are likely to suffer toxic effects. It is suspected that much of the dissolved aromatics from small slicks are lost by evaporation from aqueous solution. The most profound biological effects will occur under large, thick slicks and under quiescent conditions in shallow water when substantial concentrations of aromatics may be achieved in the underlying water and maintained for a considerable time.

There is evidence in spill five, from the apparent increase in cumene concentration, that different pools of oil in the slick weathered at different rates. Variation in weathering in different parts of the same slick is an important problem, previously unreported. It is probably associated with uneven spill thickness.

It can be inferred that napthalene, which has the same boiling point as dodecane, should disappear in 3-8 hours, depending on wind conditions. Thus, the majority of the toxic fractions (boiling point below 220°C) are inferred to disappear from a typical slick some 3-8 hours after a spill, most having disappeared at the earlier end of this time interval.

The relatively rapid decrease in the five-component concentrations of slicks 2 and 4 is related to the sudden onset of capping on the sea surface during a brief gusty period. These rates of disappearance can be compared to those of slick 5, in which the wind speed increased very gradually until about 115 minutes after the spill when widespread whitecaps suddenly appeared. It would seem, therefore, that there is a significant discontinuity in the rate of disappearance of the aromatic and aliphatic components between wind speeds below and wind speeds above those which cause the onset of extensive capping. Possibly, evaporation is suddenly enhanced by increased air turbulence. It would thus seem desirable to develop loss-rate curves for the two different sea-state-roughness regimes, one in which there is little or no white-capping and one which displays extensive capping. A further complication is that the greater turbulence during capping may result in the formation of oil-in-water and water-in-oil emulsions.

After the slick aging study had indicated the rapid loss of most of the toxic components of the crude, slick-drift roses were constructed for extreme-wind persistence and strongest-coastal-current conditions at the sea-island site (see roses,Fig. 9). The slick-tracking data verified the method used to construct the roses (see Fig. 5, for example). The roses indicated the environmental suitability of the sea-island site for capture and cleanup of small spills and a construction permit for the supertanker port was approved.

Oil spill cleanup and control operations are greatly facilitated by collection of pre-operational data such as those described above. It is a simple matter to install continuously recording wind and current-meter systems at the site of a supertanker bunker and, when a spill occurs, to use the wind and current values in a computer program which predicts the oil-slick's path, the length of shoreline covered by oil at landfall and, if chemical analysis of the type of oil spilled has been done, the rate of chemical aging as well.

RECOMMENDATIONS

1) Wherever possible, a general environmental analysis should be undertaken before industry and (or) government commit to a given coastal reach for

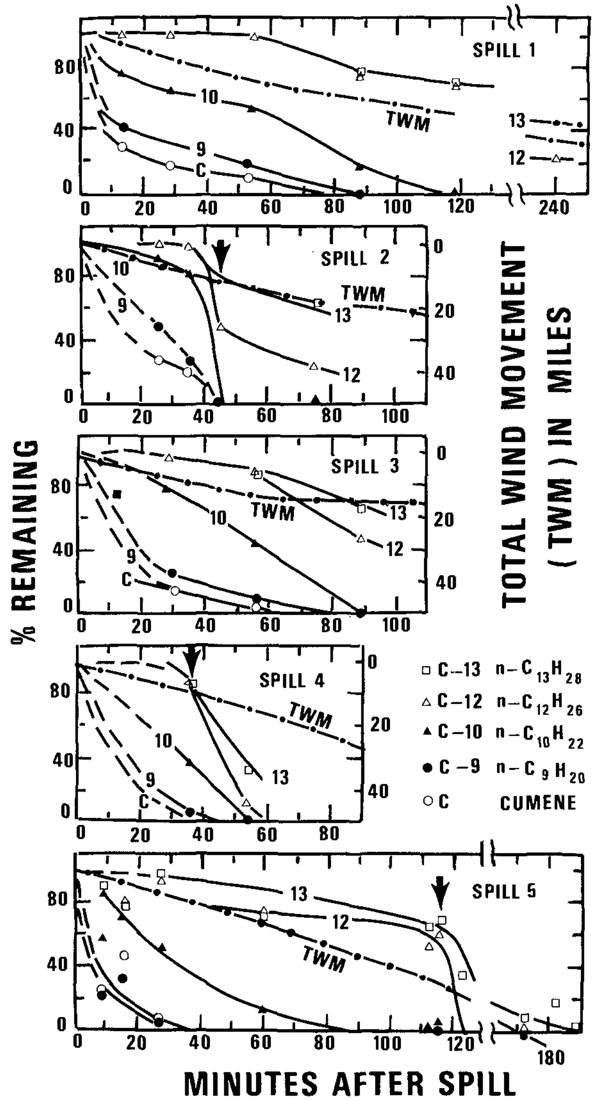

Fig. 8. Percent of low-boiling, crude-oil components remaining in slicks 1-5 as a function of time (11). Also, total wind movement in miles (miles/hr x hrs) as a function of time and moment of onset of widespread whitecapping (arrow) for slicks from spills 2, 4, and 5.

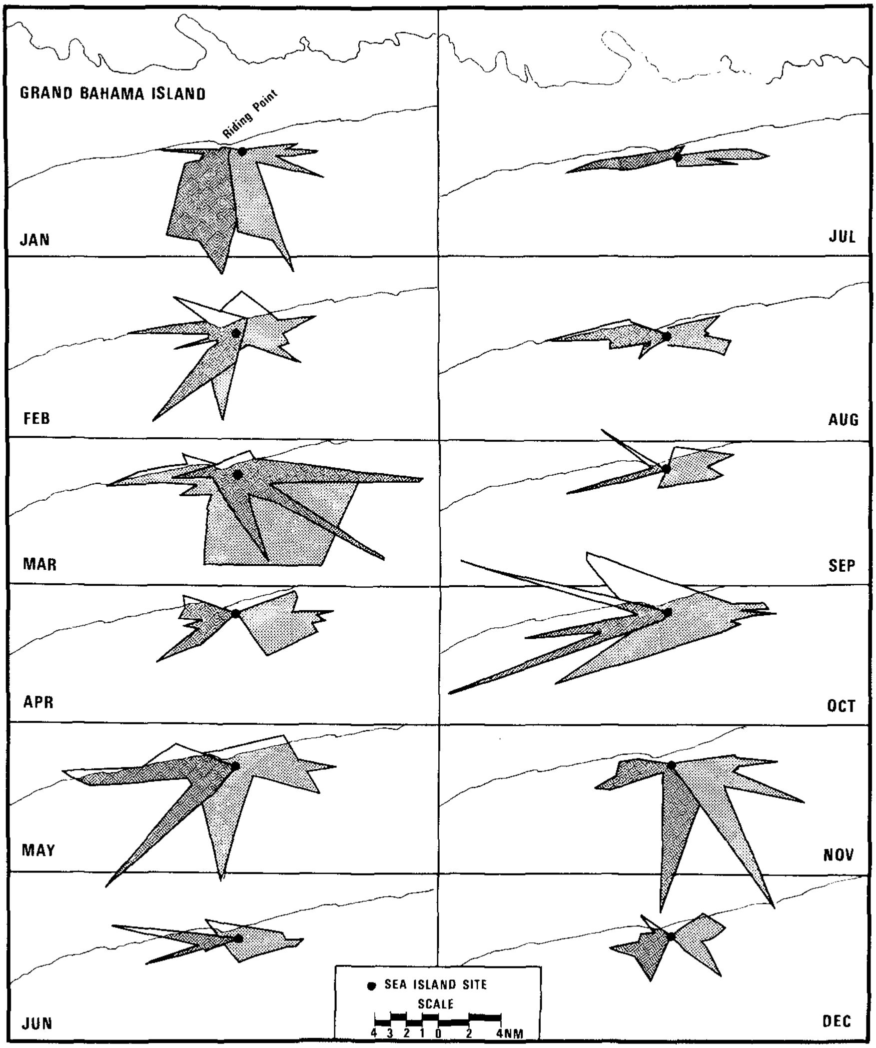

Fig. 9. Slick-drift roses constructed by Bien (9) for small spills of crude oil spilled on east or west-setting currents.

construction of a superport.

2) To be of greatest value, assessments of vulnerability to oil spills should consider the most-vigorous (generally "worst") possible conditions that could be expected at a proposed supertanker port. Slick advection, for example, should be examined by coupling historical data for the strongest, most-persistent winds with data for the most unfavorable ocean currents. Engineering design, or the port location itself, should be based on such a conservative approach to assessment of environmental vulnerability.

3) Slick-advection roses and slick-spreading diagrams should be generated for the conditions given in 2 above for the supertanker terminal and, if possible, for probable points of tanker grounding or collision in the general vicinity of the port site.

(The foregoing three points depend upon the availability of useful wind and ocean-current data. It is, therefore, incumbent upon appropriate government agencies or the petroleum industry to obtain these data before serious initiatives are started vis-à-vis superport construction).

4) Studies of the aging, spreading, and advection of small slicks, of the type of crude oil to be imported to a proposed terminal, should be carried out in the vicinity of the terminal site. Airborne mapping of slick spreading is a necessity. Such controlled spills give considerably more insight into fate mechanisms than one expects. Rates of disappearance of the low-boiling components of the slicks should be investigated more fully during different states of sea-surface roughness.

(In order to implement point 4, environmental and regulatory agencies will need to loosen their overly restrictive controls on experimental releases of oil for research purposes).

5) More empirical studies, as recommended in 4, are needed for the development and testing of predictive models of slick advection, spreading, and aging. Additional studies of large-volume, mid-ocean releases should be attempted. The roles of emulsification and Langmuir circulation on slick spreading need further study in nature.

6) For the present, use of the Blokker spreading model and Blokker constants appropriate to the environmental conditions and types of crude involved, seem most suitable for predicting the spreading of medium to large-sized spills of crude oil. For small spills, the empirical data of the present study may be used but modifications will be required for the differing physical and chemical characteristics of the various crude oils to be investigated.

ACKNOWLEDGMENTS

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