GULF COAST DEEP WATER PORT FACILITIES STUDY ①

Appendix D
Adverse Environmental Effects

a report to

U.S. DEPARTMENT OF THE ARMY
VICKSBURG DISTRICT CORPS OF ENGINEERS

1 APRIL 1973

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Gulf Coast Deep Water Port Facilities Study

APPENDIX D

ADVERSE ENVIRONMENTAL EFFECTS

a report to

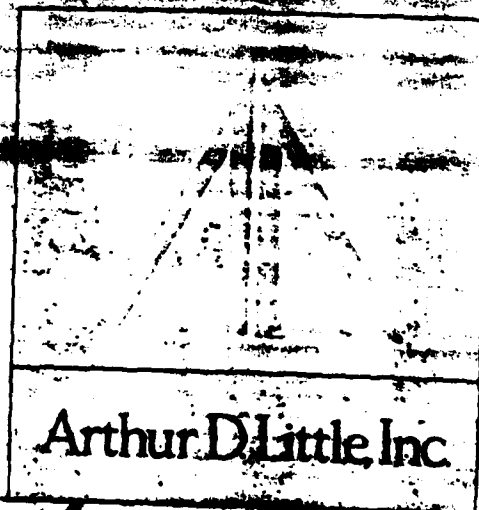U.S. Department of the Army
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B. CHANGES IN WATER MASS EXCHANGE

(Applicable to structures within an estuary or close to its mouth, including hurricane barriers and tidal dams.)

1. Reduction in tidal prism (large islands in regions of small tidal range)

2. Reduction of deep-water exchange (hurricane barriers at entrances to deep estuaries where offshore waters are significantly stratified)

3. Changes in existing currents

    a. Velocity changes affecting areas of scouring and of sedimentation

    b. Changes in direction of currents

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4. Shortening of wind fetch (reducing depth of shallow estuaries)

C. CHANGES IN SALINITY, TEMPERATURE, TURBIDITY, AND OXYGEN

(Through change in tidal prism, current direction, velocity, and turbulence)

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*Excerpted from Rounsefell, 1972.

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1. Shift in areas suitable for different groups of biota (seeking of preferred range of parameters)

2. Shift in areas of flocculation-induced sedimentation

3. Changes in amplitude of variation in parameters

4. Changes in net primary productivity and resultant effect on dissolved oxygen levels

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D. CHANGES IN SUBSTRATE

1. Loss and gain of areas of habitat types, by shifts in areas of scouring and sedimentation

2. Increase in areas of bottom oxygen deficiency, induced by reduction in bottom water exchange (hurricane barriers, reduced tidal prisms. creation of holes deeper than surrounding bottom)

3. Loss of established benthic communities, by excess sedimentation (may eventually be balanced in some instances by gain in and establishment of new communities on areas made more suitable than formerly)

E. CHANGES IN ESTABLISHED SHORELINE

1. Blocking of along-shore sand transport (by deep excavations into the land), resulting in undernourishment of beaches on the downcurrent side

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2.   Filling in, and concurrent erosion of shoreline (by construction of peninsulas where there is an along-shore current)

3.   Formation of spits between an offshore island and the mainland

F. EFFECTS OF EXPLOSIONS

1.   Minor explosions, including seismographic

2.   Heavy explosions, such as removal of Ripple Rock

3.   Nuclear blasting

G. EFFECT ON FRESHWATER SUPPLIES

(Salt water intrusion into aquifers)

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II. DREDGING

A. PURPOSE

Dredging may be undertaken to:

1. Provide a minimum ship-channel depth of 75 feet at mean low tide;

2. Provide a minimum depth of 75 feet at mean low tide in other zones of ship operation, to accommodate berthing and turning; and

3. Prepare a foundation on which to construct offshore islands and associated shoreside structures.

The dredging of ship channels and other operating zones requires either a periodic or a continuing program of maintenance dredging. The extent of maintenance dredging depends on the rate of sediment redeposited by current action on already dredged areas. Dredging to prepare a foundation is a one-time action, that does not require subsequent dredging for maintenance purposes.

B. SCOPE OF THE PROBLEM

Engineering analysis for dredging covers extremely complex dynamic phenomena; first, *to understand local sediment transport mechanisms and, second, to prepare for the movement and subsequent placement of materials. Certain environmental factors also enter into dredging engineering, because maintenance costs largely depend upon how the disturbed coastal hydraulic system responds to removal and deposition of materials. The problem is rendered even more complex by the requirement that "external" environmental effects must be accounted for in the engineering analysis. By definition, these "external" effects include all environmental and ecological changes outside the dredging function, such as the destruction of biotic habitats and interference with upstream and subsurface freshwater systems.

It is necessary to establish the engineering and economic feasibility of any large-scale bottom alterations required for deep water port construction. In general, the greater the vertical dredging, the greater the tendency for sediments to redeposit, so it must be demonstrated that a required depth can indeed be maintained.

> "In an attempt to maintain a 40-foot channel at MLW from the Delaware Bay to Philadelphia, as much as 18 million cubic yards per year were removed from the channel by hopper dredges and dumped into the rehandling basins. However, the full project depth was never attained by this method; furthermore, the redistribution of the lighter fraction of sediment produced a so-called 'double-bottom' effect over most of the navigation channel." (Simmons, 1966)

Ultimately, by using the "sump rehandler" dredging technique the desired project depth of 40 feet was achieved, but at a cost that would appear to be considerable.

The Delaware Bay project is at least one order of magnitude *less* than some of the possible dredging projects associated with deep water port development in the Gulf of Mexico; where initial construction requirements may exceed 1.6 billion cubic yards, and annual maintenance requirements may be in excess of 500 million cubic yards (channel from New Orleans to Baton Rouge) for an inshore channel location.

Part of the engineering feasibility concerns the allocation of considerable acreage (roughly 11,000 for Mobile Inner Bay; 227,000 for New Orleans to Baton Rouge) on land or under water for spoils deposition. The cost of spoils disposal increases with distance from source and with elevation of land areas. Viewing the spoils disposal as a solid waste management problem, it is interesting to note that New York City generates about 15 million cubic yards of waste per year; and the entire municipal solid waste load for the nation is approximately 380 million cubic yards per year.

While it is beyond the scope of the present discussion to evaluate the engineering-economic feasibility of alternative dredging projects, an environmental analysis must be based upon an engineering perception of the scope and nature of the project undertaking. Table D-1 provides estimates of dredging requirements for four alternative channel locations.

C. DISPOSAL OF SPOILS

Disposal of spoils may take place adjacent to a dredged channel, at a designated site at sea, on land, or some combination of the three. Moreover, each project alternative will generate different quantities of spoils material, and the material will differ in composition. Each zone was studied to determine the impact of the expected model(s) of spoil disposal. While we assumed a "typical" spoils composition (sand, silt, clay, and organic compositions), any special conditions such as contaminant load in spoils were noted. The objective was to indicate the relative vulnerability of each zone to the range of spoils disposal likely to be encountered.

The depth and horizontal extent of spoil deposits in deep water are variables that also need to be considered. One must consider bottom currents and slope to assess probable movements of deposited spoils. The spread of material, from a surface unloading point to the bottom of the Gulf, will depend on water depth, vertical velocity, and temperature stratifications, as well as on the fall velocity of different grain sizes. A natural sorting takes place, with heavier sediment particles clustering in the lower layers and close to the disposal rig. Without precise information about dumping patterns, grain-size distribution, and subsurface water motion, it is not possible to accurately determine the spoils configuration at the bottom of the Gulf, particularly in deeper waters. We assumed that the major effects of spoiling operations would be felt only within — and immediately adjacent to — the spoil receiving area.

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TABLE D-1

ASSUMED DREDGING REQUIREMENTS
(1,000-foot bottom width at 75 feet below mean low water)

Channel Location	Construction (thousand cubic yards)		Maintenance (thousand cubic yards)		Easements (thousand acres)	
	Inshore	Offshore	Inshore	Offshore	R/W	Spoil
1. Mobile						
Inner Bay	198,900	—	5,700	—	0	11
Open Gulf	—	65,900		9,100	0	0
2. Baton Rouge to Gulf						
Southwest Pass Head of Passes	238,700	—	71,600	—	0	32
to New Orleans	426,600	—	128,000	—	0	57
New Orleans to Baton Rouge	1,692,400	—	507,700	—	0	227
3. Galveston Harbor*	175,000	259,000	1,300	4,400	1.626	0.374
4. Corpus Christi†	72,400	48,000	409	781	0.180	0

* Includes 2,000-foot-radius turning basin, approximately 11.1 miles inshore from Gulf.
† Includes 2,000-foot-radius turning basin, approximately 2.7 miles inshore from Gulf.

Source: U.S. Army Corps of Engineers, Lower Mississippi Valley Division

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D. ENVIRONMENTAL IMPACTS

The environmental impact of dredging will, in each case, be a function the *sheer magnitude* of the dredging operation, plus the *ambient conditions* at each alternative locale. The amount of environmental analysis that is possible depends on: definition of the project in engineering parameters; the nature of available environmental data; and the precision of analytic techniques for relating project parameters to environmental changes. For each of the examined projects, our objective has been to realistically assess the kind and degree of environmental impacts, to the extent allowed by available information about each dredging project and environmental data.

Some environmental and ecological effects of dredging have been discussed in several recent publications or reports (Rounsefell, 1972; Windom, 1972; Nathan, 1972).

Rounsefell provided a comprehensive analysis of how offshore construction, including dredging, can impact various biotic communities. Windom reported on continuing research concentrating on the effects of dredge materials on salt marsh sediments and on the salt marsh estuarine environment. The Nathan study provided a discussion of the range of environmental impacts of dredging, somewhat parallel to that contained in the Rounsefell study, and presented a matrix index system for comparing the impacts of dredging with the impact of other deep-water port activities at specific project sites.

We have used such references and other experience in estuarine and coastline systems to prepare the summary outline of potential environmental impacts, shown in Tables D-2 and D-3.

E. BACKGROUND FOR ASSESSING IMPACTS

Most effects are extremely difficult to characterize in any precise fashion, and all are the subject of one or more research programs, whose purpose is to expand the understanding of physical and biotic coastline and estuarine systems, and permit more accurate assessment of environmental impact.

In this section, we will discuss the mechanism of suspended and bottom sediments, the range of ecological impacts, and prior experience with spoils disposal.

1. The Mechanism of Suspended and Bottom Sediments

Ippen remarks, "To anyone familiar with the difficulties inherent in the mechanics of sediment transport by streams, even under well-controlled laboratory conditions, it is clear that tidewater sedimentation problems must be more difficult by another order of magnitude" (Ippen, 1966).

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TABLE D-2

EXCAVATION EFFECTS

1.	salt wedge propagates up estuary →	increased salinity in rivers and contiguous groundwaters →	loss of fresh water resources → impacts upon irrigation and other fresh water supply systems
			alterations in biotic communities → shifting transition zone between marine and fresh water communities
2.	alteration of velocity, salinity, and temperature with increased depth affecting entire estuary →	equilibrium food chains and breeding habitats may be disrupted →	ecologic perturbation effects can result in loss of seafood and less biotic diversification in general — undesirable species may propagate → commercial and recreational consequences of seafood losses and other changes
3.	direct removal of biotic communities in benthos, including shellfish →	biotic productivity of estuary system is diminished — unlikely to be restored at lower elevations →	ecologic perturbation effects result in loss of seafood and less biotic diversification. — undesirable species may propagate → commercial and recreational activities affected
4.	removal of overburden increases vulnerability of aquifers to saline intrusion →	possible contamination of water supply systems and contiguous fresh water surface systems	

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TABLE D-2 (cont.)

5. increased short-term sediment
concentration and turbidity
dredge operation
→ loss of species by overloading
filter mechanism or by chemical
changes in the water
→ loss of species through reduced
photosynthesis
→ loss of species through oxygen
depletion
→ loss of species through resettling
of dredged sediments upon benthos
→ loss of, or contamination of, species
through exposure to toxins trapped
in excavated materials
→ *ecologic and economic perturbation*

6. periodic long-term maintenance
dredging
→ periodic disruption of re-established
communities
→ *ecologic and economic perturbation*

7. induced shoreline changes
through erosion mechanism
caused by altered currents
— encroachment upon coastal
wetland systems
→ blocking of longshore current
sediment transport mechanism
may result in undernourished
beaches
→ formation of spits between
mainland and offshore islands
→ *ecologic and economic perturbation*

8. induced bottom changes
through bottom sediment
redistribution
→ bottom load moves upstream, forming
shoals at end of saline intrusion
zone
→ erosion of bottom where currents
cross dredged zone
→ disruption of → *ecologic and economic perturbation*
benthic communities

Source: A.T. Ippen, *Estuarine and Coastline Hydraulics*

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TABLE D-3

DISPOSAL EFFECTS

1. alteration of velocity, salinity, and temperature stratifications → effects analogous to #2 Excavation Effect

2. submergence of biotic communities in the benthos → effects analogous to #3 Excavation Effect

3. increased short-term sediment concentrations and turbidity during disposal operation → effects analogous to #5 Excavation Effect

4. submergence of coastal wetland systems → biotic productivity of wetland systems is diminished → ecologic perturbation effects for land- and water-based species related to wetland systems →
   - loss of marine species
   - loss of water-fowl
   - aesthetic degradation of shoreline, and associated recreational loss

5. covering of land areas →
   - saline intrusion into fresh water surface and subsurface systems by drainage
   - leachate of toxins in spoil to surface and ground water systems
   - destruction of original land-based ecology of site
   → possible threat to fresh water supply systems, loss of land-based species

Source: A.T. Ippen, *Estuarine and Coastline Hydraulics*

In examining the potential impacts of dredging in estuaries, Ippen makes the following general observations:

- Sediments settling to the bottom zone in an estuary will, on the average, be transported upstream and not downstream.

- Sediments will accumulate near the ends of the intrusion zone and form shoals. Shoals will also form where the net bottom velocity is zero due to local disturbances of the regime such as by tributary channels.

- The intensity of shoaling will be most extreme near the end of an intrusion for stratified estuaries, and will be more dispersed in a well-mixed estuary.

With regard to human interference in estuaries, Ippen derives the following rules:

- The major portion of sediments introduced from whatever source into an estuary during normal conditions will be retained there; and, if transportable by the existing currents, will be deposited near the ends of the salinity intrusion, or at locations of zero net bottom velocity.

- Any measure contributing to a shift in the regime towards stratification will cause increased shoaling. Such measures may be structures to reduce the tidal flow and prism, diversion of additional freshwater into the estuary, or deepening and narrowing of the channel.

- Dredging of channels should be accompanied by permanent removal of sediments from the estuary. Dumping downstream is highly suspect and almost always useless. Agitation dredging falls into the same category, if permanent removal is desired.

In addition to the phenomenon of shoaling as bottom geometry is changed, the other important sediment mechanism is turbidity. Turbidity is induced both by dredging and by fluid forces, which may act on certain bottom locations to place new material into suspension following circulation changes induced by geometric changes. Analysis of the problem requires detailed knowledge of grain size and chemical composition of the material to be suspended by dredging or other mechanisms.

Generally, coarser sandy particles will settle rapidly; and subsequent movement of these particles may be associated with bed load, rather than suspended load. Brown (1950) presents classical data relating the fall velocity of sediments to sediment diameter. Particles 0.25 mm or more in diameter will settle out at 30 mm per second or greater in undisturbed water at a temperature of 60°F. Particles

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0.06 mm in diameter will settle out at a rate of 3 mm per second. Particles 0.025 mm in diameter will settle out at a rate of 0.3 mm per second. Thus, sandy and coarser silt components will settle rapidly following disturbance by dredging and are not likely to contribute to long-term turbidity of the water. However, they can smother biotic communities upon resettling.

On the other hand, very fine particles — derived from such clays as kaoline, illite, montmorillonite, and others which are essentially hydrous silicates of aluminum, iron, magnesium or calcium — are subject to chemical attack in saline waters by the strong sodium ions which may be exchanged with the metallic ions. Upon losing charge, the metallic ions no longer provide the repelling force associated with colloidal suspensions, so they attract one another and form light flocs which resist settling. This phenomenon has long been recognized as the cause of extensive zones of high turbidity (Brown, 1950).

This discussion provides some very general qualitative criteria for examining impacts associated with the movement of sediments induced by dredging or spoiling operations.

Clearly, the detailed comparison of relative impact from zone to zone depends on the extent to which the chemical and grain-size composition of dredged and spoil materials can be characterized, and depends on specific site surveys.

2. Background for the Assessment

Bouma (1971) reports that the top sediment in most of the deeper (off-shelf) portions of the Gulf of Mexico consists of globigerina ooze to a thickness of 10 to 100 centimeters. Moreover, it has been observed that bioturbation with mottling is common in layers beneath the ooze, indicating active biological activity throughout the Gulf bottoms. Pequegnat, et al. (1971) demonstrated active crustacian life activity even in the deepest portions of the Gulf of Mexico, including such common higher species as starfish and crabs. Fisher, et al. (1972) reports the existence of 14 natural subaqueous environments and biologic assemblages in four broad groupings:

1. The innermost part of the upper Gulf, and the high-energy upper and lower shoreface environments;

2. The high-energy environments of the tidal channels, and associated flood and ebb deltas that serve as permanent zones of interchange between the Bay and Gulf;

3. Land-locked fresh to brackish ponds; and

4. A variety of environments within the interior bays and estuaries, where the greatest diversity of biotic environments occurs. These are further classified as:

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a.   Open bay, where tidal interchange is most prominent and salinities approach those of the Gulf:

b.   Enclosed bay environment, away from tidal interchange and with relatively restricted circulation;

c.   River-influenced bay environments of the mouths of the Trinity and San Jacinto Rivers, where turbidity is relatively high and salinity markedly reduced;

d.   Open and enclosed bay environments, where reef growth is prominent; and

e.   Marginal areas made up chiefly of bay margin shoals and grassflats.

An additional assemblage is associated with the existence of spoil zones which are man-made environments. Biologic assemblages developed on spoil depend to a great extent on the age and position of the spoil relative to a natural environment.

Macro-biotic assemblages, including species harvested for human consumption, are important components of the ecological communities of these zones. Fisher's summary, using only the common names of species, is not necessarily comprehensive, and the following list is limited to principally benthonic assemblages:

Inner shelf and lower shoreface	clams, snails, starfish and urchins
Upper shoreface	clams, snails, starfish and urchins
Inlet and tidal delta	clams, snails, scaphopod, coral, clinoid sponges, starfish, urchin, brittle star, fiddler crab, hermit crab, oysters, and marshplants
Bay margin	marine grass, clams, snails and blue crab
Grass flats	marine grass, clams, snails, black drum and other fish
Open bay with tidal influence	clams and snails
Open bay with reefs	clams, snails, oysters, and reef forms
Enclosed bay	clams and snails
Enclosed bay with reef	similar to enclosed bay, but with additional reef forms
Reef	abundant oysters, clams, snails, sponge, barnacles, and custaceans
Reef flank and margin	blue crab
Bay with river influence	clams, snails and crustaceans
Subaqueous spoils	variable assemblages
Fresh to brackish water bodies	marsh plants, snails, and crustaceans

Clearly, dredging or spoils disposal in the coastal zones and shelf areas will impact a wide variety of benthic organisms. The variety of subaqueous environments and assemblages in the Houston-Galveston area has already been mapped by Fisher, et al. (1972). The atlas project unfortunately only covers the Texas shoreline. At present, detailed information similar to that for Houston-Galveston is not available for the remainder of the Texas Gulf coast. Even with the excellent data of the Environmental Geologic Atlas, understanding of the ecology of the coastal zones remains very limited. Therefore, observations on the ecological implications of dredging can only be based upon a general qualitative understanding of ecological processes.

Reid (1961) reports, "Salinity is a very critical factor in the distribution and maintenance of many organisms in the estuary. To these plants and animals, mean salinity is probably of less importance than the rate and magnitude of seasonal fluctuations in salinity." Bottom dwellers in estuaries are characteristically subjected to diurnal and seasonal fluctuations in salinity. Their ability to withstand changes is related to their osmoregulatory adaptations, which may be quite variable.

3. Experience with the Impact of Dredge Spoils (Ketchum, 1972)

Dredge spoils make up a major share of sea disposal operations, as shown in Table D-4. Composition depends upon the source. Saila, et al. (1968) were able to differentiate between dredged spoil from Providence Harbor dumped offshore and sediments of the natural bottom in the Rhode Island Sound dumping area. Gross (1970) suggests that dredge spoil generally consists of a mixture of sands, silts, and wastes which form the surface deposits in harbors. He compared minor element concentrations in harbor sediments, dredged wastes, and continental shelf sediments. The median values of observed concentrations were clearly different, although the ranges of concentrations overlapped.

The proportion of dredging spoils which were from polluted areas is illustrated in Table D-5.

A variety of coastal engineering projects involve changes in suspended loads and sedimentation (Ippen, 1966; Wicker, 1965). Because important biotic communities may inhabit the sites selected for these projects, conflicts arise concerning navigation, recreation, fishery, conservation, and municipal uses of the areas (Cronin, et al., 1969). Although our knowledge about the effects is limited, and the literature is widely scattered, Copeland and Dickens (1969) have attempted to construct a picture of how dredging affects estuarine ecosystems, from information gathered in the upper Chesapeake Bay, Maryland, Redfish Bay, Texas, and an intracoastal canal in South Carolina.

The biological effects of suspended loads, sedimentation, dredging methods, and spoil disposal may range from gross damage, such as habitat destruction and smothering, to more subtle effects under low but chronic conditions of sedimentation over long periods of exposure. Channelization, dumping of spoils, dredging, and

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TABLE D-4

TYPES AND AMOUNTS OF OCEAN DUMPING
(tons during 1968)

Waste type	Atlantic	Gulf	Pacific	Total
Dredge spoils	15,808,000	15,300,000	7,320,000	38,428,000
Industrial wastes	3,013,200	696,000	981,300	4,690,500
Sewage sludge	4,477,000	0	0	4,477,000
Construction and demolition debris	574,000	0	0	574,000
Solid waste	0	0	26,000	26,000
Explosives	15,200	0	0.	15,200
Total	23,887,400	15,966,000	8,327,300	48,210,700

Source: Council on Environmental Quality, 1970

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filling in the Gulf Coast estuaries had destroyed roughly 200.000 acres of swamp. marsh, and bay bottom areas by 1968 (Chapman. 1968: Marshall. 1968).

TABLE D-5

ESTIMATED POLLUTED DREDGE SPOILS

	Total spoils (tons)	Estimated percent of total polluted spoils*	Total polluted spoils (tons)
Atlantic Coast	15,808,000	45	7,120,000
Gulf Coast	15,300,000	31	4,740,000
Pacific Coast	7,320,000	19	1,390,000
Total	38,428,000	34	13,250,000

* Estimates of polluted dredge spoils consider chlorine demand; BOD; COD; volatile solids; oil and grease; concentrations of phosphorous, nitrogen, and iron; silica content; and color and odor of the spoils

Source: Council on Environmental Quality, 1970.

Ten years after dredging of Boca Ciega Bay. invertebrate recolonization of canal sediments (92 percent silt and clay: 3.4 percent carbon) was negligible. None of 49 fish species caught in these canals (as compared to 80 species in undredged areas) was demersal. apparently because of the lack of benthic fish food organisms on or in the canal deposits (Taylor and Saloman, 1968). Breuer (1962) noted that layers of dead oyster shell in South Bay corresponded to layers of deposited spoil from dredging and redredging of the Brownsville Ship Channel. He thought that this suggested destruction of South Bay oyster populations with each dredging operation.

Pfitzenmeyer (1970), and Flemer, et al. (1967) noted a 71 percent reduction in average number of individuals and a marked reduction in diversity and biomass in a spoil area in upper Chesapeake Bay after dredging ceased. One and one-half years after dredging. the number of individuals and species diversity of the spoil disposal area, but not in the channel. were the same as those of the surrounding area.

F. CONCLUSION

The most direct and easily understood effects of dredging projects on marine biota are: 1) the destruction and removal of substrate during dredging. and 2) the

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covering of existing bottom during disposal. The scale of these factors can be measured easily. Other, more subtle effects, due to increased turbidity, changes in current or salinity regimes, or poisoning by polluted spoils, are harder to predict and are more speculative.

We have primarily made use of the direct effects during our evaluation of regions for deep water port development.

In lower Chesapeake Bay, Harrison, et al. (1964) observed a transitory effect of a dredging and spoil disposal operation on infauna. Resettlement of the dredged and disposal areas was very rapid by active migration and hydrodynamic distribution of juveniles.

Mock (1967) noted that an unaltered shore in Clear Lake. Texas, produced 2.5 times more post-larval and juvenile brown shrimp (*Penaeus aztecus*), and 14 times more post-larval and juvenile white shrimp (*Penaeus setiferus*), than a similar bulkheaded shore. In a laboratory study using similar substrates, data by Williams (1958) suggested that the type of substrate may exert its influence through its effect on available cover, although a contributing factor may be the different food content of the substrate.

Bayless (1968) observed higher average hatches of striped bass eggs (*Morone saxatillis*) on coarse sand (58.9 percent) and a plain plastic pan (60.3 percent) than on silt-sand (21 percent), silt-clay-sand (4 percent) or muck detritus (none). These results tend to support the contention of Mansueti (1962) and Huet (1965) that deposition of suspended matter may interfere with or prevent fish reproduction by destroying dimersal eggs in upper estuarine areas.

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III. EFFECTS OF SHIP OPERATIONS

Until recent years, little concern was felt about the interaction of ship operations and the marine ecology. When this problem did arise, it came from spills of petroleum cargoes from tankers, rather than from the effects of ship passage through an area.

The marine industry and technical institutions have been primarily interested in ship performance. In the absence of any pressure to investigate the relationship of this performance to the environment, it has never been closely examined. For example, changes in ship performance and operational characteristics of ships in shallow water have been of great concern, but the effects of ship passage on the bottom have not. As another example, the definition of ships' wakes have been studied from the aspect of propulsion, but little effort has been expended on behavior aft of the propeller disc.

Nevertheless, the accumulation of knowledge concerning ship hydrodynamics has established a sound basis for extending such understanding of ship effects upon the environment. Several threads of development can be brought to bear upon the problem, even though such information has not previously been focussed on the problem:

- Extensive theoretical and experimental work on wakes, jets, and boundary layers exists in classical fluid dynamics, though a large part has been aimed at aerodynamics.

- The application of computers to hydrodynamics now permit the calculation of many values which previously were unpredictable, which has permitted the extension of theory into practical working tools.

- The U.S. Navy, in connection with underwater weaponry, has acquired data which could be applied to parts of the problem.

Many individual sources exist which have never been correlated into one body suitable for estimating the phenomena under consideration. For example, a group at the Massachusetts Institute of Technology has been investigating propeller wakes three propeller-diameters behind the propeller. One motivation for the study has been the fact that it simply has never been done before, and is an information gap which requires filling.

The passage of a ship in proximity to the bottom involves two distinct flow perturbations. The first is caused by passage of the hull itself; the second is caused by the stream generated by the ship's propulsor. The two flows tend to merge behind the ship into a combined effect. The following two sections provide first-order-of-magnitude estimates of the effects in typical situations. These are not rigorous theoretical developments, and only indicate general relationships and

comparative importance. Considerable experimental and theoretical work will be required to consolidate and verify present information to where it will be directly useful in assessing the environmental effects of ship passages, and in comparing such effects to those caused by natural water disturbances such as currents and tidal cycles.

A. HULL EFFECTS

As a ship moves through the water in the x-direction, as indicated in Figure D-1a, the volume $q = A_m \, dx/dt$ must pass from in front of the hull to behind the hull per unit of time, but $dx/dt = v_s$ and therefore $q = A_m v_s$. In open water, this induced flow results in small water velocities under and around the sides of the ship, as well as some volumetric distribution changes due to local changes in pressures and water levels, i.e., wave formation.

In a completely enclosed channel of depth "d" and width "w" the situation of Figure D-1b exists, where q must pass through the area $(wd - A_m)$. As a first approximation, a mean velocity to the rear, of $q/(wd-A_m)$ is induced, and we can write

$$v_i = \frac{v_s}{\left(\dfrac{wd}{A_m} - 1\right)}$$

As a numerical example, an LNG carrier of 140-foot beam and 38-foot draft has an A_m of about 5100 square feet. At a speed of 10 knots (17 ft/sec) in an enclosed channel 42-feet deep and 500-feet wide, v_i becomes 5.45 ft/sec. Since both ship and bottom generate boundary layers in this situation, the velocity distribution may be visualized as shown in Figure D-1c.

Maximum water velocity is larger than v_i because the latter is a mean velocity across the passage between ship and channel boundaries. If the boundary layer velocity distribution is approximated by $v = v_o \, (y/\delta)^{1/7}$, the maximum velocity could be up to 14.3 percent higher than the mean v_i. Additionally, the forward flow in the boundary layer along the moving hull requires further increase in the maximum velocity value rearward to satisfy the flow q. Therefore, v_{max} may be appreciably higher than the mean represented by v_i.

Thickness of the boundary layer is dependent upon various factors, including local curvature of the surface of the ship. Predictions are generally based upon extrapolations from flat plate theory and are represented by the relationship $\delta = 0.38 \times R_x^{-0.2}$. Such a first approximation, which gives results on the low side of actual values, gives a δ of 0.54 feet at the stern of a 940-foot ship at 10 knots. The boundary layer at the bottom of the channel would be less than two inches in thickness. In comparison to the total geometry of the problem, such thicknesses are small.

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a.

b

c.
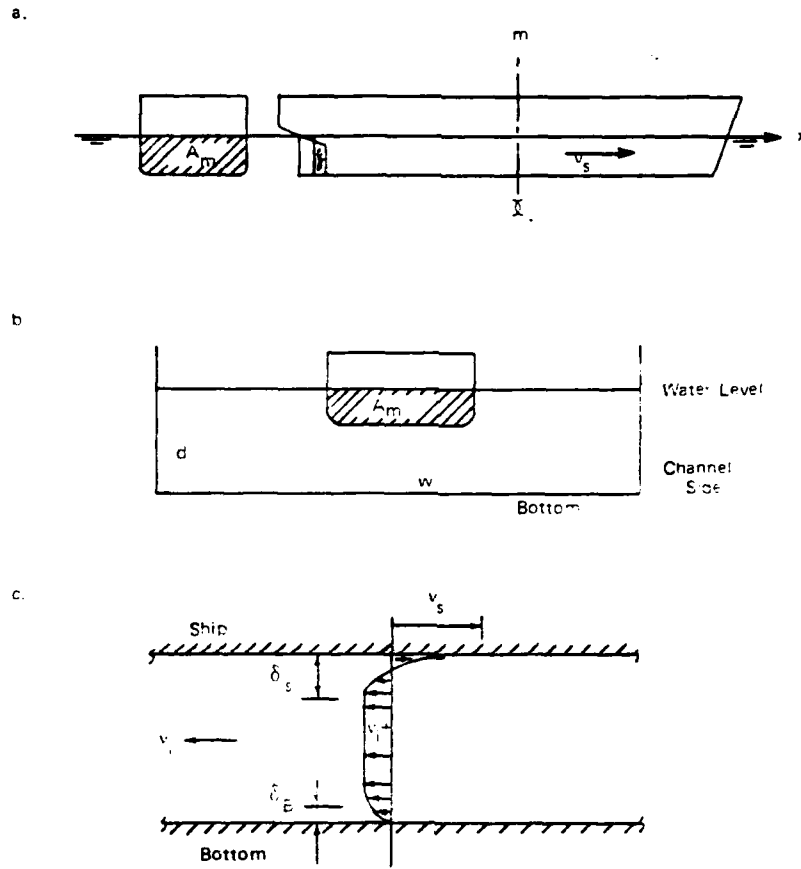
Source: Arthur D. Little, Inc.

FIGURE D–1   MOVING–HULL EFFECTS

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Toward the ends of the ship, where the cross-sectional area of the ship approaches zero, the rearward velocity disappears. The distribution of induced rearward velocity has several effects. First, net velocity along the hull increases, thereby increasing the frictional resistance of the ship to the oncoming water, or slowing it down. Second, the altered flow regime changes the hydrostatic pressure distribution which supports the hull. Therefore, the ship experiences some sinkage and some trim. For ships with bulbous bows, the bow generally trims rather than the stern. This change in position and attitude further alters the flow and pressure distribution. For steady-state conditions, an equilibrium position may be reached, or grounding of the hull may occur before such an equilibrium position is reached. When in equilibrium, a perturbation such as a change in channel depth or width, as the ship progresses, may also induce grounding. Obviously, as the speed of the ship is reduced, the effects are lessened and the ship tends to a normal attitude. Note that the angular position changes are small; for a 940-foot-long ship, trim of ± 1 foot at the ends is the equivalent of 7.3 minutes of arc.

The three-dimensional flow about a hull is governed by hull shape. When a portion of this flow is severely constrained, as by a channel bottom, a three-dimensional re-adjustment occurs. In the case of shallow water (that is, a case similar to the channel, but without the side walls of the channel), the induced velocities under the ship still occur. The phenomenon of ship sinkage and trim (or "squat") remain present even though to a lesser degree.

If and when a ship touches bottom, sediments are mechanically disturbed and brought into suspension. The suspension of small particles is governed by their terminal velocity, where frictional forces equal the sum of gravitational and buoyancy forces. This becomes a function of the parametric ratio between surface and volume of the particle. The smaller the particle, the larger is the ratio and the smaller the velocity of fluid necessary to keep it in suspension.

On the other hand, at a smooth surface, boundary-layer theory stipulates that fluid velocity at the interface is zero. Although this would appear to prohibit any possibility of sediments being brought into suspension, another mechanism does exist. Due to the viscosity of the fluid, a shear force is exerted at the solid surface and is approximated by the shear stress $t_o = 0.059 (\rho/2)v_o^2 R_x^{-0.2}$. This shear force may reach a magnitude where the individual particles are displaced sufficiently to be drawn into the turbulent boundary layer, and to remain in suspension until such time as they again reach low water velocities. Here also, the critical variable is that of water velocity and, as indicated previously, such water flows may be induced by ship passage in shallow water or in a channel.

At the stern of a ship, where the induced velocity v_i previously described disappears, further disturbances occur. At the propeller disc, the tip vortices bring about high local velocities which, if sufficiently close to the bottom, may pick up sediments. Behind the propeller disc, the propeller jet stream has both rearward and rotational motion. It gradually spreads and diffuses behind the propeller and loses its bounded identity some five diameters behind the propeller. However, the jet stream

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remains identifiable by a region of high turbulence for many ship lengths behind the ship and this turbulence contains high local velocities. The magnitude of these velocities is a function of propeller geometry, the power being transmitted, and ship speed.

For example, a 24-foot-diameter propeller turning at 30 RPM has a tip speed of 37.7 ft/sec. Both the tip vortices and the propeller stream have components of this magnitude. In the region where the boundary of the jet is still well-defined, velocities of perhaps 40 ft/sec may be encountered at the lowest tangency plane.

Four points become apparent. First, the phenomena which might cause scouring of the bottom or bring bottom sediments into suspension depend on both the ship *and* the nature of the body of water through which it moves. The conventional ship is not designed to operate in shallow water or confined channels except at low speed, and it is impractical to design features into a ship to minimize effects upon the bottom.

Second, minimizing bottom effects can be accomplished by limiting ship speed and power. By appropriate regulation of traffic, damage to the bottom can be kept to a low level.

Third, dredging channel depths to meet expected ship drafts has, so far, only considered the minimum values necessary for mechanical safety (prevention of grounding) of the ship. In view of the increased concern over bottom damage, minimum clearance requirements must be reviewed and revised.

Fourth, in view of the diversity of ship sizes and types which use a channel, it is not feasible to estimate annual tonnages of bottom sediments which may be placed into suspension. Even for a specific ship, there are both design variables and operational variables which make any estimate of typical values practically impossible. There is no question that regions of turbidity will frequently occur along a ship channel, and that persistence may be estimated from local hydrography. However, compared to analogous effects stemming from original and maintenance dredging, the effect of ship passages may be considered small.

The situation can be approached qualitatively. Assuming that some effects do occur due to ship passages, local current and tidal current configurations will indicate where the transported material may settle out. Downstream areas which are the habitat of immobile forms of bottom life (such as oysters) will suffer. Vegetation will also suffer, and if it is the refuge of mobile forms they will also suffer. The clogging of the gill mechanism of various species by suspended solids has already been established. The effects themselves increase with frequency of ship passage and with reduced clearance between ship and bottom.

In the vicinity of major ports the effects may be insignificant, because in most cases other predominant factors, such as water pollution may control the biota. However, in areas which are essentially "clean," the effects of ship passages are

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likely to be important, and may affect the fisheries. A secondary effect of the bottom disturbance by ships exists in areas where bottom deposits contain harmful materials. These substances may lie dormant, on the bottom, whereas when they are brought back into the water column they may either leach out further toxic substances or be brought into physical contact with and be ingested by marine organisms. We believe the problem cannot be ignored, but must be approached directly, because it will occur, and it can be kept to a relatively low level by appropriate channel depths and operational regulations.

B. BOTTOM VELOCITIES GENERATED BY A PROPELLER

1. Ship and Propeller

We *assume* a 250,000 DWT ship with 66-foot draft and a 30-foot propeller developing 25,000 DHP at 100 RPM and 15.5 knots ship speed. Shaft ω is equal to 10.47 rad/sec. If Power varies as $V^{2.83}$, then at 10 knots, DHP = 7300 HP and Thrust is 236,000 lbs. Since Power/Speed = Thrust, Thrust varies as $V^{1.83}$; this relationship will be referenced later.

We *assume* a four-bladed propeller and 30 RPM (3.14 rad/sec) at 10 knots, and we estimate a wake fraction of 0.36 for a single-screw tanker hull. Then $V_A = V$ (1-w) = 10.9 ft/sec or 6.4 knots.

2. Vortices

For a two-dimensional vortex:

$$\Gamma = 2\pi r^2 \omega$$

and

$$v_t = \frac{\Gamma}{2\pi r} \ ,$$

where r is the radius from the center, and

Γ = circulation or vortex strength.

For a two-dimensional lifting surface:

$$L = \rho V \Gamma$$

where

L = lift,
ρ = mass density, and
V = free stream velocity.

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remains identifiable by a region of high turbulence for many ship lengths behind the ship and this turbulence contains high local velocities. The magnitude of these velocities is a function of propeller geometry, the power being transmitted, and ship speed.

For example, a 24-foot-diameter propeller turning at 30 RPM has a tip speed of 37.7 ft/sec. Both the tip vortices and the propeller stream have components of this magnitude. In the region where the boundary of the jet is still well-defined, velocities of perhaps 40 ft/sec may be encountered at the lowest tangency plane.

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In the vicinity of major ports the effects may be insignificant, because in most cases other predominant factors, such as water pollution may control the biota. However, in areas which are essentially "clean," the effects of ship passages are

3. Propeller Vortices

Circulation distribution along the span of a lifting surface is not uniform. In a propeller, velocity magnitudes and directions change with radius, and the blades move in a helicoidal path. The free vortices at the tips of the blades are helical, and there is a combined vortex (from the blade roots) along the propeller axis. Exact calculation of the velocity fields and geometry of the vortices is a lengthy task. For our purposes, we will use simplified theory, approximations, and assumptions to reach a first estimate, rather than design a complete propeller and perform the extensive calculations.

The V in the Lift expression for a section of a propeller blade can be stated in the form:

$$V = \frac{[\omega^2 r^2 + V_A^2 (1 + k)]}{(\omega^2 r^2 + V_A^2)^{1/2}}$$

where k is a quantity dependent upon induced velocities. We *assume* a value of $k = 0.3$. We further take $r = 0.6\, R$ to compute the mean value of V, which in turn is used to derive a mean value of Γ.

We can now substitute:

$$\omega = 3.14 \text{ rad/sec}$$
$$R = 15.0 \text{ ft}$$
$$R_m = 9.0 \text{ ft}$$
$$V_A = 10.9 \text{ ft/sec}$$
$$k = 0.3$$

and V = 31.5 ft/sec.

The Thrust/blade = 236,000/4 = 59,000 lbs. $\rho = 64/32.2 = 1.99$. Then, $\Gamma = 3770 \text{ ft}^3/\text{sec}$, and $\Gamma_B = 942.5 \text{ ft}^3/\text{sec}$.

4. Velocity Fields

Recent experimental work at M.I.T. has indicated that the tip vortices trail the propeller at about 0.8 R and that the entire vorticity of the stream is contained in them.

Velocity components due to each vortex are summed up at a point directly beneath the propeller axis and at a distance "h" feet below the axis. Velocities due to offshore vortices do not lie in the cross-section plane at point h. However, we can take a similar circumferential position up or down stream to give an approximation of the velocities due to the side vortices. The vertical components of the velocities cancel out. We then get:

$$v_b = v_c = \sec \tan^{-1} 3.33/h$$

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The combined velocities tangentially and axially become:

$$v_t = 2 v_b \cos \gamma.$$

$$v_a = 2 v_b \sin \gamma \sin \alpha.$$

For one vortex we get:

$$v = \frac{\Gamma/4}{2\pi (12 + h)} \quad \text{which can be split into}$$

$$v_t = v \cos \gamma$$

$$v_a = -v \sin \gamma.$$

For another vortex we get similar expressions with a minus sign:

$$v = \frac{\Gamma/4}{2\pi (h - 12)}$$

$$v_t = v \cos \gamma$$

$$v_a = -v \sin \gamma.$$

For the central vortex we get

$$v_t = - \frac{\Gamma}{2\pi h} \quad \text{and } v_a = 0.$$

These tangential and axial components may then be summed up. The total velocity $= (v_t^2 + v_a^2)^{1/2}$ and the angle β is $\tan^{-1} v_t/v_a$.

Note that the velocities are linearly dependent upon Γ, which in turn is linearly dependent upon Lift (or Thrust) produced by the propeller.

The results of these calculations are shown in Figure D-2.

For a 66-foot-draft ship, the keel line might be at h = 16 or 17, and the shaft axis is, by definition, at h = 0 (which is equal to a submergence of 50 feet at full draft). In examining the plot, channel depth would then be equivalent to (h + 50).

The foregoing approximation *assumes* that the vortices have fully developed without decay (due to viscous energy dissipation). Boundary-layer theory and experiment indicate that this would not occur until at least 5 diameters (150 ft in this case) behind the propeller disc. Ahead of such a point, the vortices would have a specific, expanding, diameter and the *total velocity would drop off much more rapidly* as h increases. Each vortex, in effect, is surrounded by a mixing zone; so the diameter of the original vortex shrinks as the diameter of the mixing zone increases. The situation portrayed here reflects a fully expanded mixing zone.

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C. CONCLUSION

Theoretical calculations indicate that the passage of a deep-draft ship through a confined channel may cause a locally significant increase in suspended sediments in the water column. However, no definitive work has been done on this subject, and it is an area where additional research is justified.
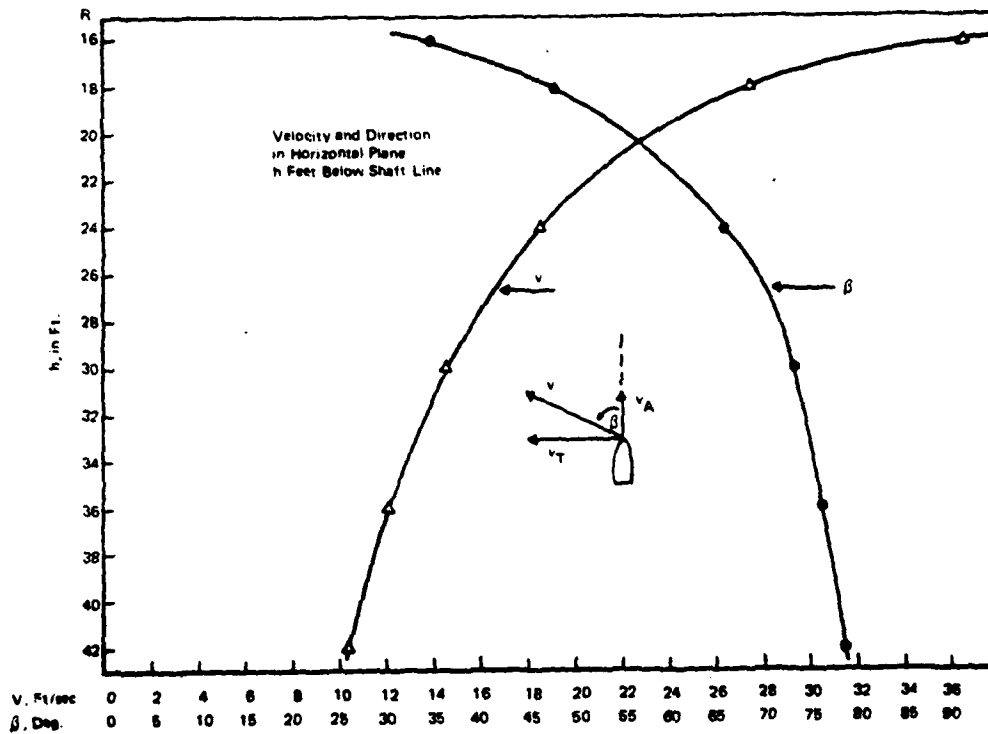
FIGURE D-2   PROPELLER TIP VORTEX VELOCITY FIELDS

IV. EFFECTS OF OIL POLLUTION

The following material summarizes the source of facts for assessing the impact of oil on marine environments.

A. A PERSPECTIVE

Oil is becoming one of the most widespread contaminants of the ocean. Blumer (1969) has estimated that 1 million to 10 million metric tons of oil per year may be entering the oceans from all sources. Most of this influx takes place in coastal regions, but oil slicks and tar balls have also been observed on the high seas (Horn, et al.. 1970: Morris, 1971). Tar balls were collected by towing a neuston net, which skims the surface. The investigators found that the tar balls were more abundant than the normal sargassum weed in the open Atlantic. and that their nets quickly became so coated with tar and oil that they were unusuable. Thus. oil pollution of the sea has become a global problem of great (though inadequately assessed) significance.

Although accidental oil spills are spectacular events and attract the most public attention. they constitute only about 10 percent of the total amount of oil entering the marine environment. The other 90 percent originates from the normal operation of oil-carrying tankers, other ships. offshore production, refinery operations, and the disposal of oil-waste materials.

We calculated the following percentages for 1969 sources of direct oil pollution. based on Revelle, et al. (1972):

Tankers	24%
Other Ships	23
Offshore Production	5
Refinery Operations	14
Oil Wastes	25
Accidental Spills	9
	100%

Projections of these values vary widely, both in quantity and in proportion, because legal, institutional, and economic factors influence the amount of new technology that will be applied for pollution abatement. Estimates of the total annual tonnage that will be deposited in the oceans between 1969 and 1980 range from a 50% increase to a 218% increase.

Two lesser-known sources of oil contamination of the sea are the seepage of oil from underwater oil reservoirs through natural causes and the transport of oil in the atmosphere from which it precipitates onto the surface of the sea. The seepage source is probably small compared to the direct input to the ocean (Blumer. 1972): but the atmospheric transport. which includes hydrocarbons that have evaporated or

been emitted by engines after incomplete combustion, may be greater than the direct input.

When spilled crude oil is burned at sea, volatile fractions may burn off quickly, but much of the oil resists combustion. Incomplete combustion is therefore common, and the smoke and volatile oils become atmospheric pollutants much of which ultimately returns to the sea through precipitation and accumulation on the water surface. Indeed, a large proportion of products of incomplete combustion from all sources, both afloat and ashore, may eventually be deposited in the oceans. The quantities involved may be hard to assess, but they obviously are increasing with the increased worldwide use of fossil fuels.

The most significant item of the tabulation lies in the 9 percent accidental spills. However, not all accidental spills are large. Furthermore, the total breakdown does not consider the deposition of airborne hydrocarbons. Therefore, the current oil content of the marine environment that is due to large or "catastrophic" oil spills may be closer to 5 percent than to 10 percent.

Oil from other sources may reach the seas already mixed and distributed in other effluents, and may not form recognizable or identifiable oil slicks. Many of the solubles that enter the water may be emulsified, or the oil may be particulated into globules distributed into the medium. In none of these instances will single heavy oil slicks be formed on the surface. Such oil spillage, as well as broken-up single slicks, may persist over large areas as individual globules, at the surface or in the water column. The oil will adhere to suspended sediment, floating seaweed and debris, and plankton. Cohesive patches of emulsified oil may also remain at the surface.

Some fractions of crude oil evaporate into the atmosphere. Others enter into solution in the water, where they are immediately subjected to microbial attack. The rate of attack, and subsequent chemical breakdown, depends on the mixing and dispersion of the oil, its chemical composition, the oxygen content and temperature of the water, and the presence of other nutrients.

Very little is known about the rate of such degradation, but it is known that no single microbial species will completely degrade any crude oil. Bacteria are highly specific, and several species are probably necessary to decompose the numerous types of hydrocarbons in crude oil. During decomposition, intermediate products are formed, and different species of bacteria and other microorganisms may also be required to attack the decomposition products (ZoBell, 1969).

The oxygen requirement of microbial oil decomposition is large, and oxidation would be slow in areas where previous pollution had depleted the oxygen content. Even when oxidation proceeds rapidly, depletion of the water's oxygen content by the active microorganisms may have harmful secondary ecological effects. Unfortunately, the most readily attacked fraction of crude oil – the normal paraffins – is the least toxic. The more toxic aromatic hydrocarbons – especially the carcinogenic polynuclear aromatics – are not degraded rapidly under natural conditions in seawater.

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That our coastal waters are not devoid of marine life, despite decades of contamination with oil, indicates that the sea is capable of recovery from such pollution. However, increasing stress is being placed on the estuarine and coastal environment by more frequent nearshore oil-pollution incidents, and once the recovery capacity of an environment is exceeded, deterioration may be rapid and catastrophic. We do *not* know how much oil pollution the ocean can accept and still recover, or whether our present rate of addition is approaching the limit of the ocean system.

Microbiological degradation is the ultimate fate of all oil left in the sea, but such degradation entails a severe oxygen requirement and a supply of other nutrients, such as nitrogen and phosphorus, for the degrading bacteria. Nevertheless, this process is a "natural" one.

The oceans appear to have recovered from the oil spilled during the six years of the second World War, though some recent oil slicks have been attributed to the slow corrosion of ships sunk during that conflict. It has been estimated that during the war, the United States lost 98 vessels with a total oil capacity of about 1 million tons, while other combatants lost 3 million tons of oil. These losses were large in the context of the 1940's, but the *total* 4-million-ton loss for that six-year period was only about *twice* the current *total annual* direct influx to the ocean. Although wartime sinkings and offshore oil releases do not appear to have caused extensive harm to the fish catch of the world, it must be emphasized that past history in this case is not a reliable base on which to predict future effects.

Some current sources of oil pollution can be controlled more rigorously than others, but without application of adequate controls wherever possible, the amount of petroleum hydrocarbons entering the sea will increase. Our technology is based on an expanding use of petroleum, and both the production of oil from submarine reservoirs and the use of the sea to transport oil will increase. World production of crude oil in 1969 was estimated to be nearly 2 billion tons: on this basis, total losses to the sea are somewhat over 0.1% of world production, or 2 million tons per year. Some losses in the exploitation, transportation, and use of a natural resource are inevitable; but if the loss ratio is not improved, the oil pollution of the ocean will continue to increase as our utilization increases.

Shipboard control measures have been introduced that appreciably reduce the sizable oil pollution from normal *tanker* operations. The Load On Top (LOT) process concentrates waste oil that is ultimately discharged with new cargo (IMCO, 1965a, 1965b). This procedure recovers somewhat more than 98% of the transported oil that would otherwise be released to the sea. It has been estimated (Revelle, et al., 1972) that 80% of the world fleet uses such control measures today, and contribute only 30,000 tons of the total oil loss each year. By contrast, the 20% of the fleet not using the control measures contributes 500,000 tons per year. If control measures were not in use by a major fraction of the tanker fleet, the contamination of the sea from this source would be about five times greater than it is today.

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B. PHYSICAL BEHAVIOR OF OIL

Crude oil spilled upon the sea surface forms an expanding slick whose thickness varies with the oil characteristics, the quantity and rate of spillage, and the environmental conditions of temperature, wind, and sea state. Four forces act on the oil: gravity, surface tension, inertia, and friction. As a slick expands, different forces predominate and there is a change in the rate of expansion. The following formulations have been developed (Fannelop and Waldman, 1972) for various slick regimes:

$$r = 1.14 \, (\Delta \, g \, V)^{\frac{1}{4}} \, t^{\frac{1}{2}} \qquad \text{Inertial} \qquad (1)$$

$$r = 0.98 \, (\Delta \, g \, V^2 / \nu^{\frac{1}{2}})^{1/6} \, t^{\frac{1}{4}} \qquad \text{Viscous} \qquad (2)$$

$$r = 1.6 \, (\sigma^2 / \rho^2 \nu)^{\frac{1}{4}} \, t^{\frac{3}{4}} \qquad \text{Surface Tension} \qquad (3)$$

where:

V = volume of oil

r = radius of slick

Δ = ratio of density difference to density of water

g = acceleration of gravity

t = time

ν = kinematic viscosity of water

σ = interfacial tension

ρ = density of water

These relationships appear to show reasonable agreement with the sparse experimental and actual observations of large oil spills. Because oil characteristics change as a slick ages, the above relationships could be developed into complex time-dependent expressions, but in their present form they do provide a first approximation of slick behavior.

Table D-6 summarizes the spreading characteristics of the two spill sizes considered in this report: 500 tons and 14,000 tons. The radius of the spills at various times are obtained from Eq. 2.

Figure D-3 shows the growth history of an oil slick over several days, during which time the spreading can be shown to be influenced by the viscosity of water (i.e., this figure is the plot of Eq. 2).

Theoretically, spreading will continue until the oil forms a monomolecular layer on the surface. Experimentally, it appears that final oil-film thicknesses do not go below about 10^{-2} or 10^{-3} centimeters. At sea, wave orbital velocities induce tension stresses into the film which cause it to break apart long before such thickness levels are reached, particularly as the oil ages and viscosity increases. At

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low temperatures, the layer of residuals breaks into asphaltic chunks, some of which may be heavy enough to sink or be driven down into the water column by the vertical water velocities. In agitated waters, the film may become emulsified, or may be broken into small globules whose surface-to-volume ratio is sufficiently high that they are also driven into suspension in the water column.

TABLE D-6

OIL SPREADING

Quantity	Symbol	Values	
Spill mass	M	500 tons	14,000 tons*
Oil density (an assumed average value)	ρ_{oil}	900 kg/m³	900 kg m³
Density of sea water	ρ_w	1030 kg/m³	1030 kg/m³
Spill volume	$V = \dfrac{M}{\rho_1}$	555 m³	15,600 m³
Gravity factor	$\Delta = \dfrac{\rho_w - \rho_1}{\rho_w}$	0.1262	0.1262
Acceleration due to gravity	g	9.8 m/s²	9.8 m s²
Kinematic viscosity of water	ν	10^{-6} m²/s	10^{-6} m²/s
Factor in Eq. 2	$\left[\dfrac{\Delta g v^2}{\nu^{1/2}}\right]^{1/6}$	26.925 m/sec¹/⁴	81.789 m sec¹/⁴
Radius of Slick			
in 1 day		442 m	1360 m
2 days		525 m	1625 m
3 days		590 m	1800 m
Mean Thickness			
in 1 day		0.09 cm	0.27 cm
2 days		0.064 cm	0.19 cm
3 days		0.051 cm	0.15 cm

* 1 metric ton = 1000 kg

Source: Arthur D. Little, Inc.

An oil slick is also subject to external forces. It will move with the mass of water on which it rests, or with the surface currents which are present. In addition, winds generate a shear force at the air-oil interface. A commonly accepted approximation of oil slick motion due to wind is a slick speed equal to 3% of the wind speed in the same direction as the wind. A further approximation which has shown reasonable accuracy is the vectorial addition to the velocities induced by the surface

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currents and the velocities induced by wind shear. Thus, an oil slick's boundaries expand with time as the entire slick is transported. If sufficiently detailed current and wind predictions for the area are available, then movements of the oil slick boundaries may be combined to predict the path and shape of a slick.
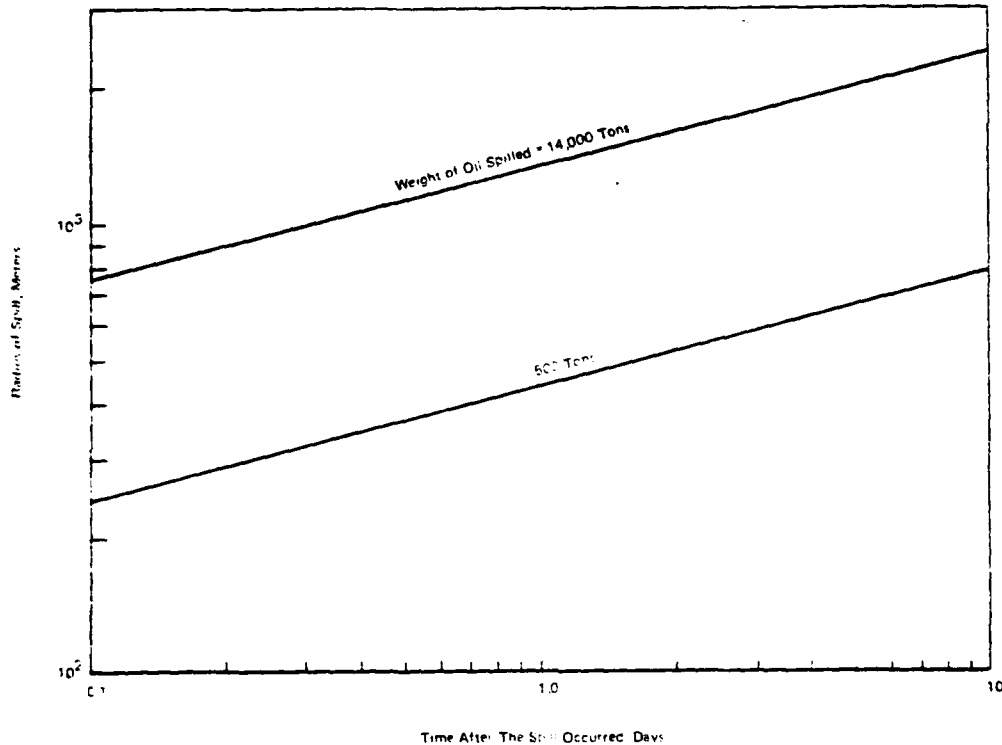
Source: Arthur D. Little, Inc.

FIGURE D–3   THE GROWTH OF AN OIL SLICK

While more sophisticated models have been studied, our interest in this work concerns only the general spreading rates of slicks and their gross movement on the surface. Both the spreading and movement problems involve many variables and can be attacked in detail for particular situations: that is, for particular oils and hydrographic and meteorological conditions at a given point. In this study, we are concerned with general behavior at selected sample points within the Gulf. Therefore, a simple but realistic hand-calculation method was developed to predict the trajectories of spills for different times of the year at each particular site.

Furthermore, definitive studies of ocean currents – at the level of detail required for site selection – do not exist for any of the prospective deep-water port sites. The detail and completeness of information varies from site to site. It is known that currents vary with the season at all sites, but detailed descriptions of this

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variation exists for none of the sites. The available information (Appendices A. B, and C) was examined, and our generalized assumptions about the seasonal current regimes at each offshore site were specified. In subsequent calculations, we assumed each current to be constant in a specified direction for three days.

Whereas the movement of both the oil and the ocean current are considered to be fully determined (by month), no such assumption can be made for the wind. (This statement reflects the availability of wind data that is considerably more detailed than current data for comparable operations.) Our calculations assumed that each site has a distinct monthly distribution of wind velocity by direction and speed (as shown in NOAA's Gulf Coast Guide). We also assumed that wind speed and direction remains constant for at least three days following a spill release. While this is a somewhat unrealistic assumption, it certainly provides an upper bound to the probabilities that a shoreline point will be reached. because shifts in the direction of the wind result in a zig-zag path instead of the straight-line path assumed in these calculations.

The actual calculations were carried out by hand as follows (see Figure D-4). Straight lines (OA and OB) are drawn from the spill site to the ends of a particular shoreline region (a, b). The resultant of the ocean current vector and 0.03 of the wind velocity vector must lie between these two lines if the spill is to reach the shore in this region. For any given point on the shoreline, there is a minimum resultant velocity needed for the spill to reach shore in a given period of time (say three days). By vectorially subtracting the ocean current ($\vec{V}_c$) from a given resultant, one determines the wind velocity vector necessary to produce that resultant. Hence, a translation $\vec{V}_c$ of the entire region of resultants between the two construction lines yields the region of wind velocities ($\vec{V}_m$) (speeds and direction) necessary to produce the resultant. i.e., for the oil to reach shore. The probability, therefore, that in a given month the wind velocity lies in this region is determined from its monthly wind velocity distribution and is equal to the probability that the oil will reach shore somewhere within the original boundaries in the given time period. The probability densities/mile of shoreline (Figures 4 through 8 in the main report) are obtained by dividing the total probability for a given segment of shoreline (as determined by the method just presented) by the length of that shoreline. The calculations were done for shoreline segment lengths from 10 to 15 nautical miles. These calculations give an average probability density for the segment, which is assumed to be the actual density at the segment midpoint. The midpoint probability densities for the set of shoreline segments chosen were graphed in such a way that the perpendicular distance from any point on the shoreline to the curve gives the approximate probability density per mile for that point. For sites which have distinct seasonal current changes and seasonal wind patterns, probability densities can be computed for different times during the year.

Calculations have been done which show that the total Shoreline Probabilities are relatively insensitive to our assumptions of the ocean current speeds when the current direction is nearly parallel to the shoreline. However, they are very sensitive to current speed in the three cases where the ocean currents have been assumed to

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be directed toward the shore; viz., Southwest Pass, Bayou La Fourche, and Freeport (only in May). If the true normal component of the current vector is greater than we have assumed, then the true Total Shoreline Probabilities will be greater than we have calculated, and if the normal component is less, then the total probability will also be less.
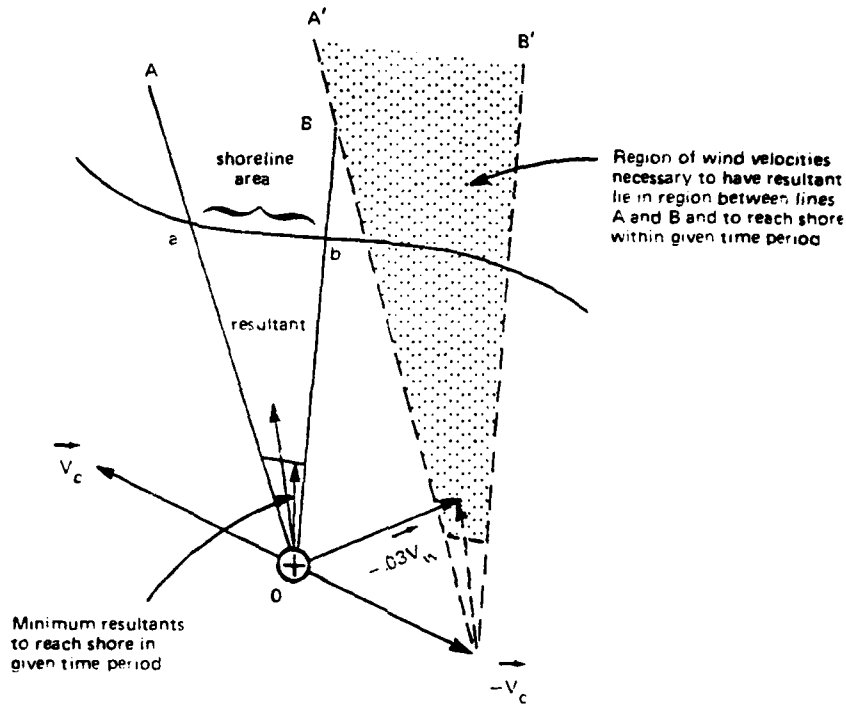
Source: Arthur D. Little, Inc.

FIGURE D–4   VECTOR ANALYSIS OF OIL SLICK MOTION

The assumption that the wind blows in the same direction continuously for 72 hours clearly needs examination. Preliminary calculations indicate that the effect of several major changes in the predominant direction of the wind would be to lower the calculated Total Shoreline Probability considerably. If there were four major uncorrelated changes in the 72 hour period, for example, calculations show our present Total Shoreline Probabilities to be about two to three orders of magnitude too high. Wind changes, however, are not uncorrelated. When Δt is on the order of minutes, or even a few hours, the probability that the wind will be blowing in the direction θ at time $t + \Delta t$, when it is blowing in direction θ_0 at time t, is much higher for small values of $\theta - \theta_0$ than for larger values. This correlation, while perhaps not so strong, may be significant for even longer periods (on the order of a few days). In this case, assuming uncorrelated changes would result in values which are smaller than the actual Total Shoreline Probabilities.

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We have examined the 1972 data from the National Climatic Center for various onshore locations near the proposed sites. Preliminary calculations indicate that the correlated wind direction changes resulting in non-straight-line paths for the spill may reduce our estimates for the Total Shoreline Probabilities by a factor of two.

C. CRUDE OIL

The term petroleum (crude) is applied to the deposits of oily materials. usually composed largely of hydrocarbons, found in the upper strata of the Earth's crust. The local distributions of plant and animal life are quite varied at the present time and, presumably, were similarly varied in earlier periods. Thus, the composition of the products derived from plant and animal species is not fixed with respect to either the molecular structures present or the proportions in which they occur. and the composition of petroleum may differ from region to region. pool to pool. and even from well to well within a pool. The presence of many similar molecular species in any one sample of petroleum makes the task of separation and identification of the components difficult at best. To date. no complete analysis of any one crude oil has been achieved.

To the best of our knowledge. the most extensive effort to characterize a crude oil completely – American Petroleum Institute Project 6 (APIRP-6) – has been described by Mair (1964). At present. they have identified 234 specific compounds with boiling points up to 475°C.

1. Composition

a. Hydrocarbons

After a careful review of the literature, it became obvious that due to variations in specific oil compositions and limited data on any one oil. we would need to synthesize a representative oil composition to satisfy the program needs. Accordingly, the composition of a hypothetical Mid-East Crude has been constructed from 1963 *Oil and Gas Journal* data for crude oils of ten Mid-East areas. Figure D-5 shows the temperature boiling point (tbp) curve and sulfur distribution vs. volume percent of crude for this hypothetical characteristic oil. Table D-7 lists chemical and physical properties of the crude, and Figure D-6 shows the variation in gravity and viscosity with crude fractionation for a 32 API intermediate-base crude.

In Table D-8, the crude has been broken down into its primary hydrocarbon fractions, corresponding to normal commercial fractions, with physical properties and chemical constituents listed for each. The composition data is that given by Martin (1963) of a 29 API gravity Iranian crude from the Darius Field.

b. Non-Hydrocarbon Species

In addition to the pure hydrocarbons, which constitute about 90-95 percent of the crude, there is also a wide variety of chemicals containing the trace elements of

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sulfur, nitrogen, and oxygen and also minor trace metals. These may all be present, bound either singly or in various combinations with the hydrocarbons.
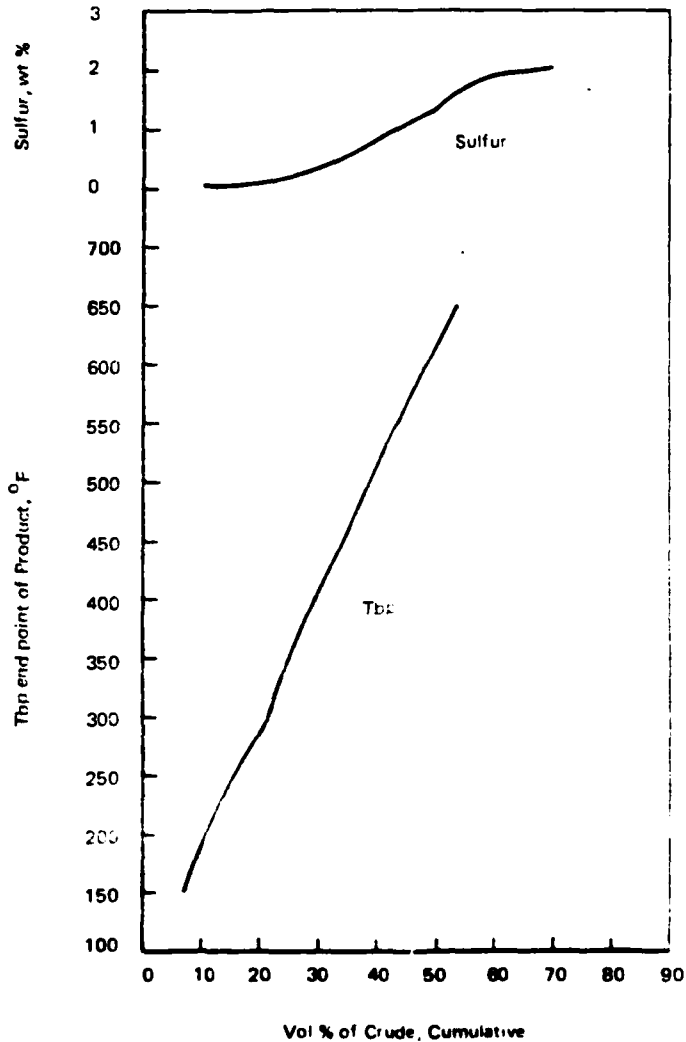
Source: *Oil and Gas Journal*, April 1963

FIGURE D–5   CHARACTERISTIC MID-EAST CRUDE
TEMPERATURE-BOILING-POINT CURVE

The presence of sulfur heterocyclics in the non-volatiles is shown in Figure D-5, which shows that less than 0.2 weight percent (out of 2.2 percent) is present in fractions boiling below 325°F. Ball (1962) has presented data showing that in a high-nitrogen crude the content of nitrogen in the distillate boiling below 570°F is very small. There is considerable evidence that, like nitrogen, oxygen is present in greater quantities as the boiling point increases; but this has not been as well documented as for nitrogen (H.M. Smith, 1968).

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TABLE D-7

CHARACTERISTIC MID-EAST CRUDE
CHEMICAL AND PHYSICAL PROPERTIES

Gravity[6]	0.8654
Viscosity[6], S.U.S. @ 100°F	57.0
Pour Point[6], °F	−5.0
Surface Tension[6], Dyne cm^{-1}	24.0
Sulfur[6], wt %	2.24
C_4 + lighter, Vol %	2.0
Carbon Residue[12], wt %	10.9
Ash[12], wt	0.04
Water[12] wt %	nil
Nickel[12], ppm	93.0
Vanadium[12], ppm	129.0
Nitrogen[12], wt %	0.58
Metalloporphyrin[7], ppm	152.0
Porphyrin metals[7] as Vanadium, ppm	14.0
Asphlatenes[5], wt %	1.6

Temperature Boiling End Point of Product[6]

°F	Volume % of Crude Cumulative
150	6.6
200	10.7
250	15.6
300	21.2
350	24.3
400	29.1
450	33.9
500	38.4
550	43.0
600	47.8
650	53.2

Source: *Oil and Gas Journal*, April 1963.

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TABLE D-8

CHARACTERISTIC MID-EAST CRUDE FRACTIONS[10]

	Light Gasoline	Naphtha	Kerosene and Gas Oil Distillate	Distillate	Residuum	Cumulative Overall Composition Vol %
Viscosity, S.U.S. @ 100°F	35	35	36.8	85	250	
Tbp range, °F	122-209	210-399	401-620	622-797	800+	
Gravity, Sp. G.	0.700	0.785	0.850	0.890	0.965	
Sulfur, wt %	0.07	.16	0.97	2.3	3.2	
Paraffins	8.2	11.3	12.4	6.1		38.0
Ring Cycloparaffins	1.6	4.1	3.5	3.9		13.1
Alkyl benzenes	0.2	3.7	1.4	0.6		5.9
Indans		0.1	0.7	0.2		1.0
Dinaphthenebenzenes			0.4	0.2		0.6
Naphthalenes			0.3	0.1		0.4
Acenaphthenes – Acenaphthylenes			0.5	0.7		1.2
Anthracenes, Phenanthrenes			0.2	0.7		0.9
Pyrenes, Chrysenes				0.4		0.4
Benzothiophenes, Naphthobenzothiophenes			0.9	2.5		3.4
Yield, vol % of total crude	10.0	19.2	20.7	15.4	34.7	
Yield, vol %, cumulative	10.0	29.2	49.9	65.3	100.0	65.3

Source: Martin, et al., *Proc. of 6th World Petroleum Congress*, 1963.

Volume Percent of Crude, Cumulative
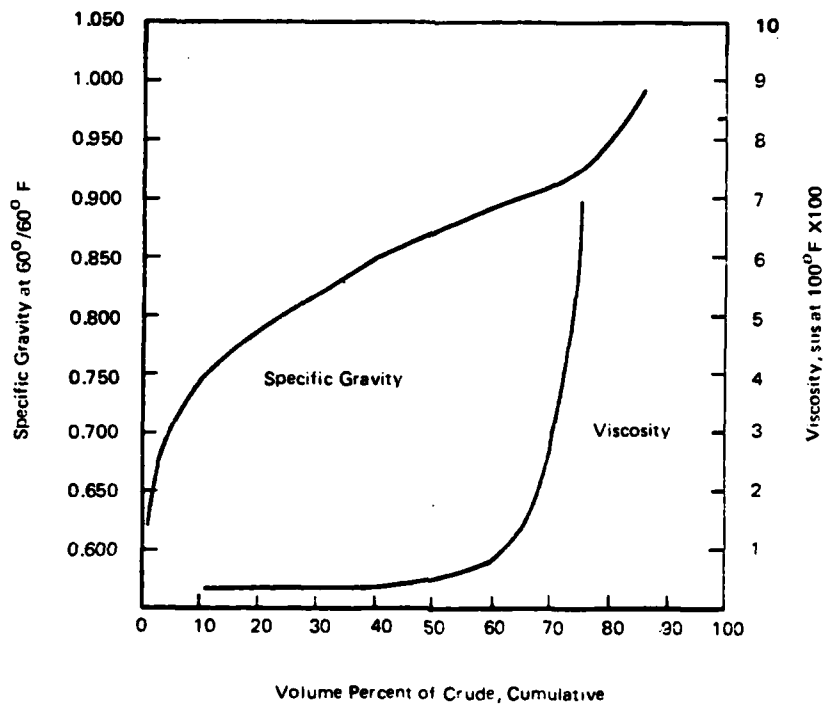
FIGURE D–6   SPECIFIC GRAVITY AND VISCOSITY FOR A
32 API INTERMEDIATE-BASE CRUDE OIL

Table D-9 shows the total sulfur compounds isolated in crude oil boiling from 50 to 560°F to be 0.04 weight percent. The oxo- and nitro-heterocyclics isolated in a California crude boiling from 400 to 1000°F are found in Table D-10, which shows the heterocyclics being more abundant in the high-boiling non-volatile fractions.

2. Weathering

a. Evaporation

The crude, being a complex mixture, will evaporate initially by loss of the lower boiling ends such as gasoline and naphtha fractions, and later, of successively higher boiling fractions. The evaporative process which occurs is a complex function of film thickness, wave action, wind, etc. Several estimates of the evaporative loss have been performed; Berridge, has found cases where fractions boiling lower than 700°F have been lost within a week. He further found from studies of the Torrey Canyon spill, that evaporation was limited to the loss of material boiling below 572°F. A laboratory study by Brunnock, who evaporated Kuwait crude oil by

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TABLE D-9

SULFUR COMPOUNDS IN CRUDE OIL

Type, Subtype	Weight Percent of Crude
Thiols:	
Alkyl	0.0200
Cycloalkane	0.0012
Sulfides:	
Alkyl	0.0062
Cyclic	0.0110
Alkyl-Cycloalkyl	i
Alkyl-Aryl	i
Thienyl	i
Dithialkyl	t
Bicyclic	i
Tricyclic	i
Thiophenes:	
Alkyl	0.0004
Bicyclic	i
Benzo	i
Dibenzo	i
Tricyclic	t
TOTAL	0.0388

i — Positively identified
t — Tentatively identified

Source: H. M. Smith, Bureau of Mines, 1968.

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TABLE D-10

SUMMARY OF NITROGEN AND OXYGEN COMPOUND TYPES IN 400-1000°F CRUDE DISTILLATES*

Aromatic Compounds	400-700°F	700-850°F	850-1000°F
$C_nH_{2n+z}N$			
Indoles	0.07% wt	0.59%wt	0.75% wt
Carbazoles	0.28	3.40	4.08
Benzcarbazoles	0.00	0.50	1.28
Pyridines	0.35	0.66	1.3
Quinolines	0.21	1.74	2.0
Benzoquinolines	0.03	0.26	1.6
$C_nH_{2n+z}NO$ (pyridones, quinolones, etc.)	0.2	1.2	2.0
$C_nH_{2n+z}N_2$ (azaindoles, etc.)	0.0	0.1	0.4
$C_nH_{2n+z}NO_2$ (dihydroxyquinolines, etc.)	0.003	0.02	trace
$C_nH_{2n+z}NS$ (thia-carbazoles, thiopheno-quinolines, etc.)	0.0	0.0	0.4
$C_nH_{2n+z}NOS$	0.0	0.0	0.1
$C_nH_{2n+z}O$	0.9	2.2	3.3
Benzofuranes	0.05	0.09	0.0
Dibenzofuranes	0.48	0.69	0.86
Benzonaphthofuranes	0.01	0.34	0.82
Dinaphthofuranes	0.00	0.00	0.16
Dihydrobenzofuranes	0.06	0.07	0.08
Phenols	0.32	0.97	1.35
$C_nH_{2n+z}O_2$ (hydroxydibenzofuranes, benzofuranodihydro-benzofuranes, etc.)	0.0	0.0	0.1
$C_nH_{2n+z}OS$ (benzofuranodibenzo-thiophenes, hydroxy-phenols, etc.)	0.0	0.0	0.1
Aliphatic Compounds	1.0	2.5	3.6
Carboxylic acids	0.50	1.74	1.35
Other Oxygen Compounds			
Monofunctional	0.50	0.58	1.65
Difunctional	0.02	0.14	0.65
Totals			
Aromatic heterocompounds	2.0	10.7	17.4
Aliphatic heterocompounds	1.0	2.5	3.6
Total	3.0	13.2	21.0

* Does not include sulfoxides (since these are not native to the original crude oil).

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bubbling 5 ℓ/min of nitrogen (used to minimize oxidation) through 250-mℓ portions of crude found that the residues from this study agreed well with a fractionated residue. The results of the study are shown in Figure D-7. Whereas evaporation is a non-equilibrium process, it is difficult to ascertain the effects of weathering. We have interpreted the results of this study to suggest that at time (t + 1) days the spill will have lost the light gasoline fraction, and at (t + 3) the naphtha fraction as well. Table D-11 contains the crude composition adjusted for the losses, maintaining the composition basis on volume of original crude.

TABLE D-11

CHARACTERISTIC MID-EAST CRUDE COMPOSITION
EFFECT OF WEATHERING

	Duration — 1 day	Duration — 3 days
Viscosity, SUS @ 100°F	35	35
Tbp range, °F	210 ↑	400 ↑
Gravity, API	58	42
Sulfur, wt %	2.2	1.9
Paraffins	29.8	18.5
Ring Cycloparaffins	11.5	7.4
Alkyl benzenes	5.7	2.0
Indans	1.0	0.9
Dinaphthenebenzenes	0.6	0.6
Naphthalenes	0.4	0.4
Acenaphthenes, Acenaphthylenes	1.2	1.2
Anthracenes, Phenanthrenes	0.9	0.9
Pyrenes, Chrysenes	0.4	0.4
Benzothiophenes, Naphthobenzothiophenes	3.4	3.4
Yield, Vol % of Total Crude	55.3	36.1
Residue	34.7	34.7
Evaporative loss, vol %	10.0	29.2

Source: Martin, et al., *Proc. of 6th World Petroleum Congress*, 1963.

b. Solubility

Dissolution of the various chemicals present in crude oil represents one of the major mechanisms of creating a toxic environment for the biota. It is difficult to obtain accurate estimates of the rates of solution of these species under spill conditions, so we have approached the problem by assuming some maximum ideal conditions and calculating the resultant concentration to determine whether these

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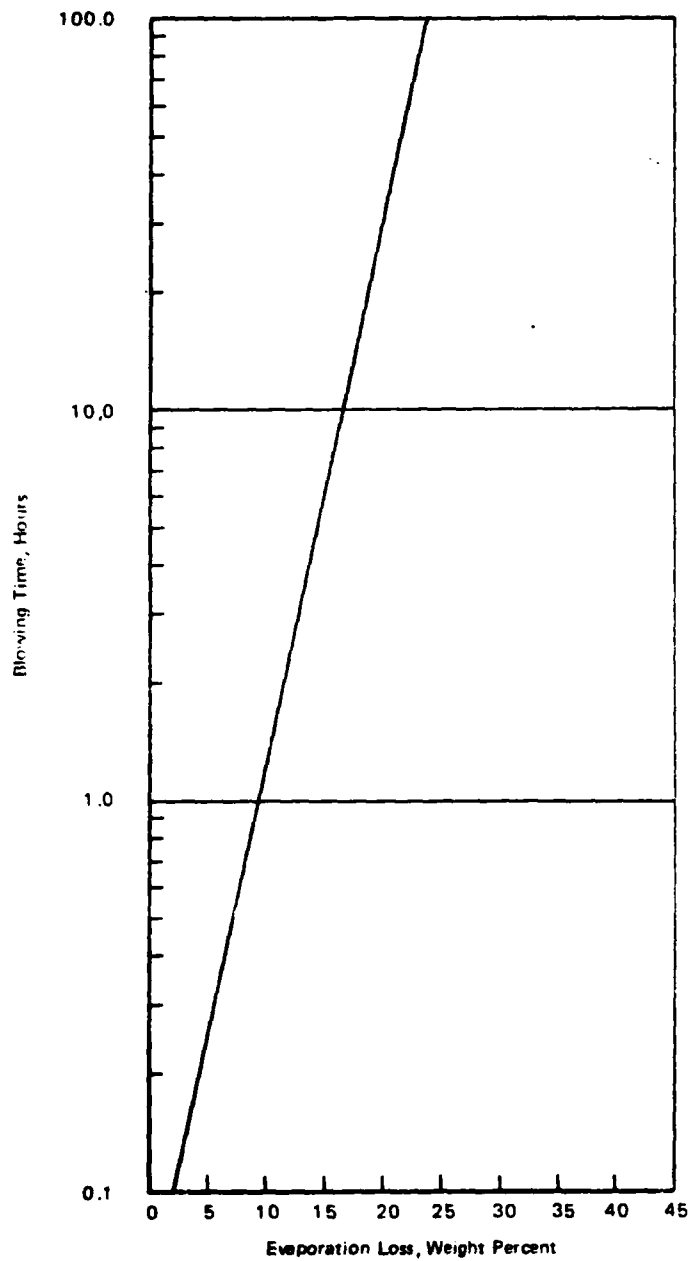
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Naphthalenes	0.4	0.4
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Pyrenes, Chrysenes	0.4	0.4
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Source: Berridge, et al., *Journal of the Institute of Petroleum*, November 1968.

FIGURE D—7   EVAPORATION LOSSES FROM NITROGEN-BLOWN KUWAIT CRUDE

are clearly above or below toxic levels. The equilibrium solubilities of a few of the more toxic (acute cellular) species in each type of major chemical class are listed below:

Species	Solubility (ppm)	Species	Solubility (ppm)
hexane	140	phenol	82,000
heptane	50	pryidine	infinite
nonane	10	aniline	36,000
benzene	820		
toluene	470		
naphthalene	300		

Clearly the paraffins are the least soluble. The aromatic hydrocarbons have moderate solubility, and the functional derivatives have high solubilities.

We estimated the possible concentrations which could be achieved of some of these same species using two sets of conditions. In estimating the magnitude of the acute toxicity problem, a break occurs at about 3 ± 1 days when most of the volatile (gasoline and naphtha) fractions have vaporized. At this time, most of the soluble toxic functional species will still be present in the crude oil.

An estimate of the possible maximum concentrations from a 500-ton spill may be made using the reported crude compositions, assuming equilibrium solubility in a one-meter depth. These data are summarized in Table D-12 for two aromatics and two functional derivatives. The values were computed using the actual composition data and the data for all similar species present in the crude oil fraction boiling up to 700°F. The species in the distillate fraction above 700°F have much lower acute toxicity.

All of the computed values are probably high by at least a factor of 10 to 100, because they assume equilibrium, a limited one-meter depth, and no mixing. However, the data does suggest that the immediate acute toxicity problem from the low-molecular-weight aromatics is greater after one day than the heterocyclics are after three days. Further, because of the exaggeration in the assumption, it is unlikely that the heterocyclics represent an acute toxicity problem at any time. However, they could contribute to longer-term chronic toxicity.

A significant point to realize from this data is that there is never enough crude oil present under normal circumstances to achieve maximum equilibrium solubility of the species present in the oil.

c. Emulsions

Berridge, et al. (1968) point out that some crude oil emulsifies readily at sea, forming rigid stable water-in-oil emulsions which can contain up to 80% water, having a film thickness of 1 mm. Such emulsions are stiff, yellowish-brown in color.

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and since the Torrey Canyon incident, have become widely known as "chocolate mousse." The process of emulsification slows down the tendency of a slick to spread. The viscosity of the mousse is in excess of 1000 cst. Berridge found that natural phenomena, such as oxidation, bacteria, etc., believed to have some effect on the rate of removal of a thin film of oil spread on the open sea. have no significant effect on the removal of lumps of mousse. Further studies suggested that the surface active material responsible for the formation of these water-in-oil emulsions is present in the non-volatile residue. The most probable components are the as-phaltenes and the metalloporphyrins, for without their presence no stable mousse were formed. Whereas Mid-East crude contains 1.6 percent by weight asphaltenes and 152 ppm metalloporphyrins which are comparatively high values when com-pared to crudes from other locales. we feel they present a great problem. Unfortu-nately. no quantitative estimate of the effect is possible. except to say the occur-rence and quantity of water-in-oil emulsion is thought to be comparatively high for Mid-East crude.

TABLE D-12

POSSIBLE MAXIMUM CONCENTRATION OF CRUDE OIL COMPONENTS

Species	Maximum Concentration* (ppm) at	
	1 day †	3 days §
Benzene	4	vaporized
Toluene	30	vaporized
Total Alkyl Benzenes	100	vaporized
Pyridines	20	2
Phenols	20	2
Total Functional Hydrocarbons	120	12

* assume equilibrium in one-meter depth
† film thickness of 1.3 cm from 500-ton spill
§ film thickness of 0.15 cm from 500-ton spill

Source: Arthur D. Little, Inc.

d. Sinking

Nelson-Smith (1970) has shown that the phenomena of sinking may occur by two mechanisms: concentration of residue after prolonged periods of exposure and by suspended matter.

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Concentration of residue results in a higher mean molecular weight, thus causing the specific gravity (sp. gr.) to increase. Fresh crude has a density of 0.855, but through evaporation of the lower boiling fractions up to gas oil distillate the sp. gr. quickly increases to 0.934. Upon further exposure, possibly 20 to 50 days the residue (1000°F+) will have concentrated to 13 percent by volume and have a sp. gr. of 1.03, whereas the sp. gr. of seawater is 1.024) thus unstable condition will occur, resulting in sinking.

Where there are large quantities of suspended matter, for example in tidal estuaries, or off the Mississippi delta, this matter may be incorporated into the oil, increasing its tendency to breakup and sink. Investigation has found that increasing salinity reduces the ease with which oil is sedimented. Removal methods for crude have been tried having powder or fine granular solid of high true density distributed over the oil patch which mix with the oil, adhere to it, and sink it. Normally, it was found that after several months under water, the sunken mass was still mobile and could be released by agitation.

e. Biological Degradation

J. W. Smith (1968) has observed the fate of oil lying on the sea bed, and found that the natural biological degradation of oil in the sea, especially where the oxygen content is high, is much more rapid than was at first believed. Based upon rates at which marine bacteria have been observed to oxidize various types of mineral oils under controlled laboratory conditions, and upon information of the abundance of bacteria in the sea, oil might be oxidized in the sea at rates as high as 100-960 mg/m^3 per day, or 36-350 g/m^3 per year. These figures are tentative, but nevertheless, they do indicate that microbiological degradation is a highly important factor in weathering.

f. Atmospheric Oxidation

Oxygen attacks hydrocarbons in the liquid phase. Berridge (1968) notes that of the types of hydrocarbons present in crude oil, paraffins and aromatic hydrocarbons with suitable side chains will be attacked most readily. In the absence of ionic catalysts, autoxidation is a free-radical chain process. The rate of propagation of the chain process is controlled by the rate of abstraction of an H-atom from the hydrocarbon by an alkylperoxy radical, as tertiary C-H bonds are weaker than primary or secondary C-H bonds, and hydrocarbons (such as isoalkanes) with tertiary hydrogens will be attacked most readily. Hydrocarbons such as tetralin and cumene, the alkyl radicals from which are resonance-stabilized, are also susceptible to relatively rapid oxidation.

This simple mechanism is complicated, however, by the occurrence of photo-oxidation and of oxidation catalysed or inhibited by a wide variety of materials which may be present in crude oil. In particular, the ions of metals of variable valency (e.g., nickel and vanadium) strongly catalyze oxidation in the liquid phase, but sulfur compounds inhibit it due to the chain-breaking reactions of sulphoxide

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formation. The kinetics of the oxidation depend on the oxygen partial pressure, temperature. and the hydrocarbon: the total quantity of products formed is a complex function of the rate constant for the decomposition of peroxides. The kinetic curve is S-shaped. After an initial induction period, there is a period of increasing rate, followed by an asymptotic leveling of the rate of oxidation. and finally the reaction ceases.

Many of the products of these oxidation reactions (e.g., acids, carbonyl compounds, alcohols, peroxides, sulphoxides) are soluble in water and will be removed. Similarly, the formation of water-soluble metal salts (e.g., vanadium salts by the reaction of vanadyl porphyrins with peroxides) can lead to the removal of metals from the oil.

It is obvious that there can be wide range of oxidation rates for oil on the sea. Thus. for example. a highly paraffinic, low-sulfur crude would oxidize in bright sunlight much more rapidly than a less paraffinic. high-sulfur crude as found in the Mid-East. It is difficult to estimate the absolute rate of oxidation of a crude oil on the sea because of the diversity of these effects. At sea temperature. however. it is unlikely. particularly in the early stages of exposure. that atmospheric oxidation is as important a factor in removing oil as are predominately physical processes. such as evaporation and spreading.

D. BIOLOGICAL RESPONSES TO OIL

The ultimate impact of oil on the biota of a region depends not only on the effect of oil on individual organisms, but also the changes that occur in species populations. communities. and ecosystems as a result of effects on individuals. Unfortunately, one of the least understood and most difficult aspects of the problem to deal with is the effect on the higher levels of biological organization. Uncertainty in the spatial and temporal distribution of oil: uncertainty in the geographic and species distribution of the biotic communities in a particular area; and uncertainty about community and ecosystem dynamics all combine to prevent quantitative assessment of the ultimate impacts of spilled oil in a particular region. However, a literature review recently completed by Moore, et al. (1973) at M.I.T. has provided some clarification of the effects of oil on individual organisms, which is some value for the task at hand.

1. Effects

The effects of oil (from any source) on individual organisms may be categorized as:

(a) immediate (acute) lethal toxicity:

(b) sub-lethal disruption of cellular level processes. causing disruption of behavioral patterns (death may follow, but not immediately and usually indirectly, if at all):

(c) lethal and sub-lethal effects of coating organisms with oil, which does not interfere with cellular activities, but mechanically interfere with organism activities such as respiration, feed, and locomotion;

(d) incorporation of hydrocarbons in organism tissue, which may cause tainting, and/or accumulation of high-boiling-point polycyclic aromatic hydrocarbons in the food chain;

(e) alterations in habitats caused by deposition of oil on substrates such as rocks, sand, and mud.

Different types of compounds in oil are responsible for causing these various effects. The lower-boiling (b.p. < 250°F), high-solubility aromatic, compounds are the primary cause of immediate toxicity, behavioral disruption, and tainting. Coating and habitat alteration result from the tarry residue components.

Due to weathering processes (described in the previous section) the particular individual response listed above which can be expected in any particular case is highly dependent upon the time elapsed since the spill occurred. As indicated previously, the lower-boiling high-solubility components of an oil slick can be expected to be lost in the first three days following the spill release. Therefore, acute toxic and other effects associated with these materials will only be expected to be significant during this initial time in the life of the slick.

In addition to dependence on oil composition, the effects of spilled oil also vary due to the different biological sensitivities of various types of organisms. For example, gastropods are apparently much less subject to acute toxicity than crustaceans. Also, sessile organisms, such as mussels, are highly subject to effects of coating, whereas fish are not because of their mobility.

Another source of confusion in assessing the biological effects of oil is the lack of dependable experimental and field observation on the toxicity and other effects of oil on marine organisms. It is difficult to evaluate the toxicity of this complex mixture of compounds, which is not completely miscible with sea water. However, a variety of techniques have been tried. In some experiments, oil is floated on the water in the test container. The concentration is derived from the quantity of oil and the total quantity of water; clearly not the concentration to which the organism has been exposed. In other experiments, extracts of oil with hot water or with various solvents are added to the test jar, without identification of the oil fraction being tested. In still other cases, care has been taken to produce a fine emulsion of oil in sea water more representative of the actual concentration to which the test organism is exposed. Considering the differences in the meaning of "concentration" in these tests, and the variation in sensitivity of the test organisms, it is not surprising that the ranges of toxicity that can be found in the literature vary by several orders of magnitude.

2. Toxicity Literature

Studies of the toxicity of oil have been reviewed by Clark (1971). Mironov (1971) carried out toxicity studies by comparable techniques using a variety of marine organisms. In testing 11 species of phytoplankton, he found that cell division was delayed or inhibited by concentrations of crude oil (unspecified type) ranging from 0.01 to 1000 ppm. He also showed that some copepods were sensitive to a 1-ppm suspension of fresh or weathered crude oil and of diesel oil. Freegarde, et al. (1970), found that the larvae of *Balanus balanoides* and adult *Calanus* copepods maintained in a suspension of crude oil ingest, without apparent harm, droplets of oil that later appear in the feces. Mironov (1967) found 100% mortality of developing flounder spawn at concentrations of three types of oil ranging from 1 to 100 ppm and an increased abnormality of development at longer periods of time in concentrations as low as 0.01 ppm. In contrast, other experimenters have found that concentrations of several percent are necessary to kill adult fish within a few days (Chipman and Galtsoff, 1949; Griffith, 1970).

Finely dispersed droplets may be ingested by filter-feeding organisms and thus become an integral part of the marine food chain. Some of the oil may pass through the gut in the feces of these organisms, but Blumer, et al. (1970), have shown that it can pass through the gut wall and be incorporated in the organism's lipid pool. Dissolved within the fatty tissues of the organisms, even relatively unstable hydrocarbons are preserved. They are protected there from bacterial attack and can be transferred from food organism to predators and possibly to man.

In addition to petroleum's toxicity to fish and the lower classes of marine fauna and flora, petroleum also presents a hazard to avian and mammalian forms. Not only are some of these forms affected by the immediate presence of oil, but they may feed upon marine life which has ingested and stored oil. The diving birds which spend most of their life at sea are most prone to death from oil pollution, but any bird that feeds from the sea or settles on it is vulnerable. In oil-matted plumage, air is replaced by water, causing loss of both insulation and buoyancy; oil ingested during preening can have toxic effects.

Hartung and Hunt (1966) fed oils directly to birds by stomach tube and later analyzed, through autopsies, the pathological and physiological effects. The lethal dose for three types of oil ranged from 1 ml to 4 ml per kilogram (ml/kg) when the birds were kept outdoors under environmental stress. The experimenters concluded that a duck could typically acquire a coating of 7 grams of oil and would be expected to preen approximately 50% of the polluting oil from its feathers within the first few days. Enough of this could easily be ingested to meet the lethal dosage of 1 to 4 ml/kg. Thus, birds that do not die immediately from exposure to cold or by drowning as a result of oil pollution may succumb later from the effects of ingestion.

Oils sink because of increased specific gravity with weathering and the accretion of heavy debris or sand into the oil, so carbonized sand has been used to sink oil

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from spills. Sinking of oil has also been experimentally achieved by scattering talc or chalk on the oil, causing it to agglutinate into globules of density greater than sea water. However, such sunken oil tends to kill bottom fauna before even the motile bottom dwellers have time to move away. The sessile forms of commercial impor-tance, such as clams, oysters, and scallops, cannot escape. Little is known about the rate of degradation of oil in bottom sediments, but it is known that some fractions will persist for over a year (Blumer, 1969).

When an oil spill occurs near shore, or an oil slick is brought to the intertidal zone and beaches, extensive mortality of marine organisms occurs. When the Tampico Maru ran aground off Baja, California, in 1957, about 60,000 barrels of spilled diesel fuel caused widespread death among lobsters, abalones, sea urchins, starfish, mussels, clams, and hosts of smaller forms (North, 1967).*

In West Falmouth, Massachusetts, a relatively small oil spill occurred within a few miles of the Woods Hole Oceanographic Institution in September 1969; since then, biologists and chemists of the Institution have studied the effects of introducing fuel oil into the coastal waters. Studies of the biological and chemical effects of this spill are still continuing, over two years after the event (Hampson and Sanders, 1969; Blumer, 1969; Blumer, et al., 1970; Blumer and Sass, 1972). Immediately after the accident, massive destruction of a wide range of fish, shellfish, worms, crabs, other crustaceans and invertebrates occurred in the region. Bottom-living fish and lobsters were killed and washed ashore. Dredge samples taken in 10 feet of water soon after the spill showed that 95 percent of the animals collected were dead and the other 10 percent were moribund. Much of the evidence of this immediate toxicity disappeared within a few days, either because of breaking up of the soft parts of the organisms or because the organisms were buried in the sediments or dispersal by water currents. Careful chemical and biological analyses reveal, however, that not only has the damaged area been slow to recover but the extent of the damage has been expanding. A year and a half after the spill, identifiable fractions of the source oil were found in organisms that still survived on the perimeter of the area.

In the crude oil spills from the wreck of the tanker Torrey Canyon and the Santa Barbara oil-well blowout, oil reached the beaches in significant amounts at varying times after release. The oil may thus have been diluted and modified by evaporation or sinking before it reached the beach. In the Santa Barbara spill, many birds died and entire plant and animal communities in the intertidal zone were killed by a layer of encrusting oil, often 1 or 2 centimeters thick (Holmes, 1967). However, in the case of the Torrey Canyon, the deleterious effects have been attributed more to the detergents and dispersants used to control the oil than to the oil itself (Smith, 1968).

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*A *beneficial* side effect of this accident was also noted by North. When the sea urchins that grazed on the economically important kelp beds of the area were killed in massive numbers by the oil spill, huge canopies of kelp returned within a few months.

The catastrophic ecological effects of the oil spills of the Tampico Maru (Baja, California) and the Florida (West Falmouth) appear to be more severe than those reported from other oil spills such as the Torrey Canyon (Salty Islands) and the Santa Barbara (California) blowout. The Tampico Maru and the Florida accidents both released refined oils (in one case, diesel oil; in the other. No. 2 fuel oil) and both occurred closer to shore than either the Torrey Canyon or the Santa Barbara accidents, which released crude oil. The differences in the character of the oil and the proximity to shore may account for the more dramatic effects of the first two accidents, but it is clear that any release of oil in the marine environment carries a threat of destruction.

3. Conclusions

Although there remain many sources of uncertainty and there are large gaps in the data base, some conclusions can be drawn:

1. Concentrations of water-soluble aromatic derivatives (aromatic and naphtheno-aromatics) as low as 0.1 ppm may be toxic to larvae of most marine organisms.

2. Most adult marine organisms are sensitive to soluble aromatic derivatives in concentrations of 1 ppm, and lethal toxicity typically occurs at concentrations of 10-100 ppm. In general, crustaceans and burrowing animals are most sensitive, fish and bivalves moderately sensitive, and gastropods and flora least sensitive. However, fish and other mobile organisms are generally known to avoid and escape contaminated areas.

3. Chemical communication plays an important role in the behavioral patterns of many marine organisms. The full implications of disruption of these communication patterns remains uncertain, as does the exact mechanism of disruption. However, concentrations of soluble aromatic derivatives in the range of 10-100 ppb may cause significant problems.

4. The incorporation of hydrocarbons in the tissue of marine organisms is primarily of interest due to public health. The individual organisms are apparently not affected. Whether or not cancer can be induced in humans from ingestion of carcinogens accumulated in seafood is as yet unknown. However, the potential seriousness of the problem implies that careful consideration be given to these issues. The actual mechanisms of build-up in the food chain also remain uncertain. There is some evidence that incorporation results primarily from uptake directly from sea water and not from ingestion of contaminated food sources. In addition, there is a general, slow degradation of hydrocarbons, indicating that the ultimate fate (after many years) may be stable, innocuous compounds.

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5. The development of objectionable taste in seafood (10-50 ppm in the organism) can result from very low ambient concentrations in water (1-10 ppb) of hydrocarbons in a relatively short amount of time (one to a few days). If the contamination in the water is short-lived, and concentrations in water are not too high, self-cleaning of the organism may be 90 percent complete. However, the maintenance of undesirable water conditions over long time periods can result in essentially permanent contamination of the organism.

6. The effects of weathered oil are coating, usually in the intertidal zone, of both organisms and substrates. If coating is heavy, the effects may be essentially permanent, due to smothering of individuals or alteration of substrate textures. Light coating of weathered oil is not, in general, a major problem. Frequency of coating is important, and areas subject to chronic discharge may accumulate the oil, leading to longer-term problems.

In summary, the relative importance of the effects listed above, and the ultimate impact of oil in a particular situation depends on many factors, including: composition and amount of oil; physiography, hydrography, and weather in the region of the spill; biota in the region of the spill; season of the year; and previous exposure to oil. The composition and amount of oil determines the nature of materials actually introduced into the marine environment. Physiography, hydrography, and weather determine the spread, trajectory, and dispersion of the oil in the environment. Because the sensitivity of the organisms actually exposed to the oil varies over a wide range, the specific biota of the region must be considered. This sensitivity is strong, and is influenced by the time of year (spawning, migration, etc.). The overriding factor is the dynamic nature of this problem. Oil weathering results in changes in the composition and characteristics of the oil through time (Blumer and Sass, 1972). Wind and currents transport spilled oil over large areas in the environment (Fay, 1971; Ichiye). The stages in the life cycle of most organisms have different sensitivities to oil (Hepple, 1971; Cowell, 1971; Nelson-Smith, 1970). Previous history of spills may determine susceptibility and adaptations of organisms (Kanter, et al., 1971). All of these factors are dynamic, changing through time and must be considered in the analysis.

Arthur D Little Inc

V. SELECTIVE SECONDARY ONSHORE IMPACTS

The impacts summarized by category in the following listed tables and figures that appear in this appendix.

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PETROLEUM DEMAND/SUPPLY PROJECTIONS – U.S. TOTAL
(in thousands of barrels daily)

Demand/Supply	1970				1980				2000			
	Crude	Residual	Other	Total	Crude	Residual	Other	Total[1]	Crude	Residual	Other	Total[2]
Demand	11,412[a]	2,204	12,512	14,716	18,700[a]	4,100	18,600	22,700	32,700[a]	4,100	30,900	35,000
Production	10,171	705	12,311	13,016[b]	11,800	1,100	17,600	18,700[b]	13,000	1,800	30,900	32,700[b]
Surplus (or deficit)	(1,241)	(1,499)	(201)	(1,700)	(6,900)	(3,000)	(1,000)	(4,000)	(19,700)	(2,300)	–	(2,300)
Exports	14	54	190	244	–	–	–	–	–	–	–	–
Imports from:												
Canada	672	–	–	–	1,900	–	–	–	2,500	–	–	–
L.A.-Carib.	291	–	–	–	–	3,000	900	3,900	–	2,300	–	2,300
M.E.-Africa	291	–	–	–	4,900	–	–	–	15,200	–	–	–
Far East	70	–	–	–	100	–	100	100	2,000	–	–	–
Total	1,324	1,528	452	1,980	6,900	3,000	1,000	4,000	19,700	2,300	–	2,300
Total (million short tons)	74.3	85.8	25.4	111.2	387.5	168.5	56.2	224.6	1,106.2	129.2	–	129.2

a. Runs to stills of crude and natural gasoline.

b. Refinery output plus natural gas liquids (NGL) blended and produced at refinery.

Source: 1970 – U.S. Department of the Interior, Bureau of Mines, *Mineral Industry Surveys*, "Monthly Petroleum Statement," December 1970, prepared by the Division of Fossil Fuels, March 23, 1970. 1980 and 2000 – projections by Robert R. Nathan Associates, Inc.

1. Demand ranges -- low 21.6 MM; high 23.9 MM.

2. Demand ranges – low 25 MM; high 39 MM.

TABLE D-14

PETROLEUM DEMAND/SUPPLY PROJECTIONS – PAD DISTRICTS II, III, AND IV

(in thousands of barrels daily)

Demand/Supply	1970				1980				2000			
	Crude	Residual	Other	Total	Crude	Residual	Other	Total	Crude	Residual	Other	Total
Demand	8,355[a]	311	6,598	6,909	13,900[a]	600	9,800	10,400	23,200[a]	800	15,400	16,200
Production	8,848	362	9,336	9,698[b]	8,600	600	13,300[b]	13,900	10,000	1,100	22,100	23,200[b]
Surplus or (deficit)	493	51	2,738	2,789	(5,300)		3,500	3,500	(13,200)	300	6,700	7,000
Exports	13	13	95	108	–		–	–	–	–	–	–
Domestic Shipments to:												
Dist. I	680	78	2,671	2,749	–	–	3,530	3,530	–	300	7,000	7,300
Dist. V	38	–	154	154	–	–	170	170	–	–	–	–
Total	718	78	2,825	2,903	–		3,700	3,700	–	300	7,000	7,300
Domestic Rects from:												
Dist. I	–	–	120	120	–		200	200	–	–	300	300
Dist. V	–	–	–	–	570		–	–	–	–	–	–
Total	–	–	120	120	570		200	200	–	–	300	300
Imports from:												
Canada	365				1,800				2,500			
L.A. – Carib.	–				–				–			
M.E. – Africa	–				2,930				10,800			
Far East	–				–				–			
Total	365	42	71	113	4,730				13,200			
Total (million short tons)	20.5	2.4	4.0	6.3	265.6				741.2			

a. Runs to stills of crude and natural gasoline.

b. Refinery output plus NGL blended and produced at refinery

TABLE D-15

CRUDE OIL IMPORT IMPLICATIONS FOR GULF COAST PETROLEUM REFINING INDUSTRY

MM b/d Imported Crude to Gulf Coast New Refineries Estimated Year	=	MM$ Capital Expenditures Gulf Coast Location ($\sim$ \$1,600/bdc)[1]	+	MM Constant 1970 \$ Value of Output at Refinery Gate ($\sim$ \$4.80/bbl)[2]	+	Refinery Employment ($\sim$ 600/250,000 b/d New Refinery)
1		$ 1,760		1,680		2,400
2		3,520		3,360		4,800
3 ($\sim$ 1980)[3]		5,280		5,040		7,200
4		7,040		6,720		9,600
5		8,800		8,400		12,000
6 ($\sim$ 1990)[3]		10,560		10,080		14,400
7		12,320		11,760		16,800
8		14,080		13,440		19,200
9		15,840		15,120		21,600
10 ($\sim$ 2000)[3]		17,600		16,800		24,000

1. Includes desulphurization units to process crudes with sulphur contents up to 2.5 percent (by weight). Capital expenditures includes 10 percent allowance for excess capacity.

2. The value of refining gain estimated at 3 to 4 percent of crude input is not included. Plants are estimated to operate 350 days/year.

3. Timing in accordance with Robert R. Nathan Associates Inc., estimates.

Source: Arthur D. Little, Inc.

Arthur D Little, Inc.

TABLE D-16

CRUDE OIL IMPORT IMPLICATIONS FOR
GULF COAST PRIMARY[2] PETROCHEMICAL INDUSTRY

MM b/d Imported Crude to Gulf Coast New Refineries Estimated Year	Percent Petrochemical Feedstock Equivalent (Going to New Plants)	= MM b/d Feedstock Output[1] or Equivalent Consumption	= MM Constant 1970 $ Capital Expenditures[2] (~$9,800/b/d)[3]	+ MM Constant 1970 $ Value of Petrochemical Output[2] (~95% of Capital Expenditures)[4]	+ Plant Operating Employment[2] (~14/MM $ Output)[5]
1	14	0.140[6]	$ 1,509	$ 1,303	18,200
2	14	0.280	3,018	2,606	36,400
3 (~1980)	14	0.420	4,527	3,909	54,600
4	14	0.560	6,036	5,212	72,800
5	20	1.000	10,780	9,310	130,300
6 (~1990)	25	1.500	16,170	13,965	195,500
7	27	1.890	20,374	17,596	246,300
8	29	2.320	25,010	21,599	302,400
9	30	2.700	29,106	25,137	351,900
10 (~2000)	30	3.000[7]	32,340	27,930	391,000

1. 37,500 bbl/day = ~1 bil. lb ethylene plant complex.
2. Representing primary petrochemical complex: Ethylene and basic organic chemicals (ethylene glycol, vinyl chloride monomer, polyvinyl chloride, ethanol, etc.) Excludes intermediate and derivative petrochemical processing.
3. A 10 percent allowance for excess capacity has been included.
4. Excess capacity allowance excluded.
5. National Average; employment levels exclude productivity considerations.
6. Representing an estimated 4 primary petrochemical complexes.
7. ADL estimates petrochemical industry's total national naphtha feedstock requirements by the year 2000 could amount to approximately 7 million bbl/day.

Source: Arthur D. Little, Inc.

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Arthur D Little, Inc.

TABLE D-17

U.S. PETROCHEMICAL FEEDSTOCK REQUIREMENTS

M bbls/day

	1970	1975	1980	1985	2000
Total Petrochemical Feedstock Requirement to Support U.S. Demand	818	1,230	1,800	2,750	7,150
Natural Gas Liquids	453	455	550	370	300
Heavy Liquids and Refinery Gas Liquids	365	775[1]	1,200[1]	2,280[1]	4,510[1]
Foreign Production Displacement	—	—	50	100	2,340
Crude Oil Imports — East, West and Gulf Coast Destination[2]		3,000	5,800	7,800	13,800
Percent Crude Oil Import Equivalent to New Petrochemical Complexes		14%	14%	24%	30%
Heavy Liquid bbl Equivalent to New Petrochemical Complexes		410	835	1,915	4,150
Total U.S. Crude Runs[3]	10,870	13,560	17,970	21,150	37,150
Petrochemical Demand for Heavy Liquids as a % of Total U.S. Crude Runs	3.4	5.7	6.6	10.7	12.1
and Percentage Assuming no Foreign Production Displacement		—	7.0	11.3	18.4

1. New heavy liquid production reduced by 1970's 365 M bbls/day assumed to be destined for existing plants and, therefore, not an indicator of new plant facility requirements.

2. Excluding crude oil imports transshipped to District II-Mid-West via Gulf Coast

3. Department of Interior estimates.

Source: Arthur D. Little, Inc.

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TABLE D-18

U.S. PETROCHEMICAL INDUSTRY SHIPMENTS

	Value of Shipments Billions of Constant 1970 ($mm)					Estimated Growth Rates[1]		
	1970	1980	1985	2000		70/80	80/85	85/2000
Organic Chemicals	$ 7.4	$16.8	$24.0	$ 65.0		8.5	7.5	6.5
Plastics	4.3	9.7	14.3	43.0		8.5	8.0	7.5
Fibers	2.8	6.6	9.7	28.0		9.0	8.0	7.5
Elastomers	1.0	1.6	2.0	3.5		5.0	4.5	4.0
Other	3.1	6.7	9.3	25.5		8.0	7.0	6.0
Total	$18.6	$41.4	$59.3	$165.0 Average		8.5	7.5	7.0

1. All growth rates have been rounded.

Source: Arthur D. Little, Inc.
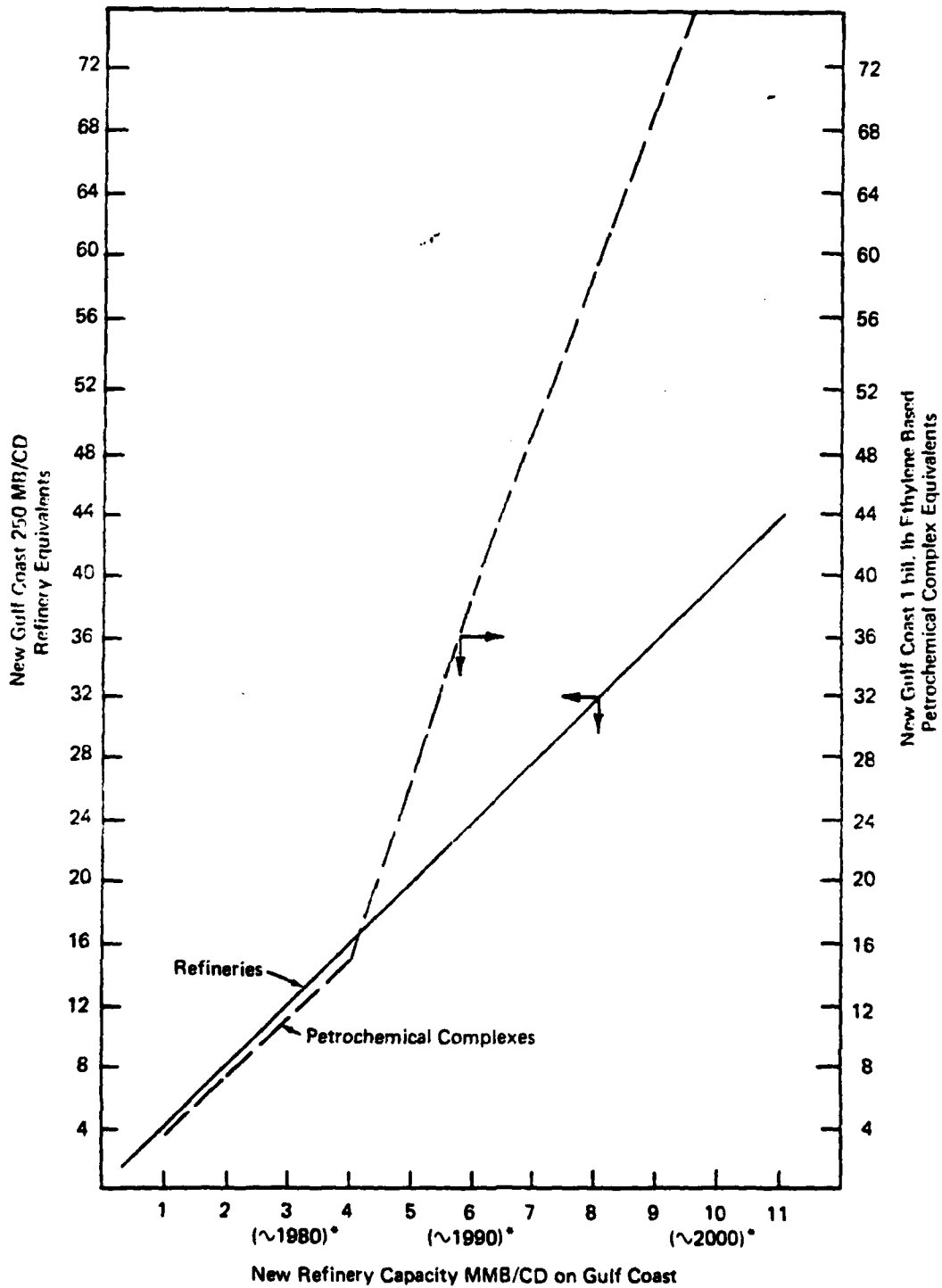
Arthur D Little Inc

FIGURE D–8   NEW GULF COAST REFINERIES AND PETROCHEMICAL COMPLEXES

Source: Arthur D. Little, Inc.   *Source: Robert R. Nathan Associates, Inc.
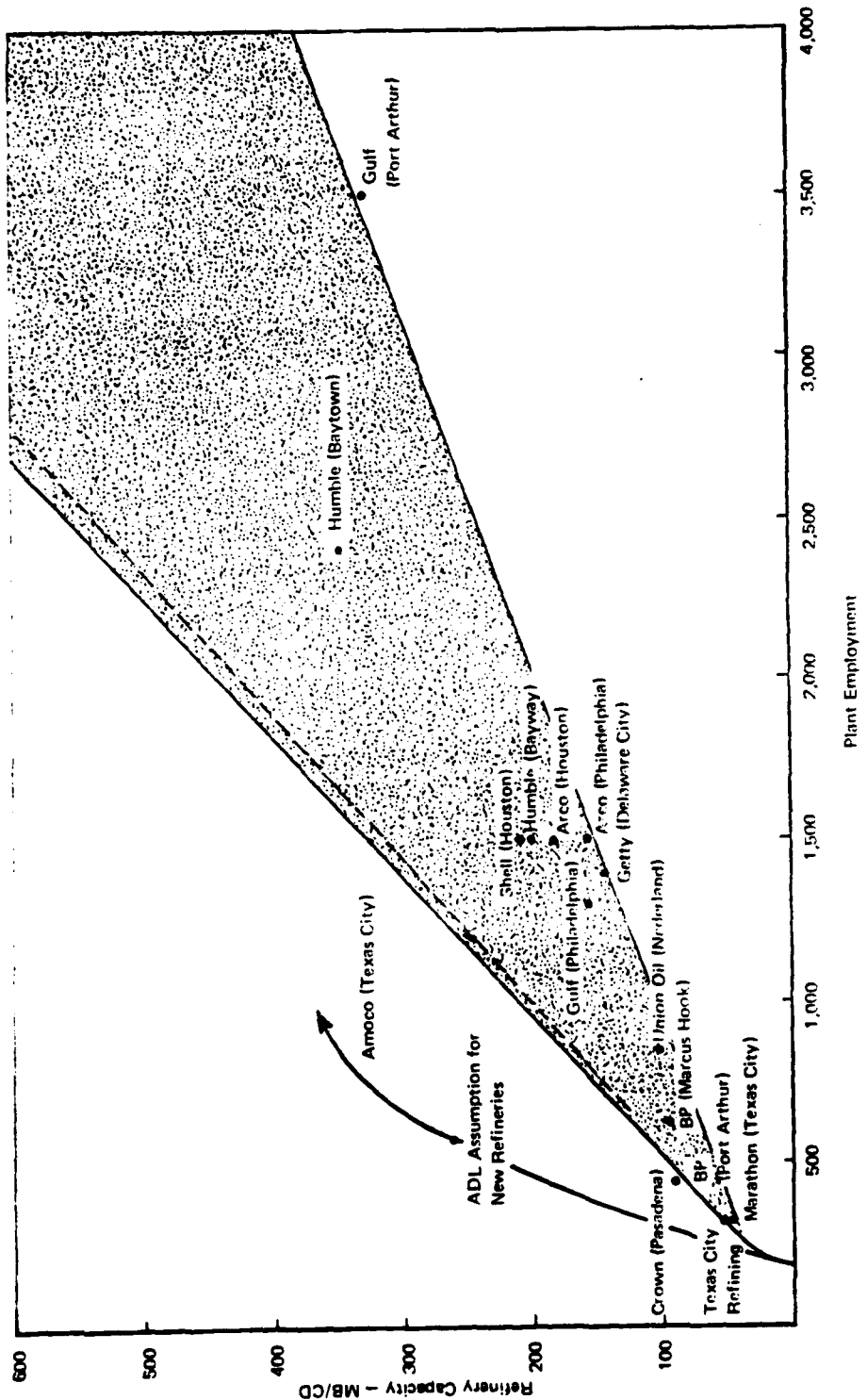
Arthur D Little Inc.

FIGURE D-9 ESTIMATED EMPLOYMENT IN SELECTED EXISTING REFINERIES
AND NEW REFINERIES

Source: Industry Contacts

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Arthur D Little Inc.

Refinery Employment in Thousands at (600 employees per 250 MB/CD Refinery)

Petrochemical Employment in Thousands at (14 employees/million dollars of sales)

Petrochemical Complexes

Refineries

(∿1980)*   (∿1990)*   (∿2000)*

New Refinery Capacity MMB/CD on Gulf Coast
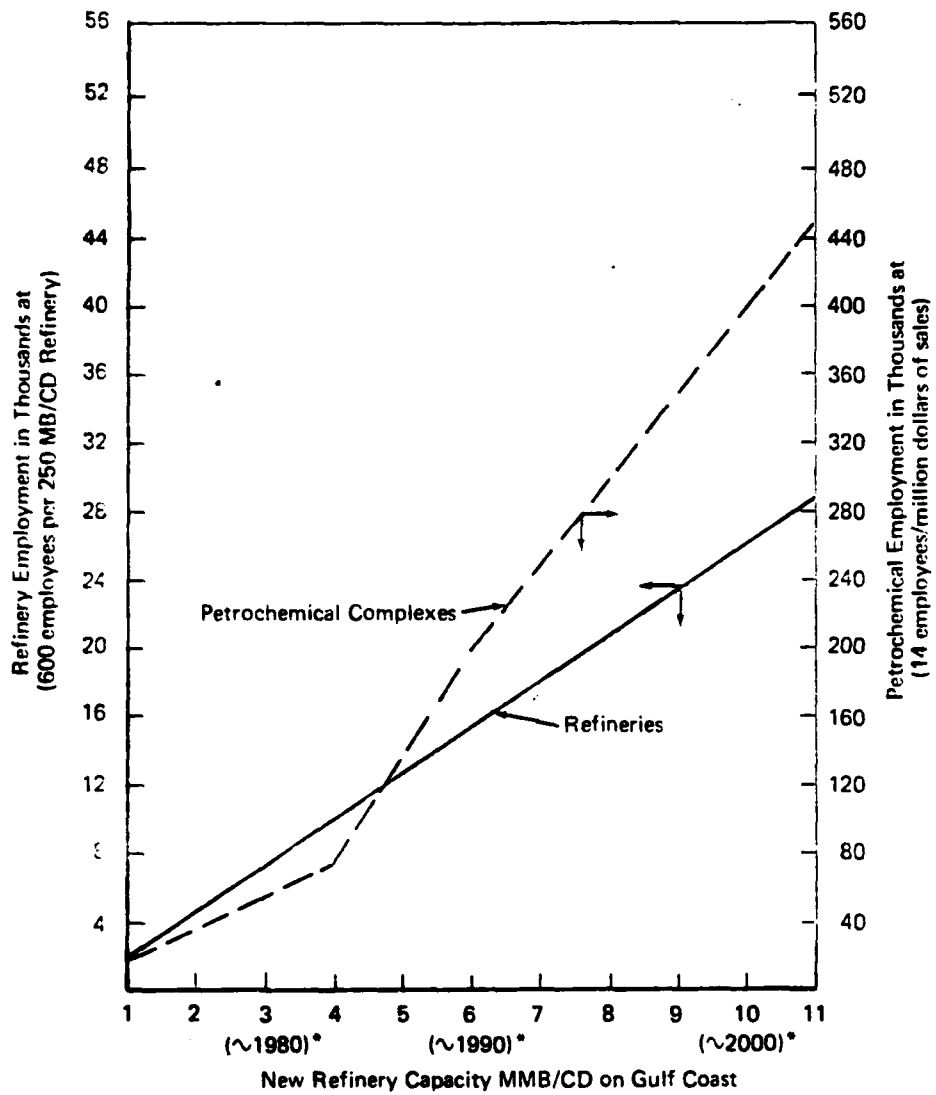
Source: Arthur D. Little, Inc.   ***Source:** Robert R. Nathan Associates, Inc.

FIGURE D—10 EMPLOYMENT IN NEW REFINERIES AND PETROCHEMICAL COMPLEXES

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Arthur D Little Inc

Source: Arthur D. Little, Inc.   *Source: Robert R. Nathan Associates, Inc.

FIGURE D–11 INDUCED PRIMARY POPULATION
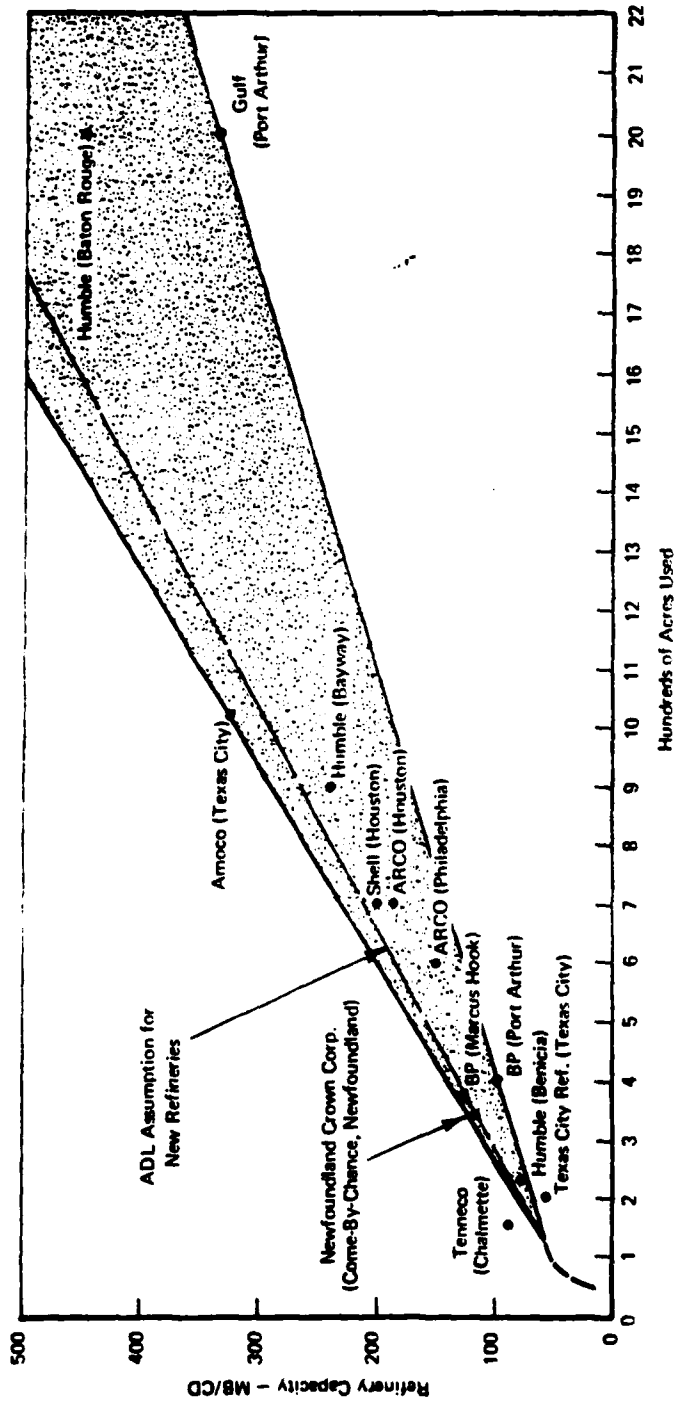
Arthur D Little Inc

FIGURE D–12 ESTIMATED ACREAGE REQUIREMENTS BY SELECTED EXISTING REFINERIES AND NEW REFINERIES

Source: Industry Contacts

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Arthur D. Little, Inc.

Refinery
Land Use
In
Thousands
of Acres
@
600 acres
per 250 MB/CD
excluding 30
day Terminal
storage

(46,800 acres = 73 sq. miles)

Total

Refineries

Petrochemical
Complexes

(4,400 acres =
7 sq. miles)

Petrochemical
Land Use
In
Thousands of
Acres
@
(200 acres per
1 bil. lb Ethylene
Based Petrochemical
Complex)

52
48
44
40
36
32
28
24
20
16
12
8
4

1   2   3   4   5   6   7   8   9   10   11

(∿1980)*   (∿1990)*   (∿2000)*

New Refinery Capacity MMB/CD on Gulf Coast

Source: Arthur D. Little, Inc.

* Source: Robert R. Nathan Associates, Inc.

FIGURE D—13 NEW REFINERY AND PETROCHEMICAL LAND USE REQUIREMENTS

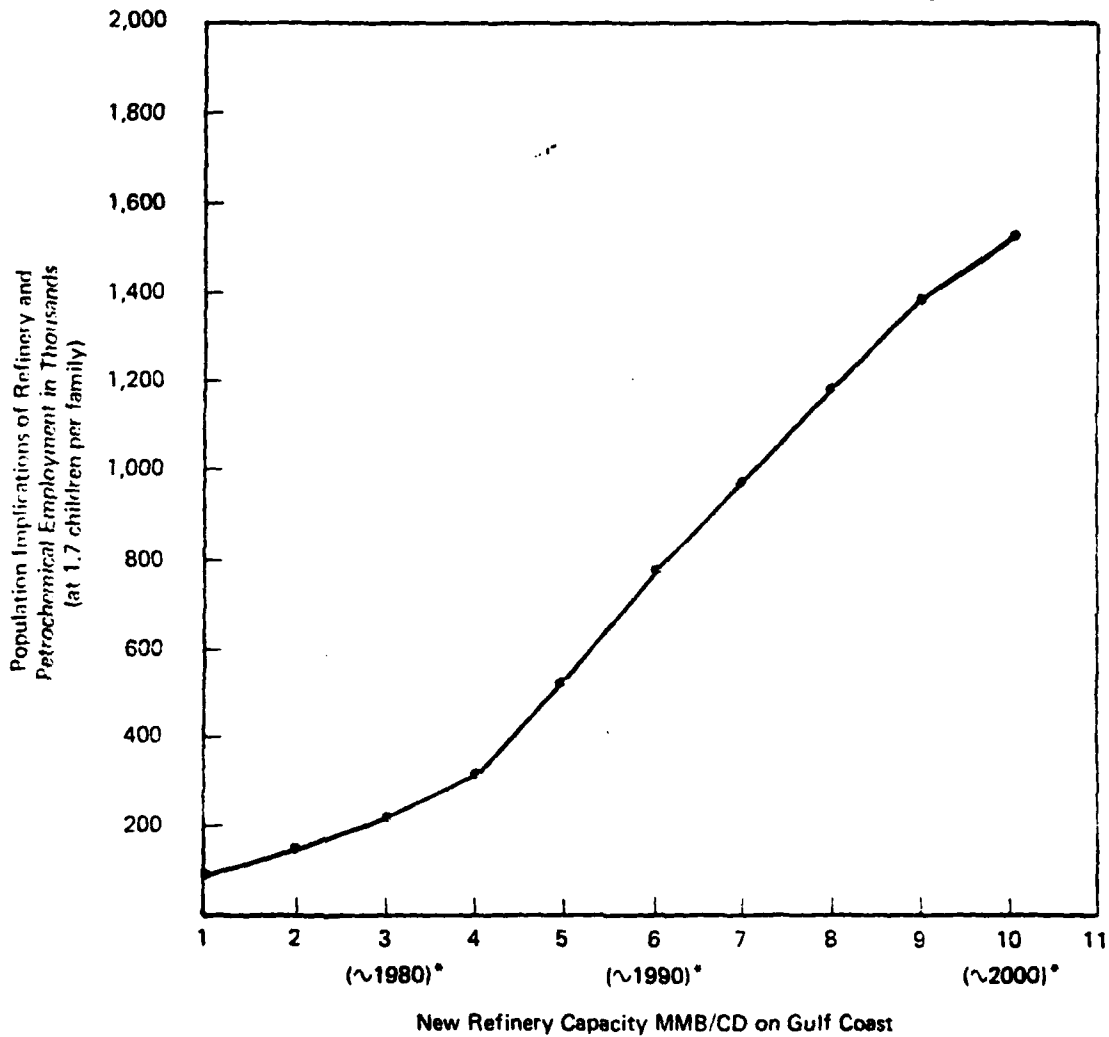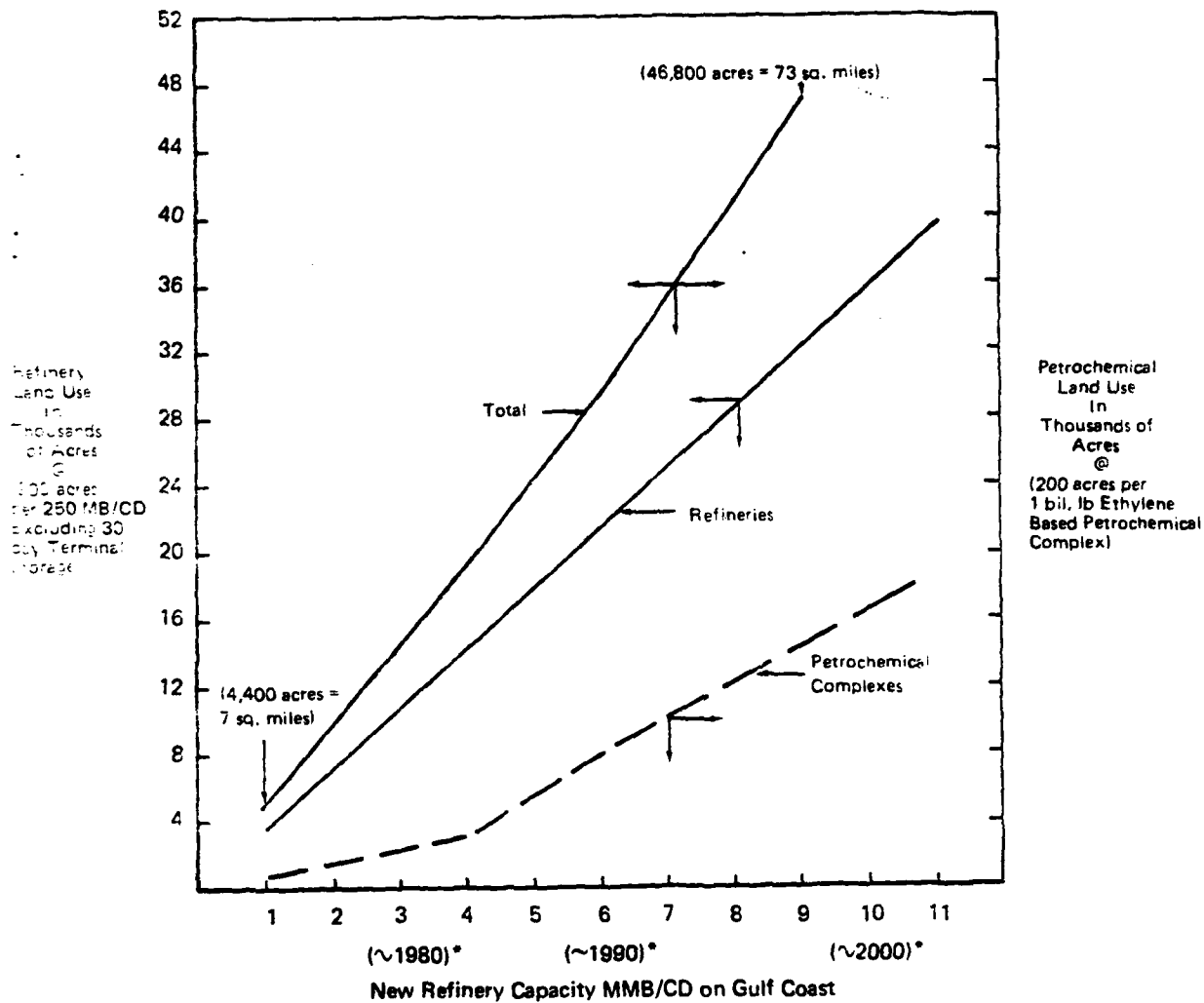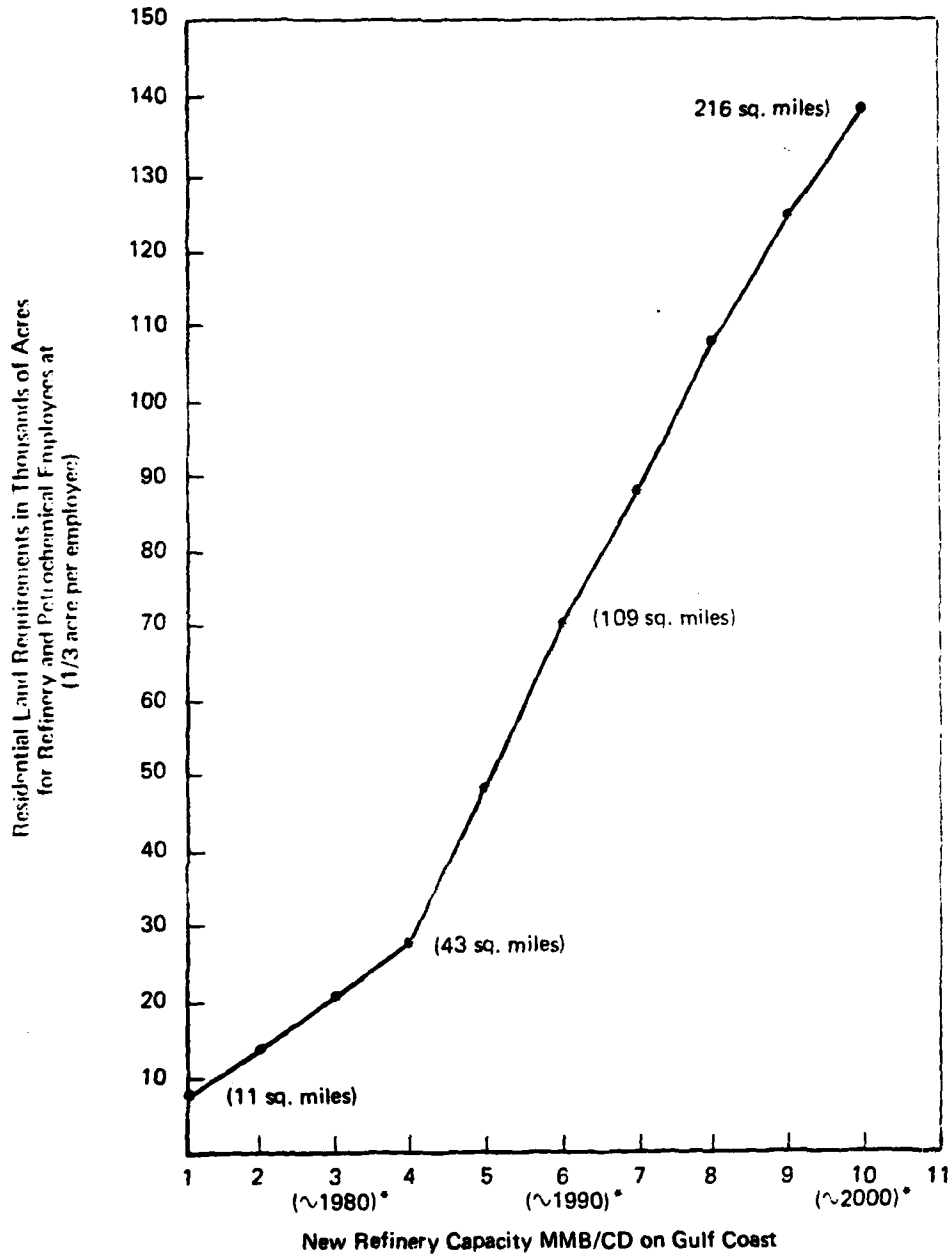Arthur D Little Inc

Basis of Estimate

1. 500 M bbl. tanks (40' x 300')
   Each tank separately diked to hold
   1.5 x total tank volume above ground.
2. Tanks entirely or partially above ground.
3. Dikes 75' or further from tanks.
4. 10% allowance for access, offices,
   pump house, services.

ADL assumes Curve II requirement

Tanks above ground, 8' dike

28.5 ac./MMB

Tanks above ground, 10' dike

13.2 ac./MMB

Tanks 20' above ground, 15' dike

Tanks 25' above ground, 10' dike

10.6 ac./MMB

14.2 ac./MMB

II
III
IV

Estimated Crude Import Volume (Million B/D)

Hundred Acres Required — 30 Day Storage

FIGURE D–14   TERMINAL CRUDE STORAGE (30 Days) ACREAGE REQUIRED

Source: Arthur D. Little, Inc., and Industry Contacts

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Arthur D Little Inc

FIGURE D—15 INDUCED PRIMARY RESIDENTIAL LAND USE REQUIREMENTS

Source: Arthur D. Little, Inc.   *Source: Robert R. Nathan Associates, Inc.
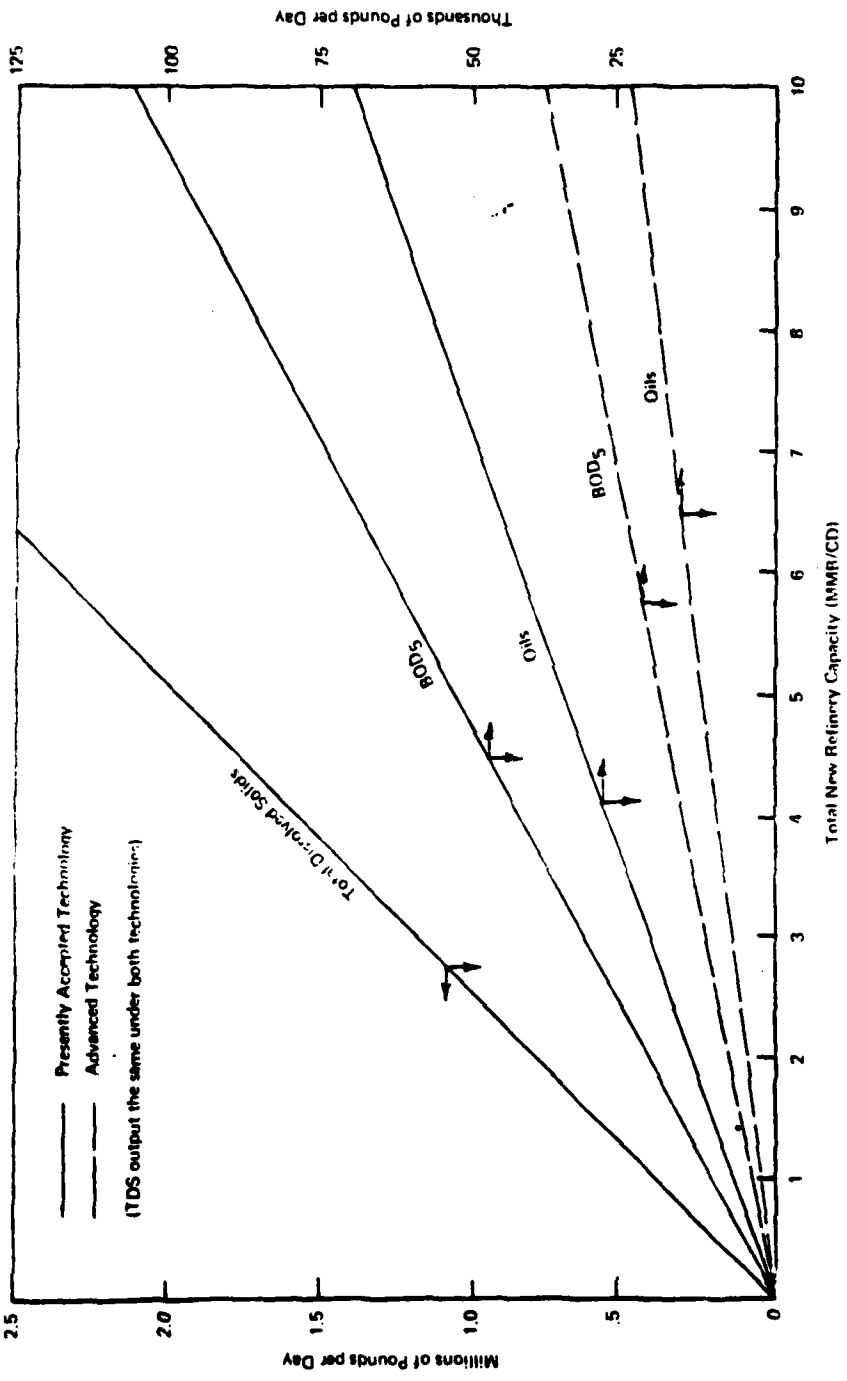
Arthur D Little Inc

FIGURE D-16   POTENTIAL WATER POLLUTION LOADS FROM REFINERY OPERATIONS

(Calculated on Basis of 250,000 B/CD Unit Size)
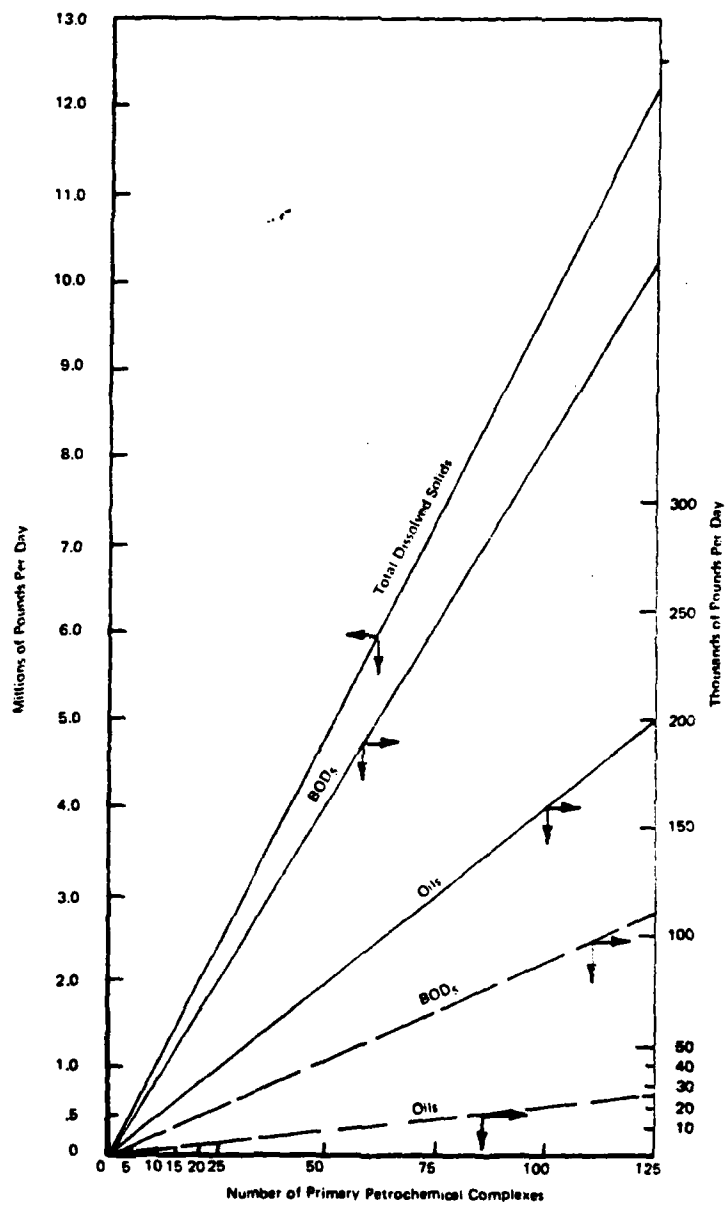
Source: Arthur D. Little, Inc.
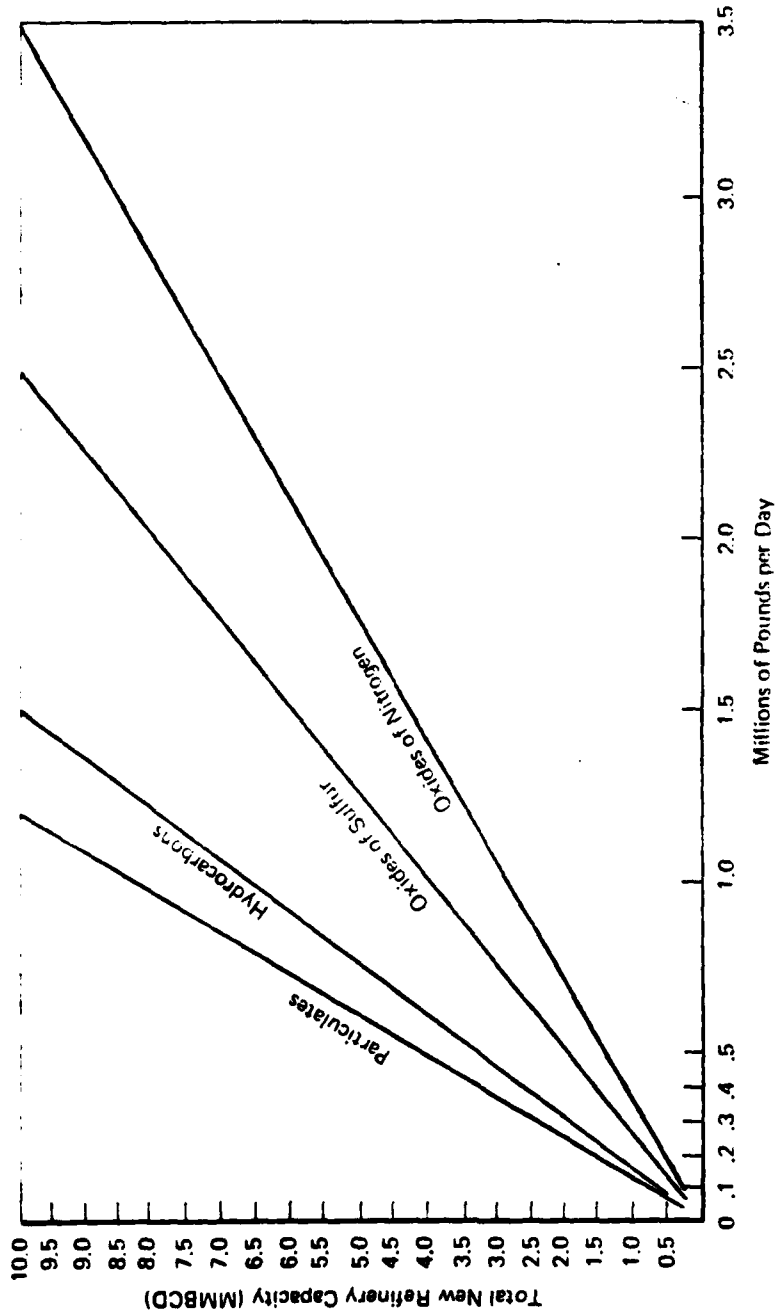
Arthur D Little Inc.

Source: Arthur D. Little, Inc.

FIGURE D–17   POTENTIAL AIR POLLUTION LOADS FROM REFINERY OPERATIONS
(Calculated on Basis of 250 MB/CD Unit Size)

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Arthur D Little Inc

FIGURE D–18   POTENTIAL WATER POLLUTION LOADS FROM PETROCHEMICAL
COMPLEXES (Calculated on Basis of One "Typical" Ethylene-based
Complex)

D-73
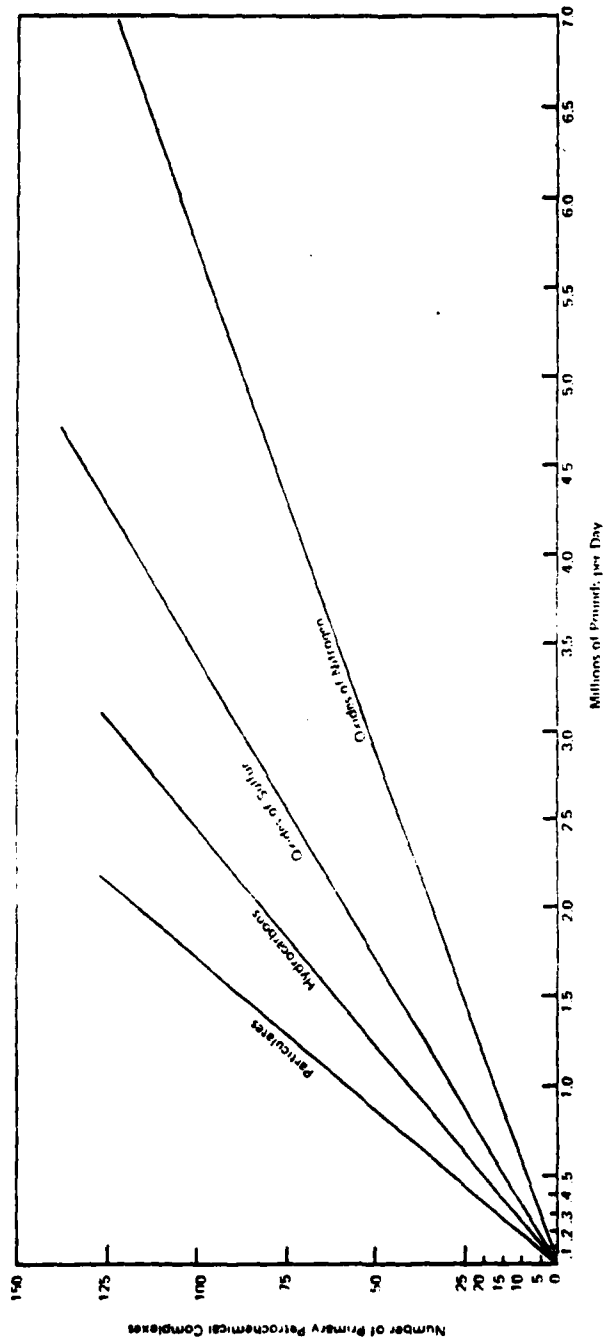
FIGURE D–19   POTENTIAL AIR POLLUTION LOADS FROM PETROCHEMICAL COMPLEXES
(Calculated on Basis of One "Typical" Ethylene-based Petrochemical Complex)

Source: Arthur D. Little, Inc.

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Arthur D. Little Inc.

TABLE D-19

SELECTED POLLUTION LOAD INDICATORS,
250 MB/CD REFINERY AND A "TYPICAL" PETROCHEMICAL COMPLEX

Water Pollution (lb/day)

	Presently Accepted Technology		Advanced Technology	
	Refinery	Petrochemical Complex	Refinery	Petrochemical Complex
Biological Oxygen Demand (BOD[5])	2,640[1]	3,290[2]	960[3]	900[4]
Chemical Oxygen Demand (COD)	15,850	14,000	4,800	7,300
Oils	1,760	1,600	600	220
Total Dissolved Solids (TDS)	99,000[5]	97,300[5]	99,000[5]	97,300[5]
Suspended Solids (SS)	7,700	2,410	1,440	630
Phenol	110	—	12	—

Air Pollution (lb/day)

	Refinery	Petrochemical Complex
Particulates	30,000	17,000
Oxides of Sulphur (SO$_x$)	62,500	33,590
Oxides of Nitrogen (NO$_x$)	87,500	56,920
Hydrocarbons	37,500	24,170

1. Population Equivalent = 132,000, secondary treatment basis (13,200 raw).
2. Population Equivalent = 164,500, secondary treatment basis (16,450 raw).
3. Population Equivalent = 48,000, secondary treatment basis (4,800 raw).
4. Population Equivalent = 45,000, secondary treatment basis (4,500 raw).
5. Under a "no discharge" waste water treatment system, approximately 22,000 tons per year of dried salts would be produced, equivalent to about 11 acre feet per year.
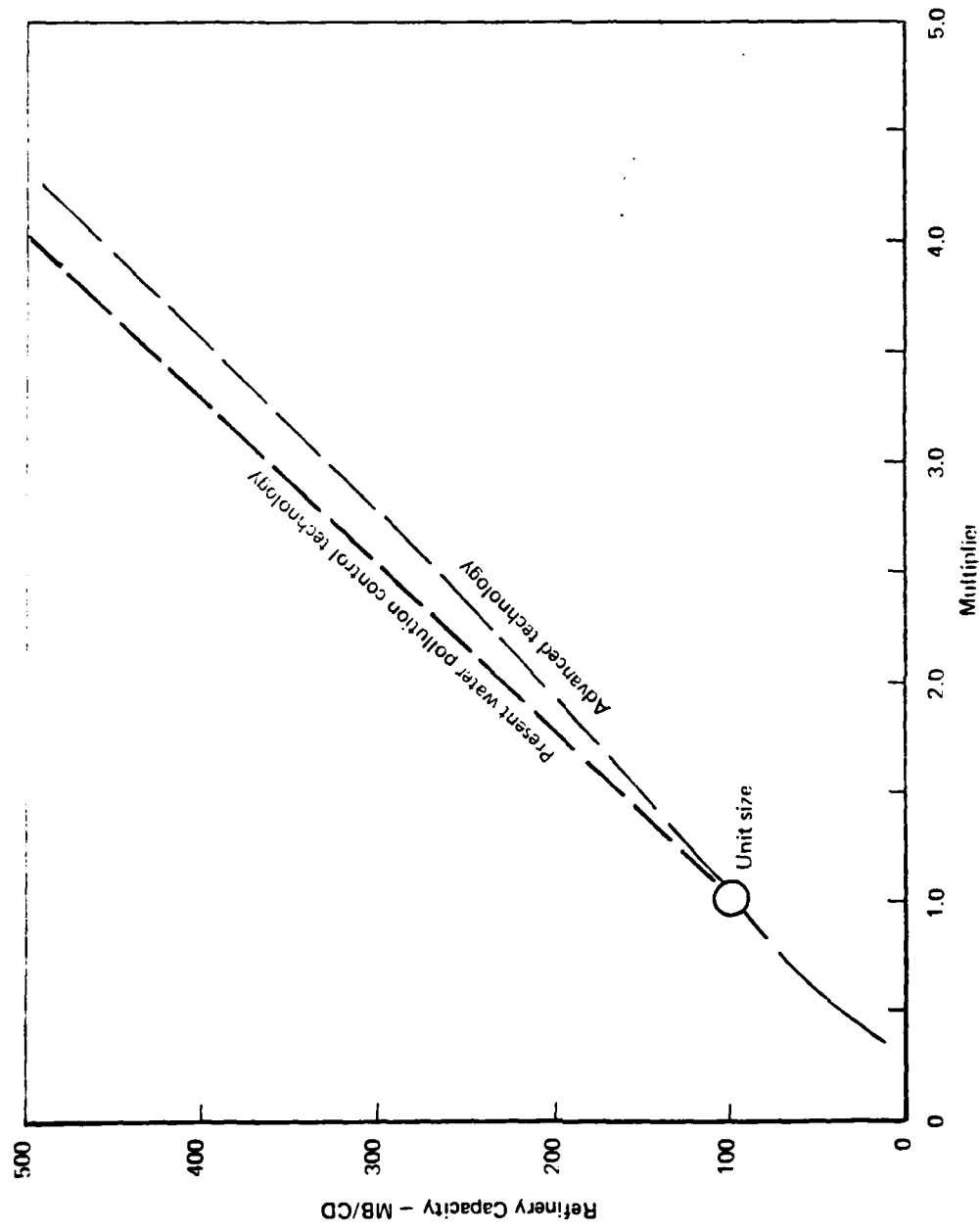
Arthur D. Little, Inc.

TABLE D-20

ESTIMATED WATER POLLUTION LOADS FROM A "TYPICAL"
100 MB/CD INTEGRATED REFINERY
(lbs/day)

Water Pollutant	Treatment Level	
	Presently Accepted	Advanced
BOD$_5$	1,200	400
COD	7,300	2,000
Oils	800	250
TDS	45,000	45,000
SS	3,500	600
Ammonia (as N$_2$)	400	40
Chromium	5	3
Pnenol	50	5
Sulfides	10	2

- See Chart for scale-up factors for larger refineries.

- Under no wastewater discharge, approximately 10,000 tons per year dried salts would be produced, equivalent to 5 acre feet per year.

Sources: EPA Contract 14-12-963, Industry Contacts, and Arthur D. Little, Inc., estimates.

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Source: Arthur D. Little, Inc.

FIGURE D-20   WATER EFFLUENT LEVEL MULTIPLIERS AT VARIOUS PETROLEUM REFINERY CAPACITIES

Arthur D Little Inc.

ESTIMATED ATMOSPHERIC EMISSION LEVELS FROM A
"TYPICAL" 100 MB/CD INTEGRATED REFINERY
(lbs./day)

Emission	Amount	Remarks
Particulates	12,000	Major sources include boilers, unit heaters, cracking units. Varies with fuel type, operating methods, etc. Could be as high as 13,000 lbs./day and still be acceptable.
SO_x	25,000	Assumes 0.3% sulfur fuel used or sulfur oxide emission control system (including sulfur recovery).
NO_x	35,000	Heaters are major source. No effective control systems other than close control of combustion.
Hydrocarbons	15,000	Includes 10,000 lbs./day from refinery plus 5,000 lbs./day from product and feedstock storage.
Aldehydes	1,000	Boilers, process heaters and cracking units are sources.
Ammonia	2,000	Cracking unit is principal source.

Scale-up factor for larger refineries assumed
to be proportional to size.

Source: EPA — "Compilation of Air Pollutant Emission Factors," February, 1972.
Arthur D. Little, Inc., estimates.

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TABLE D-22

ESTIMATED WATER POLLUTION LOADS FROM
A "TYPICAL" PETROCHEMICAL COMPLEX[1]
(lbs./day)

Water Pollutant	Treatment Level	
	Presently Accepted	Advanced
BOD_5	3,290	900
COD	14,000	7,300
OILS	1,600	220
TDS	97,300	97,300
SS	2,410	630

[1] Operations include:

Ethylene	1,000 MM lbs./yr.
Ethylene Glycol	300
Vinyl Chloride Monomer	500
Polyvinyl Chloride	300
Ethanol	170
Polyethylene	400
Polyester	30
SBR Rubber	5,000 tons per year

Source: Arthur D. Little, Inc., estimates.

TABLE D-23

ESTIMATED ATMOSPHERIC EMISSION LEVELS FROM
A "TYPICAL" PETROCHEMICAL COMPLEX[1]
(lbs/day)

Emission	Amount
Particulates	17,000
SO_x	33,590
NO_x	56,920
Hydrocarbons	24,170

[1] Operations include:

Ethylene	1,000 MM lbs./yr.
Ethylene Glycol	300
Vinyl Chloride Monomer	500
Polyvinyl Chloride	300
Ethanol	170
Polyethylene	400
Polyester	30
SBR Rubber	5,000 tons per year

Source: Arthur D. Little, Inc., estimates.

Arthur D. Little, Inc.

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