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CRITICAL REVIEW

# The environmental implications of offshore oil and gas activities

*An overview of the effects associated with routine discharges based on the American experience*

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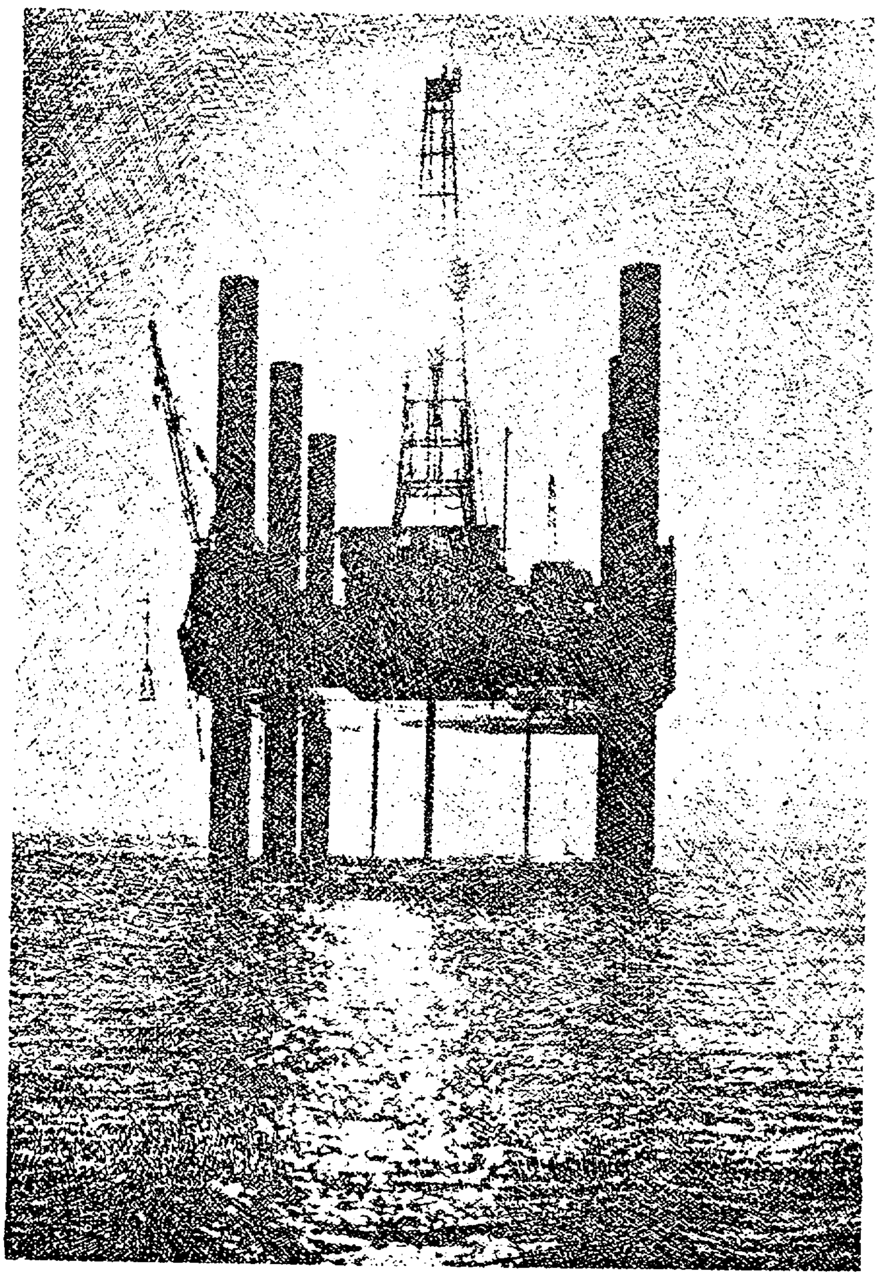

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The environmental effects **of** offshore oil and gas operations have received much attention during the past decade. Possible short- and long-term effects of routine discharges from offshore facilities have been a subject of concern, and numerous **field** and laboratory studies have been performed to assess these effects. The purpose of this article is to review the existing literature concerning the environmental fate and effects of routine discharges associated with offshore operations in order to better identify what parameters should be looked at for the purpose of monitoring. The review focuses on studies that have been performed around various drilling or production platforms as well as laboratory studies that examined the toxic effects of discharges. A general review of these studies is expected **to** provide information that is useful **for** the design of future monitoring programs.

The first section of this article summarizes the various quantities and types of discharges associated with offshore oil and gas operations **and** the monitoring requirements associated with each type of discharge. Various laboratory studies of these discharges or particular components are reviewed folIowed hy a review of field studies. The final section of this article considers the implications of these studies in terms of future monitoring purposes.

## Discharge and discharge monitoring

**Discharges. A** variety of discharges are associated with offshore oil and gas

**TABLE 1**
**Categories of major discharges from offshore oil and gas operations [a]**

| Discharge category | Exploration | Development | Production |
|---|---|---|---|
| Drilling fluids [b] | Well depths less than 10000 ft (3050 m) | | |
| (Total additives to water-based systems and volumes discharged) | 520-709 tons/well<br>417-1094 $m^3$/well | 7090–21 279 tons/platform | |
| | Well depths greater than 10000 ft (3050 m) | 10940-32820 $m^3$/platform | |
| | 672-2118 tons/well | | |
| | 900-4800 $m^3$/well | | |
| Drill cuttings [c] | 823– 1285 tons/well | 9000–27 000 tons/platform | |
| Produced water [d] | — | — | 0-2709 $m^3$/day per platform; 884 $m^3$/day was the mean flow for 10 platforms; in Gulf of Mexico |
| Deck drainage [e] | 53 $m^3$/day | 53 $m^3$/day | No information |
| Sewage" | 5.3 $m^3$/day | 5.3 $m^3$/day | 0.7 $m^3$/day |

[a] Seawater discharges such as coaling waters are not included. Drilling fluid additives are in dry weight.
[b] Discharges of drilling fluids are based on information summarized by Petrazzuolo (1981) for five wells drilled in the Gulf of Mexico and one in the mid-Atlantic bight. Discharges during development were estimated by using the highest value for exploration wells less than 3050 m in depth (709 tons/well) and multiplying by an assumed number of wells per platform (10-30).
[c] Drilling cuttings discharges for exploratory drilling are based on four case studies with well depths ranging from 5410-16320 ft (1650-4980 m). Drill cuttings discharges for developmental drilling were estimated by using a value of 900 tons/well and multiplying by an assumed number of wells per platform (10–30).
[d] Values based, in part, on information presented in Jackson et ai. 1981.
" Based orr information provided by oil companies.

operations (see Table 1). Discharges vary among major operations (exploration, development, and production), among particular operations, and among rigs or platforms engaging in similar operations, This variability is caused by the different operational conditions encountered in drilling and production and the methods operators use to approach these conditions. It is important to recognize these variations in the composition and volume of discharges in order to understand and interpret the results of discharge monitoring, laboratory studies, and field monitoring. Reviews and other information on discharges from offshore operations can be found in several recent reports (Dames & Moore, 1981; Petrazzuolo, 1981: Ayers, 1981; Jackson et al., 1981), in NPDES permits issued by the U.S. EPA, and in Environmental Reports (Exploration) submitted as part of a U.S. Geological Survey requirement for offshore exploratory drilling.

Drilling fluids, drill cuttings, and produced waters arc clearly the most significant discharges associated with offshore oil and gas operations and have received the most attention. As already mentioned, the quantities of these discharges vary among operations. During exploration, drilling is conducted to determine the nature and extent of potential hydrocarbon reservoirs. At a given site, these operations are usually of short duration, involve a small number of wells, and are generally conducted from mobile platforms or vessels. Drilling fluids and cuttings are discharged during exploration. Once a hydrocarbon reservoir has been found, development involves the drilling of a larger number of wells (10-30), usually from a fixed platform. Because the number of wells is greater, a larger volume of drilling fluids and cuttings are discharged during development than during exploration; however, during development the wells may not be as deep as those drilled during exploration and drilling fluids are recycled to a greater degree because more is known about the formation. Once the drilling unit used in development has been removed, extraction of hydrocarbons from underground formation begins. This extraction process may produce an additional effluent called produced water (brine effluent). The production platforms arc usually fixed for long periods of time. The brief descriptions of these three discharges---drilling fluids, cuttings, and produced water – presented below are based on reports and documents already cited.

**Drilling fluids.** During drilling operations, drilling fluids are circulated down the drill string and serve a number of functions—cooling and lubricating the drill bit and string. removing and transporting cuttings from the hole to the surface, and controlling formation pressures, to name a few.

Drilling fluids are generally classified according to the continuous liquid phase in the mud: water-based or oil-based. The discharge of oil-based drilling fluids into the marine waters off the U.S. coast is prohibited and these "muds" will not be described further here. To makeup water-based drilling fluids, various components are added to fresh or salt water. A typical water-based drilling fluid consists of viscosifiers (gels) such as bentonite, weighting agents such as barium sulfate, thinners such as ferrochrome lignosulfonate, materials for fluid loss control such as carboxymethylcellulose, and caustic soda for pH control. These basic components comprise the bulk of drilling fluid additives. A second class of components. used for special circumstances, consists of such materials as surfactants, defoaming agents, $H_2S$ and oxygen scavenging agents, lubricants, loss circulation materials, and bactericides.

Petrazzuolo (1981) has summarized the amounts of basic drilling fluid components used in five case study wells drilled in the Gulf of Mexico and in one mid-Atlantic well (,Ayers et al., 1980a) (Table 2). Barite was the major component of the drilling fluids

**TABLE 2**
**Basic drilling fluid additives used in drilling various wells in the Gulf of Mexico (GOM) and mid-Atlantic**

| Location et well<br>Depth of well (m) | GOM<br>1480 | GOM<br>2S87 | GOM<br>3175 | GOM<br>6935 | GOM<br>6435 | Mid-Atlantic<br>4974 |
|---|---|---|---|---|---|---|
| Fluid additives In short tons | | | | | | |
| Barite | 468.0 | 603.0 | 511.0 | 1798.0 | 1078.0 | 953.0 |
| Clays | 27.0 | 42.0 | 117.0 | 59.0 | 387.0 | 454.0 |
| Lignosulfonates | 5.0 | 14.0 | 12.6 | 50.0 | 41.0 | 53.0 |
| Lignite | 3.8 | 14.0 | 3.4 | 2.5 | 40.7 | 51.7 |
| Cellulosic polymers | 0 | 0 | 2.6 | 15.6 | 9.4 | 4.7 |
| Caustic (NaOH) | 4.1 | 39.3 | 35.1 | 45.0 | 140.0 | 55.2 |
| Soda ash/bicarbonate | 1.0 | 0.3 | 1.5 | 2.8 | 31.4 | 0 |
| Total additives | 520.0 | 709.0 | 697.0 | 2118.0 | 1724.0 | 1573.0 |

**Source:** Adapted from Petrazzuolo, 1981.

accounting for 61-90% by weight of all additives and amounting to 468-1798 short tons/well. The quantity of clay used (bentonite and attapulgite) ranged between 27 and 454 tons/well, while lignosulfonates ranged between 5 and 53 tons/well.

Petrazzuolo (1981) noted that the amounts used of other basic drilling fluid components-lignite, cellulosic polymers, caustic, and carbonate/ bicarbonate-were highly variable. All of them were added in smaller amounts, however. generally less than 50 tons/well.

Drilling fluid is discharged intermittently during the drilling process as described by Ayers ( 1981). After the drilling mud passes through the solids-control equipment and the solids are separated, it goes back to the mud pit for recirculation. The solids-control equipment is unable to separate the fine clay and colloidal particles that accumulate in the mud system during drilling. Eventually the concentration of these particles causes the mud to become too viscous for further use. When this happens, a portion of the mud is discharged, and the volume of the discarded material is replaced with water, reducing the concentration of fine solids in the mud system. Mud additives are then added in order to bring their concentrations back to proper levels. These bulk mud discharges occur only intermittently. The discharge volumes range from 16 to 160 $m^3$. Normally, every one to three days, a small volume ( 16-32 $m^3$) is released. A discharge of 160 $m^3$ is more characteristic of that which occurs at the end of the drilling operation or when for some reason it is necessary to change the mud system.

**Drill cuttings.** These discharges consist of the drilled formation solids that are carried from the hole to the surface by the drill fluid, separated with solids-control equipment, and discharged. Only during the initial phase of drilling, that is, during the first 50-150 m of well depth, are drilled materials not taken to the drilling unit but released directly on the seafloor. Most of the cuttings are discharged during this early stage because the amount of cuttings decreases with depth, as the diameter of the borehole decreases.

Ayers (198 1 ) has described the discharges of drill cuttings. A system of shale shaker screens and hydrocyclones is used to separate the drilling mud from the drill cuttings. The separated solids are discharged continuously while drilling is going on at a rate that varies from about 4 to 40 $m^3$/day; the higher number is more characteristic early in the drilling program.

**Produced water.** When oil and gas are produced, water associated with the oil and gas reservoirs is often produced as well. This water is referred to as produced water, formation water, or brine effluent. The amount of produced water generated is dependent upon the method of recovery and the nature of the formation. In some formations, water is generated with the oil and gas in the early stages of production; in others, water is not produced until the formation has been significantly depleted; and in some, water is never produced. A general schematic production system indicating the flow of materials is shown in Figure 1.

Jackson et al. ( 1981) examined the produced water that was discharged from 10 platforms in the Gulf of Mexico off Louisiana. The volume of produced water ranged between 31 and 2709 $m^3$/day and accounted for 10-91 % of the total fluids produced. in the Buccaneer Gas and Oii Field off Texas, the volume of produced water ranged between O and 232 $m^3$/day (Shell Oil Co., 1978). Based on information presented in Jackson et al. (198 i) and personal communications with Dan Caudle (CONOCO), it appears that daily discharges of produced water from platforms are generally less than 1590 $m^3$ (10 000 bbl). Discharges from central facilities handling a number of platforms are usually larger. For example, daily discharges of 27800 $m^3$ (175 000 bbl) have been reported for a central facility in the Gulf of Mexico (Caudle, personal communication) and 9858 $m^3$ (62 000 bbl) for the Trading Bay facility in Alaska (Lysyj et al., 1981).

After passing through an oil-water separator, produced water from oil and gas production platforms off the U.S. coast is usually discharged into the sea. These effluents contain small amounts of oil. The U.S. EPA Best Practicable Treatment guidelines restrict the concentration of oil and grease in produced water to a monthly average of 48 ppm and a daily maximum of 72 ppm. Results of a study on the oil content of produced water are presented in Table 3 for 10 platforms in the Gulf of Mexico off Louisiana (Jackson et al., 198 1). The infrared method of measuring oil content gave average values of 15-106 ppm and the gravimetric method, 7.6–77; data obtained with the two methods could be correlated on a platform-by-platform basis.

Some studies have been performed on the composition of hydrocarbons in produced water. Because the volatile liquid hydrocarbons (VLHs) in the $C_6$ to $C_{14}$ range are more soluble in seawater than the higher molecular weight hydrocarbons, the hydrocar-

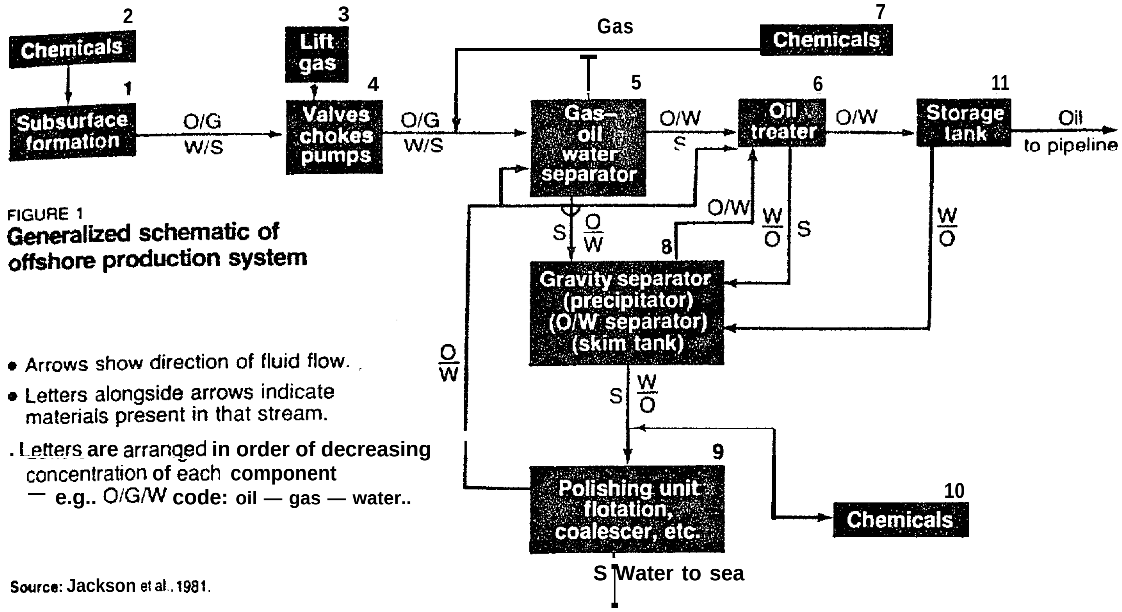


FIGURE 1
**Generalized schematic of offshore production system**

Source: Jackson et al., 1981.

bons in the $C_6$ to $C_{14}$ range are preferentially partitioned from the produced oil into the produced water. Volatile liquid hydrocarbons are important environmentally, since these compounds include the light aromatics (benzene through naphthalene) that are among the most immediately toxic components of petroleum. Wiesenburg et al. (1981) obtained a mean VLH concentration of 21.6 ppm in produced water from an oil and gas production platform in the Buccaneer Field in the Gulf of Mexico off Texas. Sauer ( 1981) obtained a similar value for this field. Over 80% of the VLHS in the produced water consisted of light aromatic compounds, with benzene, toluene, ethylbenzene, and *m*-, *p*-, and *o*-xylene (BTX) predominating. Lysyj et al. (1981) found that the average concentration of BTX compounds in treated effluents discharged to Cook Inlet, Alaska, was 9.0 ppm. The water-soluble petroleum fraction in produced water also includes diaromatics (naphthalene and derivatives). In addition, nonhydrocarbon compounds from additives or petroleum, including phenolic and carboxylic acids, and other oxygen-, nitrogen-, and sulfur-containing compounds, are present in this fraction (Lysyj et al., 1981; Sauer, 1981). The water-insoluble fraction consists primarily of higher molecular weight aliphatic hydrocarbons and other high-molecular-weight, cyclic and aromatic hydrocarbons. At present, there are little quantitative data on concentrations of polynuclear aromatic hydrocarbons (PAHs) in produced water. Onc of the interesting things that Middleditch ( 198 I ) observed in produced water from the Buccaneer Field was the presence of elemental sulfur. He determined the concentration of sulfur by a gravimetric procedure and found a maximum concentration of 1200 ppm and a mean concentration of 460 ppm.

Various metals have also been measured i n produced waters. For the Buccaneer Field, Tillery ( 1980) reported that concentrations of nine trace metals were higher in the produced water than in the receiving water and varied with time. The range of concentrations for these metals in produced water and seawater and the factors by which concentrations in produced water exceeded those of seawater are given in Table 4. A few metals in produced water—mercury, strontium, and thallium- -exceeded levels in seawater by factors of less than 10. Other metals—barium, cadmium, chromium, and manganese—exceeded sea level concentrations by

TABLE 3
**Platform flotation effluent oil content comparison for Gulf of Mexico off Louisiana**

| Platform | WI-oil, mg/L | | IR-Oil, mg/L | | "Dispersed" oil, mg/L | | "Soluble" oil, mg/L | | "Soluble" oil, fraction of IR-oil (%) |
|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | (s) | $\bar{x}$ | (s) | $\bar{x}$ | (s) | $\bar{x}$ | (s) | |
| SS 107 | 7.6 | (5.2) | 15 | (3.7) | 1.6 | (1.5) | 13 | (2.7) | 87 |
| SS198G | 18 | (9.2) | 36 | (7.8) | 5.7 | (7.7) | 31 | (2.7) | 86 |
| BDCCF5 | 26 | (6.9) | 36 | (8.3) | 26 | (8.6) | 10 | (2.3) | 28 |
| ST131 | 12 | (13) | 37 | (19) | 5.9 | (13) | 2a | (3. 1) | 76 |
| BM2C | 22 | (6.7) | 39 | (4.2) | 4.9 | (5.1) | 36 | (4. 1) | 92 |
| SM130B | 48 | (16) | 48 | (16) | 23 | (13) | 25 | (4.7) | 52 |
| EI 18 CF | 52 | (24) | 76 | (38) | 63 | (30) | 13 | (13) | 17 |
| WD45C | 63 | (95) | 81 | (109) | 66 | (106) | 30 | (32) | 37 |
| ST177 | 64 | (74) | 95 | (103) | 92 | (126) | 21 | (13) | 22 |
| SP65B | 77 | (73) | 106 | (99) | 38 | (80) | 61 | (15) | 58 |

Note: Some numbers do not check because of rounding. Two significant figures have been retained in all numbers below 100.
$\bar{x}$ = Mean.
(s) = Standard deviation.
Source: Jackson et al., 1981.

factors of 10-100. Iron in produced water exceeded that in seawater by factors of 560-2340. These iron measurements have been somewhat controversial, however. Other investigators (Koons et al., 1977: Lysyj, 1981) have reported elevated levels of As, Cd, Cr, Cu, Hg. Pb, and Zn in produced water. However, based on discussions with various investigators, there is still a need to establish good quantitative data on concentrations of metals in produced water.

Most produced water is a brine, characterized by an abundance of chlorides. The total amount of mineral matter commonly found dissolved in produced water ranges from a few pprn to approximately 300000 ppm, a heavy brine, with typical concentrations from 80000-100000 ppm.

More detail on the chemical composition of produced water is forthcoming. The EPA has implemented a monitoring program for produced water in (he Gulf of Mexico using state-of-the-art analytical techniques. The results should be available in late 1982 and should provide good information on trace metal and hydrocarbon content of produced water.

**Discharge monitoring.** Discharge monitoring requirements are summarized in Table 5 for four selected U.S. EPA National Pollution Discharge Elimination System (NPDES) permits issued in connection with offshore oil and gas exploring requirements. This table indicates the variability in requirements that have been adopted for various discharges in different geographical areas.

### Laboratory studies

Laboratory research has been conducted to determine the lethal and sublethal effects of drilling fluids on marine organisms. A brief summary of this information is presented here and is based on the review by Petrazzuolo ( 1981). Also summarized arc the limited laboratory data on biological effects of produced water.

**Drilling fluids.** Laboratory studies of acute lethal effects of drilling fluids on marine organisms have involved examinations of at least 35 drilling fluids and exposures to 48 species including representatives of phytoplankton, copcpods, isopods, amphipods, gastropod, decapods, bivalves, echinoderms, mysids, polychaetes, and finfish (Table 6). A total of 303 toxicity tests have been performed to determine 96-h $LC_{50}$ values. (The 96-h $LC_{50}$ value is the computed concentration of the test material at which 50% of the exposed organisms die during a 96-h exposure period—the lower the value, the greater the toxicity.) Petrazzuolo (1981) calculated the frequency of all tests that have been reported: 46'% had $LC_{50}$ values in excess of 100000, 44% had values bet ween 10000 and 100000 ppm, 5% were bet ween 1000 and 10000 ppm, and 1-2.5% had values between 100 and 1000 ppm. He noted that the variability in the percentage of the final class is a result of including or excluding test results from a well drilled in Alabama state waters. These test results are controversial because it is not known how applicable they are to fluids discharged from other wells offshore. The drilling fluids in question were not disposed of at sea but were handled by an appropriate land disposal method.

Petrazzuolo ( 1981) recognized that the frequency distribution was weighted more heavily for the sensitivities of those species that have been tested more often. Using normalization techniques, he recalculated the distribution as follows: >100000 ppm = 50%; 10000-100000 ppm = 33%; IOOO-10 000 ppm = 9.4%; 100-1000 ppm = 2.12.8%; not determined = 5.3%. Hc concluded from these data that for the drilling fluids and species tested, the acute lethal toxicities of drilling fluids are very low. Hc did note that some groups such as phytoplankton and copepods arc more sensitive than others such as polychaetes and isopods, that larval life stages are generally more sensitive than adults, and that molting animals are usually more sensitive than intermolt individuals.

Despite the extensive data base on the acute toxicity of drilling fluids, bioassays are still required as part of the U.S. EPA NPDES discharge requirements for particular mud types in particular offshore areas. Operators exploring for oil and gas on the outer continental shelf (OCS) in the mid-Atlantic region were required to do bioassays for the eight generic mud types that they proposed to use. A testing protocol was developed and approved by U.S. EPA Region II. For Georges Bank (off the coast of New England), the original generic mud types used there must be retested using the original test species plus other organisms more representative of the region; in addition, new muds proposed for use have to be tested. Other EPA regions (regions 111, 1X, and X) appear to be accepting this concept.

Other laboratory testing procedures have been used to evaluate the effects of drilling fluids and the results of these tests have been reviewed and evaluated by Petrazzuolo (1981) for the U.S. EPA. Studies of acute sublethal effects have included physiological/biochemical and behavioral effects. Petrazzuolo decided that no conclusions could be derived from the studies that measured physiological/biochemical effects (enzymatic changes and changes in filtration rate, respiration rate, and rate of ammonia

TABLE 4

**Ranges in mean concentration of metals in produced water and seawater from the Buccaneer Field during summer and winter 1979 sampling periods**

| Metal | Range in produced water (µg/L) | Range in seawater (µg/L) | Factor by which produced water exceeds seawater |
|---|---|---|---|
| Barium | 2.40-10.4 | 0.121-0,259 | 20-40 |
| Cadmium | 0.160-2.06 | 0.037-0.050 | 4-41 |
| Chromium | 0.879-0.970 | 0.051-0.106 | 9-17 |
| Iron | 2874-2901 | 5.14-1.24 | 560-2340 |
| Mercury | 0.076-0.239 | 0.032-0.094 | 2-2.5 |
| Manganese | 2.69-5.90 | 0.064-0.073 | 42-81 |
| Strontium | 191-269 | 46.5-53.7 | 4-5 |
| Thallium | 0.088-0.225 | 0.027-0.053 | 3-4 |

source Modified from Tillery, 1960.

TABLE 5

## Discharge monitoring requirements stipulated by selected U.S. EPA NPDES permits [a]

| Discharges | Gulf of Mexico general permits April 1981 to April 1083 | Georges Bank permit (exploration) July 198110 February 198S | Draft general permit for OCS off Southern California (beyond territorial seas) | Caak Inlet (Alaska) permits extended beyond 1976–1981 initial permitted period—no new permits issued recently |
|---|---|---|---|---|
| Drilling fluids | Estimate volume discharged monthly | Record volume hourly during discharge and measure duration of discharge. For every 305 m of well depth monitor total Hg, Cd, Ba, V, Cr, Zn, Fe, Pb, Ni, Cu, petroleum hydrocarbons (aliphatic and aromatic), grain size distribution and specific gravity. Additional monitoring of bulk discharges and major additives. Joint industry sponsored bioassay and bioaccumulation tests for each mud type proposed for use | Estimate volume monthly. Operator shell maintain precise chemical inventory of all constituents and their volume addad downhole for each well. Bioassays may be required for used drilling muds not previously testad | Estimate volume daily. Oil and grease determination made weakly |
| Drilling cuttings | Estimate volume discharged monthly | Estimate volume discharged on a daily basis and duration of discharge. For every 305 m well depth monitor metals (same as above), grain size distribution and specific gravity for first well drilled by permittee in each of three depth zones | Estimate volume monthly | |
| Produced water | Estimate ffow rate and monitor for oil and grease monthly | Not applicable | Estimate flow rate and monitor for oil and grease monthly. Monitor for As, Cd, Cr, Cu, CN, Pb, Hg, Ni, Ag, Zn, and phenols semiannually | Monitor aromatic hydrocarbons monthly |
| Produced sand | Estimate quantity monthly | Not applicable | Estimate quantity monthly | No requirement |
| Deck drainage (contaminated) | Estimate volume discharged monthly | Estimate volume of discharge on weekly basis. Monitor petroleum hydrocarbons (aliphatics and aromatics) twice/ month as operational indicator only | | Estimate volume daily. Aromatic limitation— 10 mg/L (recent permits only)—monitor once per month. |
| Sanitary sewage | Estimate flow rate and measure residual chlorine monthly. No requirement if nine or fewer individuals on platform | Estimate flow rate and measure residual chlorine monthly. No requirement when certified marine sanitation unit is used | Estimate flow rate and measure residual chloride monthly | Monitor residual chlorine weekly |
| Domestic waste | No requirement | No requirement | No requirement | No requirement |
| Water distillation blowdown | No requirement | Average flow shall be estimated quarterly | No requirement | No requirement |
| Cooling water | No requirement | No requirement | No requirement | No requirement |
| Well treatment fluids | Estimate and report volume monthly | No requirement | Estimate volume monthly | No requirement |
| Clean deck drainage | No requirement | No requirement | No requirement | No requirement |
| Blow-Out prevention (BOP) fluid discharge | No requirement | Total volume discharged during month shall be reported | No requirement | No requirement |

[a] A basic permit requirement on all discharges is the absence of free oil; this is monitored visually by looking for visible sheens

TABLE 6
**Summary of the acute lethal toxicity data for drilling fluids**

| | Number of species tested | Number of fluids tested | Number of tests | Number of 96-h LC50 values (ppm) [a]: Not determinable | <100 | 100-999 | 1000-9999 | 10000-99999 | >100000 |
|---|---|---|---|---|---|---|---|---|---|
| Plankton | 1 | 9 | 12 | 5 | 0 | 0 | 7 | 0 | 0 |
| Invertebrates | | | | | | | | | |
| Copepods | 1 | 9 | 11 | 1 | 0 | 3 | 5 | 2 | 0 |
| Isopods | 2 | 4 | 6 | 0 | 0 | 0 | 0 | 1 | 5 |
| Amphipods | 4 | 8 | 19 | 0 | 0 | 0 | 0 | 5 | 14 |
| Gastropods | 5 | 5 | 10 | 0 | 0 | 0 | 0 | 2 | 8 |
| Decapods | | | | | | | | | |
| Shrimp | 7 | 16 | 48 | 0 | 0 | 5(0)[b] | 0 | 27 | 17 |
| Crab | 3 | 12 | 24 | 1 | 0 | 0 | 0 | 11 | 12 |
| Lobster | 1 | 2 | 7 | 0 | 0 | 0 | 1 | 3 | 3 |
| Bivalves | 7 | 14 | 33 | 0 | 0 | 0 | 1 | 15 | 17 |
| Echinoderms | 1 | 2 | 4 | 0 | 0 | 0 | 0 | 1 | 3 |
| Mysids | 3 | 9 | 24 | 1 | 0 | 0 | 0 | 14 | 9 |
| Polychaetes | 4 | 14 | 22 | 0 | 0 | 0 | 0 | 4 | 18 |
| Finfish | 11 | 25 | 83 | 0 | 0 | 0 | 2 | 47 | 34 |
| Totals | 48 | 40[c] | 303 | 8 | 0 | 8 | 16 | 132 | 140 |
| Percentages as a fraction of the number of tests | | | | 2.5% | 0% | 2.5%[b] (1%) | 5% | 4470 | 46% |
| Average percentages, based on the percentage values for each of the above, 13 groups of animals testad | | | | 5.3% | 0% | 2.8%[b] (2.1%) | 9.4% | 33% | 50% |

[a] Placement in classes according to: (a) $LC_{50}$ value, (b) lowest boundary of range If $LC_{50}$ expressed as a range, (c) cited values if given as ">" or "<". There were 119 such $LC_{50}$ values; 95 were >100000 ppm; 20 were >10000 ppm; one was <60000 ppm; two were <20000 ppm; tile was <3200 ppm.
[b] These include tests conducted on drilling fluids obtained from Mobile Bay, Ala., end which may not be representati "Ve of drilling fluids used and discharged on the OCS. Values in parentheses exclude data from the Mobile Bay mud tests.
[c] The fluids used in Gerber et al., 1980, Neff et al.. 1980, and Carr et al., 1980, ware all supplied by API. Their characteristics were similar and they may heva been subsamples of the same fluids. H so, the total number of fluids tested would be 35.
Source: Petrazzuolo, 1981.

excretion) because of the methodology used and the difficulty in determining whether the effects were of pathologic or compensatory nature. The sublethal effects for corals were the only ones that could be considered unambiguous adverse behavioral reactions. Exposure to spent drilling fluids significantly decreased clearing rates. No quantification of dose, however, was possible.

Studies on the bioaccumulation of heavy metals by organisms exposed to drilling muds or their components have been reviewed by Dames & Moore ( 1981). Chromium is of course present in ferrochrome or chrome lignosulfonate, and trace metals are also present as contaminants in other components. Barite is a major source of most of these metals, but barites from various origins differ greatly in their trace metal content (Kramer et al., 1980).' The metals that have received the greatest study to date are arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), vanadium (V), and zinc (Zn). Dames & Moore (1981) noted that laboratory studies of metal bioaccumulation indicate that barium may be bioaccumulated by a factor of 30, chromium by factors as great as 15, and lead by a factor of only 2-3. Dames & Moore point out that despite growing evidence that invertebrates bioaccumulate trace metals near the base of marine food webs above normal levels, little is known of the physiological or ecological impact of such bioaccumulation.

**Produced water.** A limited number of studies have been done on the toxicity of produced waters. Dames & Moore (1981) reviewed the work of Clemens and Jones ( 1954), who obtained 96-h $LC_{50}$ values of 43000 to 112000 ppm for 10 species of freshwater fish exposed to brine wastes. Calculations by Clemens and Jones suggested that sodium chloride was present in such proportions as to cause osmotic stress.

A bioassay program was carried out by Rose and Ward ( 1981 ) on produced water from the Buccaneer Field in the Gulf of Mexico off Texas. Brown shrimp, white shrimp, barnacles, and the crested blenny were exposed to up to eight samples of formation water. Results were presented for four sets of test conditions (Table 7). Test series Nos. 1-3 were performed at a shore-based laboratory, while test series No. 4 was conducted on the production platform. The majority of tests were performed for series No. 1, which consisted of static bioassays for which the oxygen demand of the formation water was not evaluated; that is, the media were either aerated or naturally maintained above a dissolved oxygen (D. O.) concentration of4 mg/L. The 96-h $LC_{50}$ values for this series ranged between 8000 and 408000 ppm, the lowest (most toxic) value being obtained for larval brown shrimp. In series No. 2 the test media were not maintained above 4 mg/L D. O., and the $LC_{50}$ values were somewhat lower than those for the same species tested in aerated media. For test series No. 3, flow-through bioassays were conducted in the laboratory and again the media were aerated, while in test series No. 4 flow-through tests were performed on the platform with aerated media. All brine samples during this phase had been treated with crolein, a highly reactive biocide that was scavenged before discharge.

Rose and Ward (1981) also discussed a previous study (Zein-Eldin and Keney, 1978) of the acute toxicity of produced water discharged from the Buccaneer Field. This earlier evaluation, which also addressed the toxicity of water without considering oxygen demand, generated two sets of 96-h $LC_{50}$ values for juvenile white shrimp. In the first set, 96-h $LC_{50}$ values of 1850-6500 ppm were obtained for formation water treated with two biocides (K-31 and KX- 14) that were not scavenged. The second set of $LC_{50}$ values were obtained for formation water without the addition of biocides. These values exceeded 100000 ppm and were considered to reflect the basic toxicity of the water.

Because most of the bioassays cited above were performed on media that were aerated and open to air, the volatile hydrocarbons present in the waters may have been lost as has been observed by Rice et al. (1979). As indicated previously, Wiesenburg et al. (198 1) andSauer(1981 ) had reported that in the produced water from the Buccaneer Field, the concentrations of volatile liquid hydrocarbons were on the order of 21 ppm, 80% of which were the more toxic aromatics. In the above-cited bioassays, an undetermined amount of these volatile liquid hydrocarbons may have been lost during the collection and transport of produced water samples and as a result of subsequent aeration.

Studies on the water-soluble fractions of oil and treated ballast water from tankers have provided information that is helpful in evaluating the acute lethal toxicity of produced water. Water-soluble fractions ( WS Fs) of oil contain fractions of hydrocarbons (that is, the more soluble mono- and diaromatics) similar to those found in produced water. Studies by Anderson et al. ( 1974) and Rice et al. (1976) have indicated that acute oil toxicity in water is caused by the chemical toxicity of soluble aromatics, rather than the physical toxicity of dispersed droplets. Rice et al. ( 1979) have examined the sensitivities of 39 Alaskan marine species to water soluble fractions of Cook Inlet crude oil. This is the largest group of animals ever tested under similar test conditions with the same petroleum oil and analytical methods. Organisms bioassayed included fish (nine species), arthropods (nine species), molluscs ( 13 species), echinoderms (four species), annelids (two species), and nemerteans. The investigators found that although sensitivity generally increased from lower invertebrates to higher invertebrates, and from higher invertebrates to fish, sensitivity was better correlated with habitat. Pelagic fish and shrimp were the most sensitive to the WSFS of crude oil with 96-h $LC_{50}$ values from I --3 ppm total aromatic hydrocarbons. (Note: the undiluted WSF of Cook Inlet crude oil contains about 7 ppm of aromatic hydrocarbons. ) Benthic animals, including fish, crabs, and scallops, were moderately tolerant with 96-h $LC_{50}$ values of 3-8 ppm total aromatic hydrocarbons. Intertidal animals including fish, crabs, starfish, and many molluscs were the most tolerant to the WSF of crude oil. The majority of the inter-tidal animals were not killed by static oil exposures. Rice et al. ( 1979) estimated that static concentrations in the WSF declined over the 96-h exposure period, by evaporation and biodegradation, to about 20% of the initial concentrations.

Rice et al. ( 1981 ) also examined the toxicity of ballast-water treatment effluent to marine organisms at Port Valdez, Alaska. They noted that the treated effluent contained light aromatic hydrocarbons in the range of 1-16 ppm, similar to the levels of light aromatics in produced water reported by Wiesenburg et al. ( 1981) and Lysyj et al. (1981), as discussed in a previous section of this article. For the larvae of crustaceans and fish, the static acute 96-h $LC_{50}$ values for treatment effluent were between 100000 and 200000 ppm; the concentrations of total aromatic hydrocarbons for these static tests were generally between 0.5 and 3.0 ppm. For acute flow-through tests, the 48-h $LC_{50}$ values for fish ranged from 190000 to 430000 ppm for effluent (0.8- 2.8 ppm total aromatic hydrocarbons), while the 96-h $LC_{50}$ values for shrimp ranged from 210000 to 400000 ppm (0.9-3.2 ppm aromatic hydrocarbons). Rice et al. ( 1981) noted that the aromatic hydrocarbons did not cause the total toxicity of the effluent but that it was difficult to define the contributions of other components.

Although the acute toxic effects of produced water discharges appear to be low, chronic lethal and sublethal effects such as behavioral impacts must be considered. Such effects occur at concentrations below those that are acutely toxic (Colwell and Walker, 1977; Steele, 1977; Lee, 1978; Rossi and Anderson, 1978). Chronic exposures to organisms in the water column could occur in areas where the hydrocarbons discharged to the water column are not rapidly removed from the system and where there is a continuous input. The potential for buildup of hydrocarbons in the water column would be greater in semi-enclosed coastal embayments with limited flushing than in offshore regions. In either case, however, the rate of dilution, advection, and other losses such as evaporation and sedimentation would have to be considered before judging whether chronic effects on pelagic organisms could occur.

Petroleum hydrocarbons that have become associated with the sediments are a more likely cause of chronic exposure. Sources for these hydrocarbons could include produced water as well as other sources such as oil spills associated with transfer operations and leaks in pipelines. A number of studies have indicated that petroleum hydrocarbons can become incorporated into the sediments (NAS, 1975; Teal et al., 1978; Armstrong et al., 1977; Roesijadi et al., 1978; Gearing et al., 1979). Several studies suggest that the lighter aromatics such as naphtha lenes are lost more rapidly from the sediments than are the polynuclear and more highly substituted aromatics (Teal et al., 1978; Gearing et al., 1979; Anderson et al., 1979). However, because produced water may be discharged continuously, lighteras well as higher molecular weight hydrocarbons have the potential for accumulating in the sediments and exerting effects on benthic organisms. Among the higher molecular weight hydrocarbons are the polynuclear aromatic hydrocarbons that may be present in low concentrations but for which there is little quantitative data.

Polynuclear aromatic hydrocarbons such as phenanthrene, dibenzothiophene, and their derivatives occur in relatively low concentrations in crude oil (Pancirov and Brown, 1975); however, chronic inputs can cause significant levels of these compounds in sediments as they may accumulate and remain in the sediments and tissues for longer periods of time than the lighter aromatics (McLeod et al., 1977; Teal et al., 1978; Anderson et al., 1978, 1979). These compounds are of concern because some are suspected carcinogens or mutagens (Christensen et al., 1975; Payne et al., 1979) and because they may be more toxic to marine organisms on a molar basis than the lighter aromatics (Hutchinson et at., 1979).The work of Hutchinson et al. (1979) has indicated that hydrocarbons with low vapor pressure and low water volubility--such as anthracene, phenanthrene, and pyrene --are more toxic on a molar basis than the compounds such as benzene with high vapor pressure and high water solubility. These investigators postulated that the strongly lipophilic nature of hydrocarbons causes them to be rapidly and powerfully absorbed by cells and suggested that the lipoprotein cellular membrane may be a key site of action. Polynuclear aromatics (PAHs) can be degraded by most marine animals to more polar metabolites and excreted rapidly. However, the metabolic intermediates of some PAHs are highly carcinogenic, mutagenic, or teratogenic (Neff, 1979). Therefore. rather than enhancing detoxification. the metabolism of some carcinogenic PAHs could result in higher steady-state levels of toxic products in induced animals (Stegeman, 1981). Effects will probably depend on the rate at which metabolites arc formed relative to the rates at which they arc further metabolized or excreted.

The actual toxic effects of PAHs and highly substituted aromatics in sediments may be limited because of their strong affinity for sedimentary material, As a result, these compounds may be less available to organisms living on or in the sediments. The bioconcentration of these compounds may depend on their concentrations in the interstitial pore water and the rate at which the compounds partition from the sediments into the pore water. It should also be noted that there are many sources of PAHs to the marine environment and this should be considered when evaluating the signifi-

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**Median lethal concentrations ($LC_{50}$s) and associated 95 % confidence intervals for organisms acutely exposed to formation water under various experimental conditions**

| Organisms | Season of test | Formation water used | Testing temperature | $LC_{50}$ (ppm) | 95% Confidence interval |
|---|---|---|---|---|---|
| Test Series No. 1 | | | | | |
| Brown shrimp | | | | | |
| Larva | Spring 1979 | D | 28 | 10000 | 7000-15000 |
| | | E | 28 | 12000 | 9000-16000 |
| | | F | 28 | 8000 | 6000-12000 |
| | | G | 28 | 8000 | 5000-11000 |
| Subadult | Summer 1978 | A | 25± 1 | 94000 | 63090-172000 |
| | Fall 1978 | B | 22±1 | 60000 | 0-100000 |
| | Winter 1979 | c | 18*2 | 183000 | 130000-279000 |
| | Spring 1979 | D | 24± 1 | 61000 | 47000-76000 |
| Adult | Summer 1978 | A | 25± 1 | 94000 | 63000-172000 |
| | Fall 1978 | B | 22* 1 | 76000 | 38000-163000 |
| | Winter 1979 | c | 1 8*2 | 176000 | 132000-240000 |
| | Spring 1979 | D | 24±1 | 90000 | 61000-156000 |
| white shrimp | | | | | |
| Subadult | Summer 1978 | A | 25*1 | 56000 | 51000-62000 |
| | Fall 1978 | B | 22*1 | 61000 | 48000-76000 |
| | Winter 1979 | c | 18±1 | 133000 | 67000-366000 |
| Adult | Summer 1978 | A | 25±1 | 81000 | 48000-153000 |
| | Fall 1978 | B | 22±1 | 62000 | 27000-110000 |
| | Winter 1979 | C | 18±1 | 92000 | 58000-150000 |
| | Spring 1979 | D | 24* 1 | 37000 | 24000-52000 |
| *Barnacle* | Summer 1978 | A | 25± 1 | 33000 | 25000-38000 |
| | Fall 1978 | B | 22*1 | 84000 | 66000-104000 |
| | Winter 1979 | C | 18±2 | lti4 000 | 111000-222000 |
| | Spring 1979 | D | 24±1 | 60000 | 49000-71000 |
| Crested blenny | Summer 1978 | A | 25±1 | 158000 | 100000-320000 |
| | Fall 1978 | B | 22± 1 | 406000 | 320000-560000 |
| | Spring 1979 | D | 24± 1 | 178000 | 135000-235000 |
| Test series NO. 2 | | | | | |
| Barnacle | Winter 1979 | c | 18±2 | 8000 | 5000-13000 |
| Cr. blenny | spring 1979 | D | 24±1 | 7000 | 5000-12000 |
| Test series No. 3 | | | | | |
| White shrimp | | | | | |
| Subadult | Fall 1978 | B | 22* 1 | 62000 | 48000-76000 |
| Test series NO. 4 | | | | | |
| Brown shrimp | | | | | |
| Subadult | Spring 1979 | H | 25-29 | 44000 | 25000-60000 |
| Barnacle | Spring 1979 | H | 25-29 | 51000 | 34000-68000 |

**Source:** Rose and Ward, 1981.

cance of inputs due to offshore operations.

The degree to which hydrocarbons accumulate in sediments around platforms will depend on the quantities of discharged material as well as the rate at which the sediments are resuspended and transported from the area. Discharged hydrocarbons are more likely to accumulate in sediments where the water is shallow and the wave and current action is minimal. Areas of sediment deposition near production operations may serve as sinks for discharged hydrocarbons.

## Field monitoring programs

A variety of field monitoring programs have been carried out to examine the environmental effects of offshore drilling and production. Because the major discharges associated with drilling operations (that is, the drilling fluids and cuttings discharged during exploration and development) differ from those associated with production, primarily produced water studies designed to evaluate these two major classes of operations are presented separately below. It should be recognized, however. that areas where production is taking place have already experienced, and may still be receiving, discharges associated with drilling operations.

**Field studies designed to examine the fate and effects of drilling discharges.** Field programs have been conducted off the coasts of California and Alaska, in the Gulf of Mexico, and off the U.S. cast coast. These studies include water column studies, sediment trap studies, and benthic studies (Table 8). The Georges Bank benthic monitoring program being conducted off the New England coast (results not available at this writing) is also described because it is the most comprehensive and intensive program of its kind conducted to date. Special studies such as recolonization studies or in situ bioassays are not included here.

*Water column studies.* These have been conducted primarily to examine the short-term fate of bulk discharges of drilling fluids and cuttings in the water column. Methods that have been used to track discharge plumes include water quality sampling from helicopters in which visual observations and transmissivity measurements were used to track the plumes (e.g., Meek and Ray, 1980; Ayers et al., 1980a, b), the addition of a fluorescent tracer to the effluent and monitoring its concentration over time and space with a fluorometer (Houghton et al., 1980), radiotracer studies (Shell Oil Company, 1978), diver observations (Ayers et al., 1980a,b; Meek and Ray, 1980), and acoustic monitoring (Proni et al., 1981).

These studies have shown that during bulk discharges of drilling fluids and cuttings, the plume tends to separate into two plumes. Most of the solids decend rapidly in the lower plume. The initial descent of the lower plume does not appear to be inhibited by pycnoclines (Ayers et al., 1980b).

The upper plume is transported with the prevailing currents and may contain up to 5-7% of the discharged solids that have separated from the lower plume due to turbulence effects and have escaped extensive flocculation (Ayers et al., 1980b). Various investigators have examined the dispersion rates of these materials and the distance from the rig at which background conditions are achieved. Excluding the data from the high energy Cook inlet study (Houghton et al., 1980), Petrazzuolo ( 1981) presented the following generalized distances required to achieve specified levels of dispersion of drilling fluids for whole plumes at high discharge rates: $10^4$ at 100 m, $10^5$ at 500 m, and $10^6$ at 1000 m. Most of the work presented to date suggests that background levels (for suspended solids or transmissivity) are achieved less than 1000–1 500 m from the well site. Houghton et al. (1980) also noted that drill-rig-induced turbulence was an important factor in plume dispersion. The studies performed to date suggest that the upper plume contains a relatively small percentage of the total discharged material and is rapidly diluted in the water column. Most of the discharged solids appear to descend rapidly to the seafloor. The short- and long-term fate and environmental effects of this material are of more importance than those associated with the lighter upper plume. However, with regard to effects of the upper plume, some questions still remain concerning the degree to which materials accumulate on density gradients in the water column. Accumulations of particulate on the pycnocline have been detected by Proni et al. ( 1981 ) using acoustical methods.

*Sediment trap studies.* These have been conducted in order to better estimate the quantities of solids discharges reaching the seafloor. Sediment trap deployments include 14 sediment trap moorings around a drilling rig in the Southeast Georgia Embayment in 40 m of water (EG&G, 1980), 19 sediment traps around a rig at Tanner Bank off California (Meek and Ray, 1980), two sediment traps in a study of a rig in the lower Cook Inlet, Alaska. (Dames and Moore, 1978), 17 sediment traps deployed by helicopter at distances of 30--200 m downcurrent of a platform in the Gulf of Mexico (Ayers et al., 1980), and six traps at Baker Bank in the Gulf of Mexico in 61 m of water (Continental Shelf Associates, 1979).

Results from these studies generally indicate that solids settle to the seafloor in the vicinity of the well site. Meek and Ray ( 1980) estimated that 12% of the discharged solids settled on the seafloor in the Tanner Bank within 50-150 m of the discharge while, based on assumed settling characteristics, the majority of sediments settled within 50 m of the discharge. The study carried out in the Gulf of Mexico (Ayers et al., 1980b) showed that the bulk of discharged solids (>90%) settled rapidly to the seafloor with the lower plume,

*Benthic studies.* At present, research on the fate and effects of drilling fluids and cuttings is focused on the benthic environment. This is consistent with the observations presented previously that the bulk of discharged materials descends rapidly to the seafloor. Benthic studies have involved various kinds of investigations including those of obvious physical alterations, changes in granulometric and chemical (e.g., trace metal) characteristics of sediments, bioaccumulation of trace metals in organisms, and changes in the epibenthic and infaunal biological communities.

Obvious physical alterations of the seafloor have been examined using underwater television (UTV) and side-scan sonar (Menzie et al., 1980, Gillmor et al., 1981), diver observations (Zingula, 1975; Ray and Shinn, 1975; Ecomar, 1978), and visual examination of cores (Dames & Moore, 1978). Accumulations of solids and cuttings piles (50 I 50 m in diameter) have been observed in the less turbulent regions of the Gulf of Mexico (Zingula, 1975) and in the mid-Atlantic bight (Menzie et al., 1980; Gillmor et al., 1981). The accumulations in the mid-Atlantic exhibited a patchy distribution. These were not observed in the more turbulent environments of Tanner Bank (Ecomar, 1978) or Cook Inlet (Dames & Moore, 1978). In the latter study, however, the investigators did report that cuttings were entrained down into the surficial sediments as a result of the extensive sediment motion associated with strong tidal currents. [n the Southeast Georgia Embayment, EG&G (1980) observed small patches of drilling

TABLE 8

**Characteristics of field monitoring studies designed to examine the fate and effects of drilling discharges**

| Type of study | General ● nmpling methodology | References |
|---|---|---|
| Water column studies | Plume dispersion monitoring<br>Hydrographic sampling from helicopters<br>Dye tracers<br>Acoustic monitoring | Ayers et al. (1980a, b); Meek and Ray (1980); Houghton et al. (1980); Proni et al. (1981) |
| Sediment trap studies | Helicopter or vessel deployed sediment traps at various depths and distances from the well site | EG&G (1980); Maak and Ray (1980); Ayers et al. (1980b); Dames & Moore (1980) |
| Benthic studies | | |
| Visual physical alterations | UTV, Side-Scan Sonar, bottom photographs, divers, visual analysis of cores | EG&G (1980); Menzie et al. (1980); Gillmor et al. (1981); Zingula (1975); Lees and Houghton (1980) |
| Physical and chemical alterations of sediments | Grabs and cores from sediment around well site. Generally analyses of uppar few cm | Mariani et al. (1980); EG8G (1982): Union Oil Company (1977); Mobil Oil Corp. (1978); CSA (1979); Meek and Ray (1980); Lees and Houghton (1980) |
| Bioaccumulation of bate metals In benthic fauna | Collection of grab samples and sieve for fauna | Mariani et al. (1980); Crippen et al. (1980); EG&G (1982) |
| Abundances and compositions of infauna and epifauna | UTV, bottom photographs, trawls, benthic grabs | Menzie et al. (1980); Gillmor et al. (1981, and in press); Lees and Houghton (1980); Crippen et al. (1980); EG&G (1982) |

muds a few centimeters in diameter on the seafloor immediately following bulk discharges of drilling fluids; these patches were dispersed within 24 hours. In the relatively low energy area of the mid-Atlantic study, discharge accumulations were still observed in UTV, side-scan, and bottom photographs one year following drilling (Gillmor et al., in press).

Mariani et al. (1980) examined alterations in sediment particle size in the mid-Atlantic study area. Significant increases in clay content, derived from drilling operations, were observed out as far as 800 m from the well site, at the least. Shifts in clay mineralogy suggested that this increase was due primarily to formation solids (kaolinite increased) and not drilling fluids (montmorillonite decreased).

Sediment chemistry, concerning trace metals primarily, has been studied around exploratory wells in the mid-Atlantic (Mariani et al., 1980; EG&G, 1982), Southeast Georgia Embayment (EG&G, 1980), Gulf of Mexico (Union Oil Company, 1977; Mobile Oil Corporation 1978; U.S. Depart ment of Interior, 1976; and Continental Shelf Associates, 1979), Tanner Bank (Meek and Ray, 1980) and Cook Inlet (Dames & Moore, 1978). These investigations usually focused on barium as a tracer for drilling fluids, while in some studies chromium, which is discharged with chrome lignosulfonate, was also measured. Other trace metals such as Cd, Cu, Fe, Pb, Ni, V, and Hg have also been monitored. Barium was the only metal consistently found in sediments at elevated concentrations following drilling, probably because considerably larger amounts of this metal are found in drilling fluids. In the mid-Atlantic and Gulf of Mexico study areas where the water is fairly quiescent, barium concentrations in the upper 2-3 cm of sediment were significantly elevated at the well site and decreased to background 1000-3300 m from the well site. In contrast, measurements made in the higher energy, turbulent areas such as the Southeast Georgia Embayment and Cook Inlet suggested that barium was not significantly elevated in sediments around an exploratory well (EG&G, 1980; Dames & Moore, 1978).

Bioaccumulation of trace metals in benthic organisms around drilling operations was examined in the mid-Atlantic (EG&G, 1982) and in the Beau fort Sea (Crippen et al., 1980). Specifically, increases in the mean concentrations of barium were detected in brittle stars (~1 OX) and polychaetes (-3X) shortly after drilling operations were terminated in the mid-Atlantic study (concentrations were highest near the well site). Surprisingly, the concentration of barium in molluscs decreased between pre- and post-drilling surveys. One year later, the mean concentrations of barium had decreased in polychaetes and brittle stars to levels typical of pre-drilling conditions. Elevated concentrations of chromium in polychaetes also were observed and may have been caused by drilling discharges. In the Beaufort Sea study, the data suggested that mercury was taken up by organisms at two out of 43 stations near the discharge; elevated levels of other metals were not observed. The available field data indicate a potential for bioaccumulation of trace metals in benthic organisms around drilling operations.

A study of the effects of drilling discharges on benthic faunal composition and abundance was performed in the mid-Atlantic (reported in Menzie et al., 1980; Maurer et al., 1981; Gillmor et al., in press; and EG&G, 1982). Benthic studies have been conducted in Cook Inlet (Lees and Houghton, 1980) and the Beaufort Sea (Crippen et al., 1980). In the Cook Inlet study, however, the investigators noted that a major factor limiting the statistical strength of their conclusions, was their inability in subsequent surveys to precisely locate the same stations used in the pre-drilling survey. In the Beaufort Sea study, excavation of surficial sediments to construct an artificial island and the resulting sedimentation from erosion of the island created disturbances that complicated the investigators' ability to discern effects associated with the discharges of drilling fluids.

The mid-Atlantic study involved a pre-drilling survey, a post-drilling survey conducted within two weeks following the termination of drilling. 'and a second post-drilling survey performed one year later. The study focused **on the** effects around the rig site out to a distance of 3.2 km; it did not attempt to ascertain regional effects associated with a number of operations. The major findings of this study are as follows: Cuttings and other debris accumulated on the bottom as a result of exploratory drilling provided microrelief attractive to certain species of bottom-dwelling fish, especially red hake, *Urophycis chuss*. Compared to pre-drilling densities, fish and decapods appeared to have higher densities in the overall study area after drilling operations had occurred. While this was true for both post-drilling surveys, decapods generally and *Munida* sp. in particular showed decreases in density as the well site was approached during the one-year-after study. These animals may have been sensitive to the presence of drilling discharges on the bottom, although the influence of predation by fish in the vicinity of the well site may also account for the observed differences.

The decreased abundance of macrofauna such as polychaetes, molluscs, and crustaceans observed in the overall study area during the first post-drilling survey were attributable to natural factors as well as the effects of drilling discharges. Increases in both species richness and abundance were observed in the one-year-after survey. The abundance of macrofauna in both post-drilling surveys exhibited only weak spatial trends and no correlations with barium concentrations in the sediments. A possible exception was the burrowing brittle star *Amphioplus macilentus*, whose low abundance characterized several stations close to the well site. Immediately following the termination of drilling, polychaete abundance tended to be lower at stations exhibiting elevated levels of clay. Lower abundances of the brittle star *A. macilentus* and of polychaetes could reflect decreased recruitment caused by changes in the sediments ( Menzie et al., 1980; Gillmor et al., in preparation). Generally, the impacts of drilling discharges on benthic biota that could still be observed one year after drilling operations had ceased were relatively minor and highly localized.

Because the mid-Atlantic study area was a more quiescent environment than many of the other study areas previously mentioned (for example, Tanner Bank, Cook Inlet, Southeast Georgia Embayment), discharges of drilling fluids and cuttings were able to settle, remain in the area, and have an effect on the benthos. Therefore, the observed impacts should be greater in the mid-Atlantic study area than in the higher-energy environments.

**Georges Bank benthic monitoring**

This program is being funded by the U.S. Bureau of Land Management and is designed to assess the effects of drilling discharges on the benthic environment of Georges Bank. During the development of the program, a large number of different kinds of studies, such as water column and plankton investigations, were considered by the Biological Task Force (BTF) for Georges Bank. However, the final program's focus on the benthic environment is consistent with previous observations on the fate and effects of drilling discharges. In addition to a rig monitoring study, the program also involves a regional monitoring study to address questions regarding Iarge-scale effects or possible deposition of discharged materials in quiescent areas. The major elements of the program are described below.

As part of the rig-monitoring study, a radial array of 29 stations will be used to take samples out to a distance of 6 km from the well site. Nineteen of these stations are considered primary and will be used for analyses; 10 of these stations are considered secondary and will be employed for analyses only if the results from the primary stations suggest they are needed. Sediment samples will be obtained for analysis of petroleum hydrocarbons. Trawls or dredge hauls will be made in three general areas to obtain megabenthic fauna for identification and for tissue analyses of trace metals and petroleum hydrocarbons. Photographs of the bottom will be taken to document the physical characteristics of the seafloor and to identify megafauna.

Fifteen regional stations will be sampled quarterly for the parameters already described for site-specific stations. At three of the regional stations, trawls or dredge hauls will be made to collect megafauna for identification and tissue analyses. Petroleum hydrocarbons in sediments will be examined at three of these stations.

Data from the Georges Bank Monitoring Program will be integrated with particular historical data and data generated from other ongoing studies to provide a more complete assessment of fate and effects of drilling discharges. Of particular importance will be the discharge monitoring data provided as part of the N PDES discharge requirements (Table 5) and physical oceanographic data. The Georges Bank Monitoring Program together with studies performed in other areas should provide a data base that collectively could be used for predicting effects of discharges in areas where no monitoring studies have been performed.

**Field studies around production platforms.** Several studies have been conducted to examine the effects of petroleum production operations. Four of these programs, three from the Gulf of Mexico and one from the Santa Barbara Channel, are presented here. The Central Gulf of Mexico platform study was funded by the U.S. Bureau of Land Management and carried out by a number of investigators under the direction of the Southwest Research Institute ( 1981 ). Four primary and 16 secondary platforms were examined on the Louisiana OCS west of the Mississippi Delta. The platforms were located 5-120 km offshore in water depths of 6-75 m. The Mississippi River had a pronounced influence on the study area, and during one of the years, outflow from the river resulted in anoxic bottom conditions covering a large area. The influence of the Mississippi made it difficult to sort out the effects attributable solely to platform operations.

The Buccaneer Field Study was funded by the U.S. EPA through the National Marine Fisheries Service. This multidisciplinary program involved a number of principal investigators. The Buccaneer Field, which consisted of two production platforms, two quarters platforms, and 14 satellite platforms, had been in production for 15 years. The field was located 50.5 km south of Galveston, Tex., in a water depth of 21 m. Based on sediment and physical oceanographic studies, the area appeared to be a relatively high-energy environment.

The Trinity Bay Study was funded by the American Petroleum Institute and was reported by Armstrong et al (19”//). Trinity Bay is an estuarine area along the coast of Texas and has a water depth of approximately 2.5 m. Sediments are of a silty-clay nature and the water is turbid. Brine effluent is discharged one meter from the bottom.

The Santa Barbara Channel (California) study involved the examination of two oil platforms located two miles offshore in approximately 30 m depth. At the time of the study, the platforms had been operating for about 15 years. The work was supported by the American Petroleum Institute and is reported in Mearns and Moore (1976).

These studies are useful for evalusting what chemical, biological, or physical parameters are being modified by operations related to production platforms, at least in the immediate vicinity of the platforms. It is more difficult to assess the impacts of operations over a greater area because the studies have been performed in regions that have already experienced a number of years of production activity as well as relatively large effects from other sources of contaminants such as the Mississippi River, runoff from other estuaries, tanker discharges, and atmospheric inputs.

Observations obtained from these field studies have been organized into the following categories for purposes of discussion: hydrocarbons in seawater; hydrocarbons in sediment; hydrocarbons in organisms: trace metals in water, sediments, and organisms; microbiological studies: histopathology of invertebrates and fish; benthic populations; and artificial reef studies.

*Hydrocarbons in seawater*. Studies of hydrocarbons have included measurements of gaseous hydrocarbons with carbon numbers of $C_1$-$C_4$, volatile liquid hydrocarbons ($C_6$-$C_{14}$), and higher molecular weight hydrocarbons (HMW-HC). The studies of Wiesenburg et al. (1981) and Sauer (1980, 1981) suggest that the gaseous hydrocarbons may be indicative of underwater venting of gases, while the volatile liquid hydrocarbons may be more indicative of produced water discharges.

Gaseous hydrocarbons in seawater were examined in the Central Gulf of Mexico study and Buccaneer Field study (Nulton et al., 1981; Brooks et al., 1980). The Central Gulf of Mexico area had baseline levels above those of the open ocean. At selected platforms, elevated levels of gaseous hydrocarbons were observed probably due to pipeline breaks or hydrocarbon venting. Gaseous hydrocarbons in the Buccaneer Field were typical of unpolluted waters along the Texas coast.

Volatile liquid hydrocarbons (VLHs) were measured in seawater at the Buccaneer Field but were not specifically looked for in the Central Gulf of Mexico or Trinity Bay studies. However, Sauer (1980) did report elevated levels over open ocean water in waters of the Louisiana OCS (≈0.5 ppb); aromatic VLHS accounted for 60-80% of the total VLHS in surface waters. In the Buccaneer Field, elevated levels of VLHS (≈65 ppb) were observed immediately below the discharge pipe but were rapidly diluted with distance (Brooks et al., 1980). At a grid of stations 25 and 50 m from the discharge, VLHs ranged from 0.13 to 6.4 ppb. VLHs in produced water averaged about 21 ppm and, therefore, the data suggests that VLHS are diluted on the order of $10^4$ to $10^5$ within about 50 m of the platform. Concentrations of VLHS around the platform were approximately four times higher than at a platform 3 km away, which had no discharges. Values at this latter platform were still higher than those given by Sauer (1980) for anthropogenically influenced water. Samples of bottom water taken 15 m from the shallow water (2–5 m) platform in Trinity Bay indicated that total hydrocarbons were diluted from 25 ppm in the brine effluent to 10.5 ppb in the sample water, a dilution factor of 2000. This degree of dilution is similar to that observed at the Buccaneer Field.

*Hydrocarbons in sediments.* At the Central Gulf of Mexico platforms, no excessive values of total organic carbon in sediments were observed. Pyrogenic aromatic hydrocarbons such as pyrene were detected at most sites and could be due to continental runoff or atmospheric precipitation. Anthropogenic compounds such as PCBS in sediments may be the result of Mississippi River runoff. Unresolved complex mixtures of HMW-HC and the presence of multiple isomers of alkyl aromatic compounds and parent compounds (e.g., naphthalene and phenanthrene) indicated the presence of petrogenic hydrocarbons at six platforms.

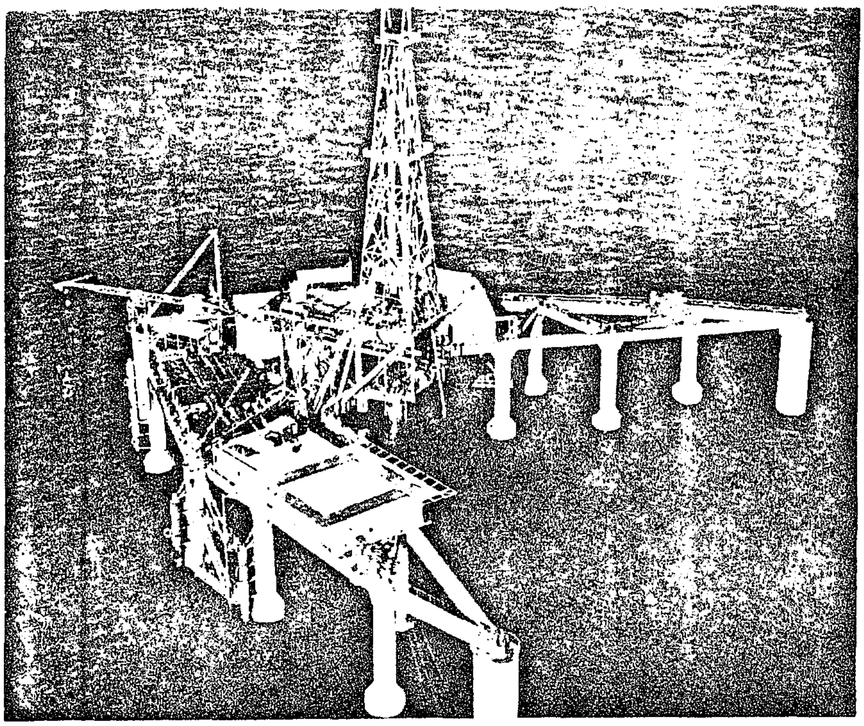
Only a few sediment samples in areawide studies in the Buccaneer Field contained evidence of petroleum hydrocarbons based on analyses of high molecular weight (HMW) alkane fractions (Middleditch, 1981). Elevated concentrations were found in the immediate vicinity of production platforms; however, concentrations of these HMW alkanes decreased with increasing distance from the discharge out to a distance of approximately 20 m (the spatial extent of sampling). The distribution of alkanes indicated fresh oils.

At the shallow (2.5 m) Trinity Bay study area, elevated levels of naphthalene (18-21 ppm) were observed in sediments within 15 m of the outfall (Station 1) over the 21-month study period (Armstrong et al., 1977). Stations located 75 m from the outfall had concentrations that were 20–50% of those at Station 1, while stations over 450 m from the discharge had concentrations at or near background levels. The petroleum hydrocarbon content of sediment samples around platforms in the Santa Barbara Channel was higher than values for areas with no natural seeps (Mearns and Moore, 1976). While levels at the platforms were higher than those at the control site, the GC fingerprints for all samples were characteristic of highly weathered oil indicating no present-day (1976) hydrocarbon contamination.

*Hydrocarbons in organisms.* In the Central Gulf of Mexico studies, GC/MS analyses of some tissues demonstrated the presence of low levels of alkylated benzenes, naphthalene, alkylated naphthalenes, phenanthrene, alkylated three-ring aromatics, and pyrene in a variety of fish and macroepifauna. Isomer distributions of alkylated benzenes and naphthalenes, were similar to those seen in crude oil. No instances of massive contamination were observed (Nulton et al., 1981). The investigators concluded that biota in the study area have been exposed to a low level of petroleum hydrocarbons and man-made combustion products. All concentrations of various exotic components in fauna were in the 1-20 ppb range (except in one fish where a monophenoxybiphenyl was found at 1 ppm). The executive summary for this report noted that the ecological significance of these levels is unknown, but that the occurrence of carcinogenic compounds, at any level, is a cause for concern. The summary further noted that identifying saturated fractions and analyzing for higher aromatics (3+ rings) did not demonstrate petroleum contamination as effectively as analyzing for benzene, naphthalene, and their alkyl-substituted derivatives.

In the Buccaneer Field study, biota were examined for HMW alkanes (Middleditch, 1980). Many different animal species were studied. Petroleum hydrocarbons were encountered in certain barnacles, fish, shrimp, and other organisms. The feeding habits of some fish could be correlated partially with their content of petroleum hydrocarbons. Fish that feed on the platform fouling community contained higher concentrations of petroleum hydrocarbons than those that fed in the water column. Hydrocarbon concentrations were generally higher in the livers of these fish than in other tissues. There was no evidence for biomagnification of hydrocarbons in the food web.

In the Santa Barbara Channel studies, the hydrocarbon content of tissue samples determined by GC



*Studies of marine life. Research continues concerning the effects of offshore oil drilling on the marine biota*

analysis showed no detectable hydrocarbons in mussels and crabs but very high levels in rockfish. However, all the hydrocarbon components identified could be reasonably attributed to biogenic sources (Mearns and Moore, 1976).

***Trace metals in water, sediment, and fauna.*** The Central Gulf of Mexico studies found no strong evidence for high levels of trace metal contamination in sediments surrounding petroleum platforms (Tillery et al., 1981). Generally, significant increases of trace metal concentrations above regional levels were observed at stations that were within 100 m of the platforms. Sediments collected farther away had trace metal levels that usually could be explained by natural geochemical processes. The investigators noted that inputs from the Mississippi River probably exerted the dominant influence on trace metal concentrations in the sediments. Concentrations of Cr, Cu, Fe, and Ni in sheepshead, spadefish, and red snapper collected at the platforms may be related to sediment concentrations. However, bioaccumulation specifically related to production operations cannot be proved by comparing the mean trace metal concentrations and ranges in the tissues with similar data from other Gulf of Mexico studies.

At the Buccaneer Field, trace metal concentrations in seawater were within the range reported for nonpolluted shelf waters (unfiltered). Temporal variationsin the concentrations of the trace metals Ag, Ba. Be, Cd, Co, Cr, Cu, Hg, Mn, Pb, Sr, and Zn were observed in surficial sediments within 180 m of platform structures (Tillery, 1980). A comparison with other sediments from the Gulf of Mexico indicated short-term accumulations of Ba, Cn, Co, Cr, and Pb and more persistent accumulations of Hg, Mn, Sr, and Zn in sediments. Wave action, currents, and turbulence around platforms tend to disperse bottom sediments, thus preventing long-term buildup of most metals, and suspended particulate matter contained higher trace metal concentrations than bottom sediments. Even though elevated levels of trace metals were present in the produced brine discharge, they have not accumulated in biofouling communities (Table 4). Nor was there evidence of excessive bioaccumulation of trace metals in other marine organisms around the production platforms, although temporal variations of trace metals were observed in various species.

High zinc levels were observed in sediments in the immediate vicinity of platforms in the Santa Barbara Channel (Mearns and Moore, 1976). The investigators suggested that the high zinc levels may have been caused by metal flakes from the platform or metal debris on the seafloor. Rockfish showed increased levels of vanadium.

Results of trace metal studies suggest that trace metals may accumulate in sediments in the immediate vicinity of production platforms (100-180 m), and that some of these may be bioaccumulated. Sources of these metals could include corrosion of metal structures, use of sacrificial electrodes, various activities associated with operations on production platforms, produced brine discharges, corrosion of metallic debris on the bottom, engine exhausts, and previous drilling discharges (Wheeler, 1979).

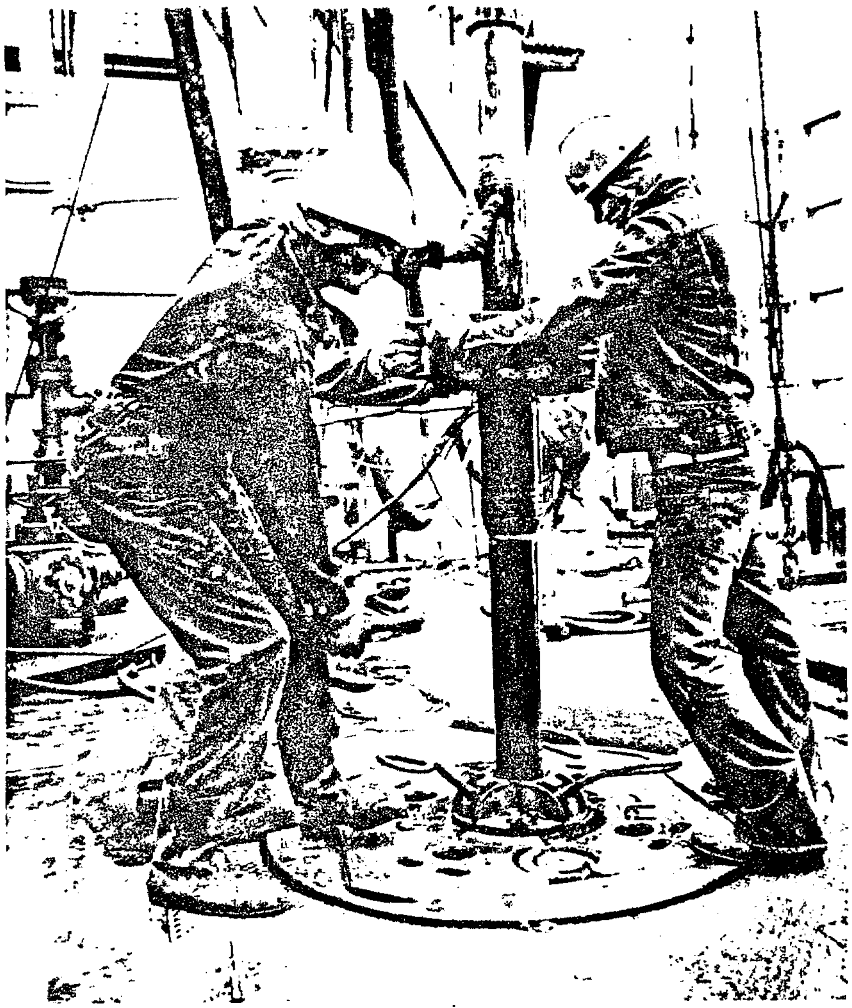
***Microbiological studies.*** In the Central Gulf of Mexico, these studies showed that based on colony counts or microbial processes, there were occasional statistically significant microbial differences between platforms and control sites (Brown & Walker, 1981). Where differences existed, microbial counts associated with platforms were higher than those at control areas. Because the program was designed to look at only the top 1-2 cm of sediment, the effects of recent sedimentation and redistribution were magnified, and these processes may have obscured effects caused by the platforms. The outflow of the Mississippi River was also shown to contribute significantly to spatial patterns in sediment microbiota. Studies performed on the oil degrading potential of microbes in the sediments yielded inconsistent results. Because the research results were highly variable and it was impossible to pinpoint environmental conditions that influence oil degradation, the executive summary of the final report stated that considerably more research needs to be done on degradation potential before these data are used for predictive purposes.

Observations of the microbiota in the water column of the Buccaneer Field revealed slightly higher bacterial numbers and biomass at the control site than at the platforms that discharge produced water (Sizemore et al., 1981). Bacterial numbers in the sediment were also slightly higher at the control site ($4.1 \times 10^6$ as compared to $3.4 \times 10^6$ bacteria per gram dry weight sediment). These differences between the platforms and control site (generally less than a factor of 2) were considerably less than temporal variations. When the bacterial populations of the platform were compared to those of the control site, no taxonomic differences were found in either the water column or the sediments. The general physiological profiles of the bacterial populations were also similar, Although the number of oil-degrading and sulfur-oxidizing bacteria were generally low at both sites, the platform site consistently contained a higher number and percentage of both types of bacteria. The investigators concluded that populations around the platform have adapted to the presence of discharge products such as hydrocarbons and sulfur but that this adaptation has not resulted in a dramatic change in the population.

The results presented above indicate that compared to populations in control areas, microbial populations around platforms may be modified. The degree to which such differences are established probably depends upon the nature of the environment such as the rate at which sediments are resuspended and transported or the presence of exogenous factors such as river inputs. Where platform-induced microbial changes have occurred, they appear to be limited to the immediate vicinity of the platform, For example, during the early stages of the Buccaneer Field study. sites were sampled at intervals up to several kilometers from the platforms; however, as the study proceeded, it became apparent that effects could be observed only in the vicinity of the platforms (Sizemore et al., 1981).

*Histopathology studies.* In the Central Gulf of Mexico study, all of the sites at which relatively higher occurrences of histopathological conditions in fish were observed were located in the eastern part of the study area, while sites in the western part of the study area ranked either medium or low in the number of conditions (Sis et al., 1981). The investigators suggested that the platform locations in the eastern part of the study area, which were consistently contaminated with hydrocarbons or trace metals either from production or other sources, are those where stress was greatest on fish. Because the spadefish had a high incidence of histopathological conditions, its distribution among platforms and control areas (where it was absent) affects the frequency of occurrence of these conditions.

Histopathological conditions were examined in the Buccaneer Field for spade fish, sheepshead, crested blenny, and red snapper (Gallaway and Martin, 1980). The investigators attributed disease epidemics in spadefish to the actions of opportunistic pathogens during periods of natural seasonal stress for the fish. Much of this stress was believed to be due to a combination of high density, change in habitat, reduction in feeding efficiency, and change in food habits. Gallaway and Martin did note, however, that there was a slight possibility that winter disease epidemics may have been related to chronic, low-level discharges of contaminants. Sheepshead residing at the platforms were characterized by a higher degree of histopathological conditions (or parasitism) than



***Benthic communities. Studies have been conducted to examine the effects of drilling discharges on benthic organisms***

sheepshead that migrated in and out of the study area, suggesting possible effects associated with platforms. Although the crested blenny was closely associated with structures and thus would be exposed to discharges, it was relatively free of histopathological conditions. The red snapper was commonly found associated with structures and the investigators reported no marked difference in the frequency of various anomalies in red snapper at production platforms as compared to individuals at satellite platforms. For this species, no evidence of disease or poor condition was observed at any location or during any season.

The results summarized above do not appear to provide strong evidence that discharges from production platforms induce histopathological conditions. In the Central Gulf of Mexico studies, other sources of contaminants such as the Mississippi River and the variable spatial distribution and abundance of fish, which may have naturally high occurrences of histopathological conditions, make it difficult to discern the effects of platforms. In the Buccaneer Field Study, the investigators suggested that natural and platform-related factors might be involved.

*Studies of benthic populations.* Interpretation of results from the Central Gulf of Mexico studies was complicated by the occurrence of two irregularly occurring phenomena, a tropical cyclone and anoxic bottom conditions. The investigators noted that over much of the study area, the frequency and areal impact of storms and "dead bottoms" caused so much disruption of the benthic fauna that it was impossible to clearly describe populations (Baker et al., 1981). Therefore, the effects of platforms could not be discerned.

Benthic fauna in the Buccaneer Field were described by Harper et al. (1981). They observed that the assemblages around the platform were different from most of those in the study area. The stations within 100 m of the platform had depressed faunal abundance, a relatively high species turnover rate, and the occurrence of a few species that were more frequently found at these stations than in the remainder of the study area. Three possible explanations were offered for these observations: Toxic substances from the platforms were periodically killing organisms relatively quickly after they settled, causing a low abundance and a high turnover rate; the harder substrate in the vicinity of the platforms was unsuitable for habitation for many of the benthos; or the fish and larger invertebrates that congregated around the platforms were preying heavily on the benthic fauna. The investigators presented data which suggested that the third explanation is the least likely. They also concluded that harder bottoms associated wit h scouring of sediments around the platform were probably not the definitive cause of the reduced abundance. Thus, toxic effects, perhaps associated with the presence of hydrocarbons, appeared to be contributing at least in part to the altered benthic community composition and abundance.

Similar benthic impacts were observed in the Trinity Bay study (Armstrong et al., 1977). Within approximately 15 m of the discharge, the sediments were almost devoid of benthic infauna. The numbers of both species and individuals increased with distance out to 600-1500 m from the platform. The investigators considered stations more than 450 m from the platform as unaffected because their organism densities exceeded 300 individuals (the level representative of control areas). Increased levels of naphthalenes in the sediments correlated with low numbers of benthic organisms. The investigators concluded that persistent low levels of naphthalenes apparently restricted many species. Other hydrocarbons that were not measured in the study might also have contributed to the effects on the benthos.

No adverse effects on fauna around the Santa Barbara Channel platforms were observed (Mearns and Moore, 1976). There was an indication that the polychaete fauna were enhanced in the direction of prevailing subsurface currents, suggesting biostimulation resulting from discharge of organic material from the abundant populations of biofouling organisms on the platforms.

The Buccaneer Field and Trinity Bay studies suggest that production platforms can have an adverse effect on local benthic infaunal populations. The effect may be related in part to hydrocarbons discharged with produced water. The larger area affected in Trinity Bay as compared to the Buccaneer Field probably reflects the shallower depth of the bay (2.5 m). Other factors that may affect the degree to which produced water discharges affect the benthos include the volume of discharge, local dispersion characteristics, presence of suspended sediments, and physical characteristics of the seafloor.

***Artificial reef studies.*** Structures in offshore environments develop or attract populations of fish and invertebrates characteristic of reef systems. Such fauna were observed on and around platforms in the Central Gulf of Mexico (Gallaway et al., 198 la), in the Buccaneer Field off Texas (Gallaway et al., 1981 b), and in the Santa Barbara Channel ( Mearns and Moore, 1976). Organisms on and around the platform have been examined for hydrocarbon and trace metal content as well as histopathological conditions. These studies have already been summarized. The structure, abundance, and biomass of the fouling communities on the platforms have been examined for obvious effects of produced water discharges. Localized reductions in abundance and biomass were observed in the Central Gulf of Mexico and Buccaneer Field studies. In the case of the Buccaneer Field, a region on the platform of approximately 10 $m^2$ was obviously affected.

## Research considerations

The information presented in this paper considers the nature of routine discharges associated with offshore oil and gas operations, the toxicity of these discharges, and their observed effects based on field studies. Such information should provide guidance for the design of future monitoring programs. The need for such programs should be determined on a case-by-case basis taking into account such factors as the nature of the environment, anticipated quantities and characteristics of discharges, existing information, and local concerns.

The objectives of field monitoring programs such as those described in this paper primarily have been to detect changes in the environment resulting from discharges. The environmental or public health implications of these changes must be evaluated in terms of the spatial extent of the alterations, the degree to which marine populations and communities are actually affected, and the risks associated *with* the transfer of various contaminants in seafood to humans. These evaluations generally require information on the fate and effects of particular classes of compounds, such as heavy metals and hydrocarbons, in the marine environment. While much information has been obtained, important areas of research still remain. For example, available information suggests that the effects of some contaminants like metals and PAHs are dependent upon the relative rates of a number of processes (Jenkins et al., in press; Stegeman, 1981). These include processes that limit the availability of contaminants to organisms, as well as processes related to how organisms "deal with" contaminants that have been bioaccumulated.

Effects are not necessarily related to the concentrations measured in the environment but rather to the rates at which these various processes are occurring. Research addressing questions related to the fate and effects of major classes of contaminants, however, lies within the larger realm of waste disposal and contaminant input to the marine environment and should be addressed within this broader context. Considerations specific to monitoring the effects of offshore oil industry operations are discussed below.

Available information on the effects of offshore operations suggests that future monitoring should be focused on the sedimentary environment. Water column effects from routine discharges appear to be minor in terms of spatial extent and duration. Laboratory tests have indicated that the acute toxicities of water-based drilling muds and produced water are low, and that toxic constituents would generally be rapidly reduced in concentration in the water column upon discharge. But the potential for buildup of hydrocarbons in the water column exists in semi-enclosed coastal embayments with limited flushing and in this respect differs from offshore areas. Moreover, discharges from large central facilities may have more severe local effects than those from individual platforms.

Effects of offshore operations have been observed in benthic environments. This is consistent with the observed fate of discharged materials and the fact that many of the contaminants such as heavy metals and PAHs have a high affinity for particulate material and tend to accumulate in sediments. Field studies have indicated that, upon discharge, most of the solids associated with drilling fluids and cuttings descend rapidly to the seafloor: elevated hydrocarbons associated with production operations have also been observed in sediments. Subsequent resuspension and transport of bottom materials determine the degree to which near-field or far-field effects occur. In higher energy areas, discharged materials are more rapidly resuspended and transported away from the well site. In lower energy areas, discharged materials remain in higher concentrations near the well site for longer periods and, therefore. have a greater likelihood of affecting the local benthic environment. The short- and long-term fate of contaminants associated with sediments should be considered in future monitoring programs. As data are gathered and synthesized on the fate of discharges in environments differing in depth, sediment type, flushing rates, energy level, and other environmental features, it should be possible to develop a framework of information that can be used to assess the potential effects of operations proposed in new areas.

Among the studies considered, chemical analyses of sediments around offshore drilling and production platforms varied with respect to sampling methods, analytical techniques, and chemical parameters measured. Analyses for hydrocarbon content and hydrocarbon fractions present in sediments around production platforms tended to be least consistent. For example, in one study, analyses were conducted on one group of aromatic hydrocarbons (naphthalenes), while in another study analyses were conducted on the HMW alkane fraction. This inconsistency makes it difficult to compare results of different studies and impedes the development of a general base of information that can be used to assess effects of operations in new areas.

Information has been generated on the chemical content of discharges including produced water, and more information should be forthcoming when the results of the EPA Gulf of Mexico study are published. These data, together with available information on the fate and effects of particular contaminants, should be used to identify classes of contaminants or specific fractions (in the case of hydrocarbons), which should be monitored in sediments as part of future programs.

At present, there is evidence for limited accumulation of metals in sediments around offshore drilling and production platforms and for limited bioaccumulation within organisms. Although the biological effects of metals at the concentrations observed around offshore operations appear to be mirror, questions remain concerning the effects of metals in the marine environment. As additional information is gathered on these effects, an evaluation should be made regarding future monitoring of metals in sediments and organisms around oil and gas operations. Present information suggests that the hydrocarbon fractions most likely to cause short- and long-term toxic effects in marine organisms are the low- and high-molecular weight aromatics. The concentrations of these hydrocarbons in produced water should be documented (as is presently being done by the EPA Gulf of Mexico study), an assessment made regarding the degree to which they could accumulate and exert effects, and, based on that information, an appropriate monitoring program developed.

A number of biological effects of offshore drilling operations have been reported. Mobile megabenthos and demersal fish maybe attracted to the area by the increased microrelief afforded by cuttings accumulations and debris on the seafloor as well as by biological material falling from the biofouling community. On the other hand, cutting piles may bury sessile macro- and megabenthos in the immediate vicinity of the drilling platform. Farther away from the well site, lighter accumulations of drilling discharges may occur and the fauna may be affected by alterations in the sediments. In the mid-Atlantic study, it was suggested that reductions in macrobenthos beyond the immediate vicinity of the well site were caused, in part, by diminishment of larval recruitment. (Planktonic larvae of benthic organisms can test the suitability of sediments for settlement and, if the sediments have been altered in some way, the larvae may not settle.) Toxic effects offered a less likely explanation because the toxicity of water-based drilling fluids is low. Sublethal effects such as the possible diminishment of larval recruitment resulting from behavioral responses are not directly evaluated as part of standard bioassay programs. This means that it is important to obtain field data to verify the effects of discharges and help focus research efforts,

Reduced macrobenthos abundance and species composition have also been observed around production platforms. There is some indication that these effects may be due to accumulations of hydrocarbons in the sediments. Such accumulations might be directly toxic to organisms living within the sediments or might be rendering the sediments less attractive to settling benthic larvae resulting in diminished recruitment. Although some reductions have been observed for macrobenthos around platforms, these structures have been found to serve as artificial reefs developing rich biofouling communities and attracting fish, crustaceans, and echinoderms.

Most of the field studies conducted to date have foeused on the near-field, localized effects of discharges. Questions related to larger-scale cumulative effects of a number of drilling or production operations have been raised with particular concern for possible accumulation of contaminants in depositional areas. Because studies around production platforms have been performed in areas that have experienced area-wide inputs of production-related as well as other sources of contaminants, it is difficult to assess the area-wide effects of production operations. The Georges Bank Monitoring Program was designed to address questions related to possible regional effects of drilling discharges. This program, together with studies performed in other areas, should provide a data base that could be used for predicting effects of discharges in areas where no monitoring studies have been performed.

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## Bibliography


Anderson, J. W.; Neff, J. M.; Cox, B. A.; Tatum, H. E.; Hightower, G. M. "Characteristics of dispersions and water-soluble extracts of crude and relined oils and their toxicity to estuarine crustaceans and fish," *Mar. Biol.* 1974, 27, 75-88.

Anderson, J. W.; Riley, R. G.; Bean, R. M. "Recruitment of benthic animals as a function of petroleum hydrocarbon concentrations in the sediment," *J Fish Res Bd. Can.* 1978, 35, 776-790.

Anderson, J. W.; Kiesser, S. L.; Blaylock, J. W. "Comparative uptake of naphthalenes from water and oiled sediment by benthic amphipods," *Proc. API, EPA, and USCG, 1979 Oil Spill Conference (Prevention, Behavior, Control, Cleanup)*, Washington, D. C., American Petroleum Institute, 1979; pp. 579-584.

Armstrong, H. W.; Fucik, K.; Anderson, J. W.; Neff, J. M. "Effects of oilfield brine effluent on benthic organisms in Trinity Bay, Tex.," American Petroleum Institute Report No. 4291, Washington, D.C., 1977.

Ayers, R. C.; Sauer, T. C.; Meek, R. P.; Bowers, G. "An environmental study to assess the impact of drilling discharges in the mid-Atlantic. I. Quantity and fate of discharges," *Proc Symp. Res. Environ. Fate and Effects of Drilling Fluids and Cuttings*, Lake Buena Vista, Fla., Jan. 21-24, 1980.

Ayers, R. C.; Sauer, T. C.; Stuebner, D. O.; Meek, R. P. "An environmental study to assess the effect of drilling fluids on water quality parameters during high rate, high volume discharges to the ocean," *Proc. Symp. I-%. Environ. Fate and Effects of Drilling Fluids and Cuttings*, Lake Buena Vista, Fla., Jan 21-24, 1980.

Ayers, R. C. "Fate and effects of drilling discharges in the marine environment"; Testimony presented at Proposed North Atlantic OCS Oil and Gas Lease Sale 52 Public Hearing. Nov. 19, 1981. Boston.

Baker, J. H.; Jobe, W. D.; Howard, C. L.: Kimball, K. T.; Janousek, J.; Chase, P. R. "Pollutant Fate and Effects Studies. Benthic Biology"': Southwest Research Institute: San Antonio, Tex., 1981; Vol. 1, Part 6.

Brooks, J. M.; Estes, E. L.; Wiesenburg, D. A.; Schwab, C. R.; Abdel-Rohaim, H. A. "Investigations of surficial sediments, suspended particulates, and volatile hydrocarbons at Buccaneer gas and oil field in the northwestern Gulf of Mexico," in "Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, 1975-1980'": Jackson, W. B; Wilkens, E. P., Eds.; NOAA Technical Memorandum NMFS-SEFC-47, NTIS: Springfield. Vs., 1980; Vol. 1.

Christensen, H. E.; Luginbyhl, T. T.; Carroll. B. S Suspected carcinogens, a subfile of the NIOSH toxic substances list, " U.S Department of Health, Education and Welfare, Public Health Service, Center for Disease Control, Natl. Inst Occupational Safety and Health: Rockville, Md., 1975.

Clemens, H. P.; Jones, W. "Toxicity of brine water from oil wells," *Trans Am. Fish Sot.* 1954, x4, 97-109

Colwell, R. R.; Walker. J. D. "Ecological aspects of microbial degradation of petroleum in the marine environment," In "Crit. Rev Microbiol."; CRC: Cleveland, 1977; pp. 423-445.

Continental Shelf Associates. Monitoring program for Platform A, Lease OCS-G-3061, Block A-85, Mustang Island Area East Addition, near Baker Bank: prepared for Continental Oil Company. 1979

Crippen, R. W Green, G.; Hodd, S. L. "Metal levels in sediment and benthos resulting from a drilling fluid discharge into the Beaufort Sea," *Proc Symp Res. Environ. Fate and Effects of Drilling Fluids and Cuttings*, Lake Buena Vista, Fla. Jan. 21 24, 1980.

Dames & Moore. "Drilling fluid dispersion and biological effects study for the Lower Cook Inlet C. O. ST. well," prepared for Atlantic Richfield Company by Dames & Moore, Anchorage, Alaska, 1978.

Dames & Moore. "Fate and effects of drilling fluids and cuttings discharges in Lower Cook Inlet, Alaska and on Georges Bank," prepared for Bureau of Land Management by Dames & Moore, Seattle, Wash., 1981.

Ecomar, Inc. "Tanner Bank mud and cuttings study,"' prepared fur Shell Oil Company by Ecomar, Goleta, Calif., 1978.

EG&G, Environmental Consultants. "Data Report: Monitoring Program for Exxon's Block 564, Jacksonville OCS Area (Lease OCS-G 3705),"' prepared for Exxon Company by EG&G, Waltham, Mass., 1980.

EG&G, Environmental Consultants. "Final Report: Mid-Atlantic NPDES Rig Monitoring Program," prepared for the Offshore Operators Committee by EG&G, Waltham, Mass., 1982.

Gallaway, B. J.; Martin, L. R. "Effect of gas and oil field structures and effluents on pelagic and reef fishes, demersal fishes and macrocrustaceans," in "Environmental Assessment of Buccaneer gas and oil field in the northwestern Gulf of Mexico, 1978-1979"; Jackson, W. B.; Wilkens, E. P., Eds.; NOAA Technical Memorandum NMFS-SEFC-37, 1980; Vol. 3.

Gallaway, B. J.; Johnson, M. F.; Margraff, F. J.: Howard. R. L.; Martin, L. F.; Lewbel, G. L.; Boland, G. S. "The Artificial Reef Studies." in "Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexico"; Southwest Research Institute: San Antonio. Tex., 19X1; Vol. 2.

Gallaway, B. J.; Martin, L. R.; Howard, R. L.; Boland, G. S.; Dennis, G. S. "Effects on artificial reef and demersal fish and macrocrustacean communities," in "Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study"; Middleditch, B. S., Ed.; Plenum Press; New York, 1981.

Gearing, J. N.; Gearing, P. J.; Wade, T.; Quinn, J. G.; McCarty, H. B. "The rates of transport and fates of petroleum hydrocarbons in a controlled marine ecosystem and a note on analytical variability," *Proc. API, EPA, and USCG, 1979* Oil *Spill Conf. (Prevention, Behavior, Control, Cleanup)*, Washington, D. C., American Petroleum Institute, 1979; pp. 555-564.

Gillmor, R. B.: C. A.; Menzie, Ryther, J., Jr. "Side'scan sonar and T. V. observations of the benthic environment and megabenthos in the vicinity of an OCS exploratory well in the Middle Atlantic Bight," in "Conference Record"; Oceans 81 : Boston, Sept. 16-18, 1981; Vol. 2; IEEE Publication Number 8 I CH 1685-7; IEEE Service Center, Piscataway, N.J., 1981.

Gillmor, R. B.; Menzie, C. A.; Mariani, G. M,; Levin, D ; Ayers, R. C.; Sauer, T. C , Jr. "Effects of exploratory drilling discharges on the benthic environment in the Middle Atlantic OCS: biological results of a one-year post-drilling survey," *Proc. Third Int. Ocean Disposal Symp.* Woods Hole Oceanographic Institution, Woods Hole, Mass., Oct. 12- [6, 1981, in press.

Gillmor, R. B.; Menzie, C. A.; Grimm, H. "Effects of exploratory drilling discharges on the burrowing ophiuroid *Amphioplus macilentus*, a dominant species on the Mid-Atlantic Outer Continental Shelf,"' in preparation.

Harper, D. E.; Potts, D. L.; Salzer, R. R.; Case, R. J.; Jaschek, R. L.; Walker, C. M. "Distribution and abundance of macrobenthic and meiobenthic organisms. " in "Environmental Effects rsf Offshore Oil Production: The Buccaneer Gas and Oil Field Study". Middleditch, B. S., Ed.: Plenum Press: New York, 1981.

Houghton, J. P.; Britch, R. P.: Miller. R. C.; Runchal, A. K., Falls, C. P. "Drilling fluid dispersion studies at the lower Cook Inlet. Alaska, C. O.S.T. Well," *Proc. Symp. Res. Environ. Rate and Effects of Drilling Fluids and* Cuttings. Lake Buena Vista, Fla., Jan. 21-24, 1980.

Hutchinson, T. C.; Hellebust, J. A.; MacKay, D.; Tam, D.; Kauss, P. "Relationship of hydrocarbon volubility to toxicity in algae and cellular membrane effects," *API, EPA, and USCG, 1979 Oil Spill Conf (Prevention, Behavior, Control, Cleanup) Washington.* D.C., American Petroleum Institute, 1979; pp. 541-548.

Jackson, G. F.; Wade, M. J.; Kirsch, M. "Oil content in produced brine on 10 Louisiana production platforms," prepared for Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, 1981.

Jenkins, K. D.; Brown. D. A.; Hershelman, G. P.: Meyer, W. C. "Contaminants in White Croakers (*Genyonemus lineatus*) from the Southern California Bight; I. Trace metal detoxification," (Submitted for publication in Fifth Symposium on Pollution and Physiology of Marine Organisms); Academic New York, in press.

Kramer, J. R.; Grundy, H. D.: Hammer, L. G. "Occurrence and rate of [race metals in barite for ocean drilling operations," *Proc. Symp. Res. Environ. Fate and Effects of Drilling Fluids and Cuttings,* Lake Buena Vista, Fla., Jan. 21-24, [980.

Koons, C. B.; McAuliffe, C. D.; Weiss. F. T. "Effects of Produced Waters *on* the Marine Environment," Oceans 1977.

Lee, W. Y. *Mar. Environ. Res. 1978, 1, 5-19.*

Lees, D. C.; Houghton, J. P. "Effects of drilling fluids on benthic communities at the lower Couk Inlet C. O.S.T. well," *Proc. Symp. Res. Environ. Fate and Effects of Drilling Fluids arrd Cuttings*, Lake Buena Vista, Fla., Jan. 21-24, 1980.

Lysyj, 1. "Oil and Gas Extracting Operations."' Report to EPA Municipal Environmental Research Laboratory. Cincinnati, 1981.

Lysyj, I.; Perkins, G.; Farlow, J. S. "Effectiveness of offshore produced water treatment,". *Proc. API, EPA, and USCG, 1981 Oil Spill Conf. ( Prevention, Behavior, Control, Cleanup).* Washington. D. C., American Petroleum Institute, 1981; pp. 63-68.

Mariani, G. M.; Sick, L. V.: Johnson, C. C. "An environmental monitoring study to assess the impact of drilling discharges in the Mid-Atlantic. III. Chemical and physical alterations in the benthic environment." *Proc. Res. Environ. Fate and Effects of Drilling Fluids and Cuttings,* Lake Buena Vista, Fla., Jan. 21-24, 1980.

Maurer, D.: Leathem, W.; Menzie, C, *Mar Poll. Bull.* 1981, 12, 342-347.

McLeod, W D., Jr.: Brown, D. W., Jenkins. R G.; Ramos, R S "Intertidal sediment hydrocarbon levels at Iwo sites on the Strait of Juan de Fuca," in "Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms"'; Wolfe. D A., Ed.; Pergamon Press: Oxford, 1977; pp. 385-396.

Mearns, A. J.; Moore, M. D. "Biological study of oil platforms Hilda and Hazel, Santa Barbara Channel. Calif.," A final report to the Institute of Marine Resources Scripps Institution of Oceanography, Contribution No. 65. Southern California Coastal Water Research Project. El Segundo, Calif., 1976.

Meek. R. P.: Ray, J. P. "induced sedimentation, accumulation, and transport resulting from exploratory drilling discharges of drilling fluids and cuttings on the southern California outer continental shelf, " *Proc. Symp. Res. Environ. Fate and Effects of Drilling Fluids and Cuttings*, Lake Buena Vista, f-la , Jan, 21 24, 1980

Menzie, C. A . Maurer, D.; Leathem, W. A. "An environmental monitoring study to assess the impact of drilling discharges in the Mid-

Atlantic. IV. The effects of drilling discharges on the benthic community,'" *Proc. Symp. Res Environ Fate and Effects of Drilling Fluids and Cuttings*, Lake Buena Vista, Ha., Jan. 21-24, 1980

Middleditch, B S. In "Environmental Effects of Offshore Oil Production. The Buccaneer Gas and Oil Field Study"; Middleditch, B. S., Ed.; Plenum Press: New York, I 98 1; pp. 15-54.

Mobil Oil Corporation. Monitoring program for Wells No. 3 and No. 4, Lease OCS-G-2759, Block A-389 High Island Area East Addition South Extension; prepared by Continental Shelf Associates: Vol. 1, Technical Section, 1978.

National Academy of Science. "Petroleum in the marine environment. Workshop on inputs, fates, and the effects of petroleum in the marine environment May 21-25, 1973"; National Academy of Sciences: Washington, D. C., 1975.

Neff, J. M. "Polycyclic Aromatic H ydrocarbons in the Aquatic Environment"; Applied Science Publishers: London, 1979.

Nulton, C. P.; Johnson, D. E.; Bohnstedt, C. F.; Martin, S. J. "Organic chemical analyses," in "Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexieo" prepared by Southwest Research Institute, San Antonio, Tex., for the Bureau of Land Management: New Orleans OCS, 1981; Part 3, Vol. 1.

Pancirov, R. J.; Brown, R. A. "Analytical methods for polynuclear aromatic hydrocarbons in crude oils, and marine tissues," *Proc. 1975 Conf. Prevention and Control of Oil Pollution*, Washington, D.C., American Petroleum Institute, 1975; pp. 103-113.

Payne, J. F.; Maloney, R. "Are petroleum hydrocarbons an important source of mutagens *in* the marine environment?" "*Proc. API, EPA, and USCG, 1979 Oil Spill Conf. (Prevention, Behavior, Control, Cleanup)* Washington, D. C., American Petroleum Institute, 1979; pp. 533-536.

Petrazzuolo, G. "Preliminary report on an environmental assessment of drilling fluids and cuttings released onto the outer continental shelf for the Gulf of Mexico," prepared for the Office of Water Enforcement and the Office of Water and Waste Management, U.S. Environmental Protection Agency Washington, D. C., 1981.

Proni, J. R.; Trefry, J. "Drilling mud discharge in the Gulf of Mexico," *Proc. Third Int. Ocean Disposal Symp.* Woods Hole Oceanographic Institution, Woods Hole, Mass., Oct. 12-16, 1981, in press.

Ray, J. P.; Shinn, E. A. "Environmental effects of drilling muds and cuttings," *Conf. Proc. Environ. Aspects of Chemical Use* in *Well-Drilling Operations,* May 21-23, 1975, Houston, Tex., EPA-560- 1-75-004, 1975; pp. 533-545.

Rice, S. D.; Short, J. W.; Broderson, C. C.; Mecklenburg, T. A.; Moles, D. A.; Misch, C. J.; Cheatham, D. L.; Karinen, J. F. "Acute toxicity and uptake-depuration studies with Cook Inlet crude oil, Prudhoe Bay crude oil, No. 2 fuel oil and several subarctic marine organisms," N WAFC Processed Report, 90 pp., Northwest and Alaska Fisheries Center, Auke Bay Laboratory, NMFS, NOAA: P.O. Box 155, Auke Bay, Alaska 99821, 1976.

Rice, S. D.; Moles, D. A.; Taylor, T. L.; Karinen, J. F. 'Sensitivity of 39 marine species to Cook Inlet crude oil and No. 2 fuel oil," *Proc. API, EPA, and USCG, 1979 Oil Spill Conf. (Prevention, Behavior, Control, Cleanup)* Ameriean Petroleum Institute, Washington, D. C., 1979; pp. 549-554.

Rice, S. D.; Kern, S.; Brodersen, C. C.; Lindsay, S. A.; Andrews, S. A. "Toxicity of ballast-water treatment effluent to marine organisms at Port Valdez, Ala.," *Proc. API, EPA, and, USCG 1981* Oil *Spill Con (Prevention, Behavior, Control, Cleanup (*American Petroleum Institute, Washington, D.C., 1981; pp. 55 61.

Rose. C D.. Ward, T. J. "Acute toxicity and aquatic hazard associated with discharged formation water," in "Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study"; Middleditch, B.S., Ed,; Plenum Press: New York. 1981.

Roesijadi, G.; Anderson, J. W.; Blaylock, J. W *J. Fish. Res. Bd. Can.* 1978, 35,608 614.

Rossi, S. S.; Anderson, J. W. *Water Air Soil Pollut. 1978,9, 155-170.*

Sauer, T. C. *Sea. Limnol. Oceanogr.* 1980,25, 338-351.

Sauer, T. C. *Environ. Sri. Technol.* **1981,** *15, 917-923.*

Sis, R. S.; Neff, J.; Jacobs, V. L.; Armstrong, H.; McArthur, N.; Corkern, C. C.; Tarpley, R.; Stott, G. "Normal histology and histopathology of benthic invertebrates and demersal and platform-associated pelagic fishes," in "Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexico"; prepared by Southwest Research Institute, San Antonio, Tex., for the Bureau of Land Management: New Orleans OCS, 1981.

Sizemore, R. K.; Hsu, C. S.; Olsen, K. D. "Bacterial community composition and activity,'" in "Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study"; Middleditch, B. S., Ed.; Plenum Press: New York, 1981.

Southwest Research Institute. "Ecological investigations of petroleum production platforms in the central Gulf of Mexico," prepared for the Bureau of Land Management: New Orleans OCS, 1981.

Steele, R. L. "Effects of certain petroleum products on reproduction and growth of zygotes and juvenile stages of the alga *Fucus edentatus* (Phaeophyceae: Fucales)," in "Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms"; Wolfe, D., Ed.; Pergamon Press: Elmsford, N.Y., 1977.

Stegeman, J. J. "Polynuclear aromatic hydrocarbons and their metabolism in the marine environment," in "Polycyclic Hydrocarbons and Cancer"; Gelboin, H. V.; Ts'o, P.O.P., Eds.; Academic Press: New York, 1981.

Teal, J. M., Burns, K.; Barrington. J. *J. Fish. Res. Bd. Con. 1978,35,510-520.*

Tillery, J. B. "Trace metals," in "Environmental assessment of Buccaneer gas and oil field in the northwestern Gulf of Mexico, 1978-1979"; Jackson, W. B.; Wilkens, E. P., Eds.; NOAA Technical Memorandum NMFS-SEFC-42, 93 p. Available from NTIS, Springfield, Vs., 1980; Vol. 8.

Tillery, J. B.; Thomas, R. E.; Windon, H. L. "Trace metals studies in sediment and fauna," in "Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexico"; prepared by Southwest Research Institute, San Antonio, Tex., for the Bureau of Land Management: New Orleans OCS, 1981; Vol. 1, Part 4.

Union Oil Company (Calif.). "Ecological assessment of rilling activities.. Well No. 1 Block 384 High Island East Addition South Extension," prepared by Marine Technical Consulting Services, 1977.

Wheeler, R. BM.S. Thesis, Rice University, Houston, Tex., 1979.

Wiesenburg, D. A.; Bodennec, G.; Brooks, J. M. *Bull. Environ. Contam. Toxicol.* **1981,** 27, 167-174.

Zein-Eldin, Z. P.: Keney, P. M. "Environmental Assessment of an active oil field in the northwestern Gulf of Mexico—Bioassays of Buccaneer Oil Field effluents with juvenile and adult penaeid shrimp," progress report prepared for the National Marine Fisheries Service; Galveston, Tex., 1978.

Zingula, R. P. "Effects of drilling operations on the marine environment," *Conf. Pmt. Environ. Aspects of Chemical Use* in *Well- Drilling Operat ions, Houston, Tex.*, May 21-23, 1975. EPA-550 /l-75 -004, pp. 443.450.