TC-3883

# TECHNICAL SUPPORT DOCUMENT FOR REGULATING DILUTION AND DEPOSITION OF DRILLING MUDS ON THE OUTER CONTINENTAL SHELF

NOVEMBER, 1984

FOR:

EPA REGION X
SEATTLE, WASHINGTON

AND

JONES AND STOKES ASSOCIATES
BELLEVUE, WASHINGTON

TETRA TECH

TC-3883 - Final Report

# TECHNICAL SUPPORT DOCUMENT FOR REGULATING DILUTION AND DEPOSITION OF DRILLING MUDS ON THE OUTER CONTINENTAL SHELF

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# I. INTRODUCTION

The potential impacts to the marine environment from drilling mud discharges from exploratory drilling activities on the outer continental shelf have been the subject of recent research and debate. In the past there has been little scientific consensus regarding the physical fate and biological effects of drilling discharges. This lack of consensus has led to problems for regulatory agencies involved in permitting drilling discharges. The overall objective of this report is to evaluate discharge limitations needed to ensure compliance with state and federal water quality standards and criteria.

Ocean Discharge Criteria Evaluations (ODCE) have been completed as part of EPA's general NPDES permitting procedure for exploratory oil drilling activity at several areas on the Alaskan Outer Continental Shelf. The evaluation procedure included analysis of the fate of discharged drilling muds. This analysis included review of mud dispersion field studies and computer simulations of mud discharges using the Offshore Operators Committee (OOC) model and EPA's model. The purpose of this report is to assemble the results of field studies and OOC model runs to describe how the dispersion and bottom deposition of discharged drilling mud is influenced by different variables such as water depth, discharge rate, current velocity, density stratification, predilution, and initial suspended solids concentration (mud bulk density). With this information as background, alternative means of regulating drilling mud discharges from both exploratory, and development and production operations to assure compliance with water quality criteria are presented.

The second part of this report presents field observations and OOC model simulations of drilling mud dilution. Brief descriptions of the OOC and EPA model formulations and limitations are also presented. Solids deposition results from field studies and the OOC model are discussed in the third section. The fourth section discusses the factors considered in determining discharge limitations. Recommendations for discharge regulations and future OOC model runs, and important characteristics of a sample drilling mud discharge monitoring study are summarized in the fifth section.

# II. DRILLING MUD DILUTION

## FIELD STUDIES

Several field studies have been conducted to measure dilution and dispersion of drilling muds under various oceanographic conditions. Table 1 summarizes the important variables measured in these studies and suspended solids dilution for various drilling sites. There are several problems in gathering and interpreting field data, and calculating associated dilutions. Important field studies and associated problems are discussed in detail in Appendix C. Problems with existing field data include poor study design, difficulty in locating and sampling the plume, small discharge volumes studied, and results that do not represent expected plume behavior.

It is difficult to directly compare the results of different field studies due to varying sampling techniques, frequency and location, oceanographic conditions, and discharge characteristics. However, general conclusions supported by the results of these field studies include:

- Drilling muds (particulate) are generally diluted by factors greater than 2,000:1 at 100 m (328 ft) from the discharge site.

- Suspended solids dilutions generally increase as depth or distance from the discharge increases.

- The minimum dissolved fraction dilution of 112:1 occurred in shallow water at 61 m from the source. Dissolved fraction dilutions should be less than or equal to particulate dilutions due to settling of solids from the effluent plume.

## TABLE 1. SUSPENDED SOLIDS DILUTION CHARACTERISTICS OF VARIOUS DRILLING SITES

| Location | Reference | Current (cm/sec) | Depth (m) | Flow (bbl/h) | Distance from Discharge (m) | Suspended Solids Dilution | Initial Suspended Solids Concentration (mg/l) |
|---|---|---|---|---|---|---|---|
| Tanner Bank | Ecomar (1978) | 11.8-45.2 | 63 | 10-754 | 3 | 500-1,000:1 | 250,000 |
| | Ray and Meek (1980) | | | | 100 | 10,000-400,000 | |
| Gulf of Mexico | Ayers et al. (1980a) | 0-20 (min-max) | 23 | 275-1,000 | 100 | 2,000-40,000:1 | 1,430,000 |
| | | | | | 500 | 200,000:1 | |
| Mid-Atlantic | Ayers et al. (1980b) | 21-27 | 120 | 275 | 97 | 80,000:1 | 277,400 |
| | | | | | 192 | 110,000:1 | |
| | | | | 500 | 119 | 60,000:1 | 250,400 |
| | | | | | 193 | 70,000:1 | |
| Norton Sound | Ecomar (1983) | 15-77 | 12-13 | 1,065 | 100 | 10,000:1 | 302,000 |
| Lower Cook Inlet[a] | Houghton et al. (1980) | 31-98 (min-max) | 62 | 180 | 940 | 46,000:1 | 103,000 |
| | | | | | 1,980 | 119,000:1 | |
| | | 78-121 | 62 | 1,200 | 830 | 22,000:1 | 700,000 |
| | | | | | 1,760 | 107,000:1 | |
| | | 122-144 | 62 | 20 | 100 | 38,000:1 | 20,000 |
| | | | | | 200 | 104,000:1 | |
| Tern Island (Beaufort Sea) | Northern Technical Services (1983) | 11-12 (near bottom avg.) | 6.7 | 84 | 100 | 5,000:1[b] | 250,000 |
| | | | | 34 | 160 | 24,000:1[c] | |
| Reindeer Island (Beaufort Sea) | Northern Technical Services (1981) | 4.5 | 8.4 | 1,510 | 61 | 112[a] | 696,000[d] |
| | | 4.4 (near bottom avg.) | 5.5 | 21 | 61 | 500,000[a,e] | 630,000[d] |

[a] These dilutions are for a dye tracer, not suspended solids.

[b] Predilution of 30:1 with seawater.

[c] Predilution of 75:1 with seawater. Background levels may have been reached at 100 m (328.1 ft).

[d] A water content of 40 percent was assumed. Bulk mud density was 10.6 lb/gal.

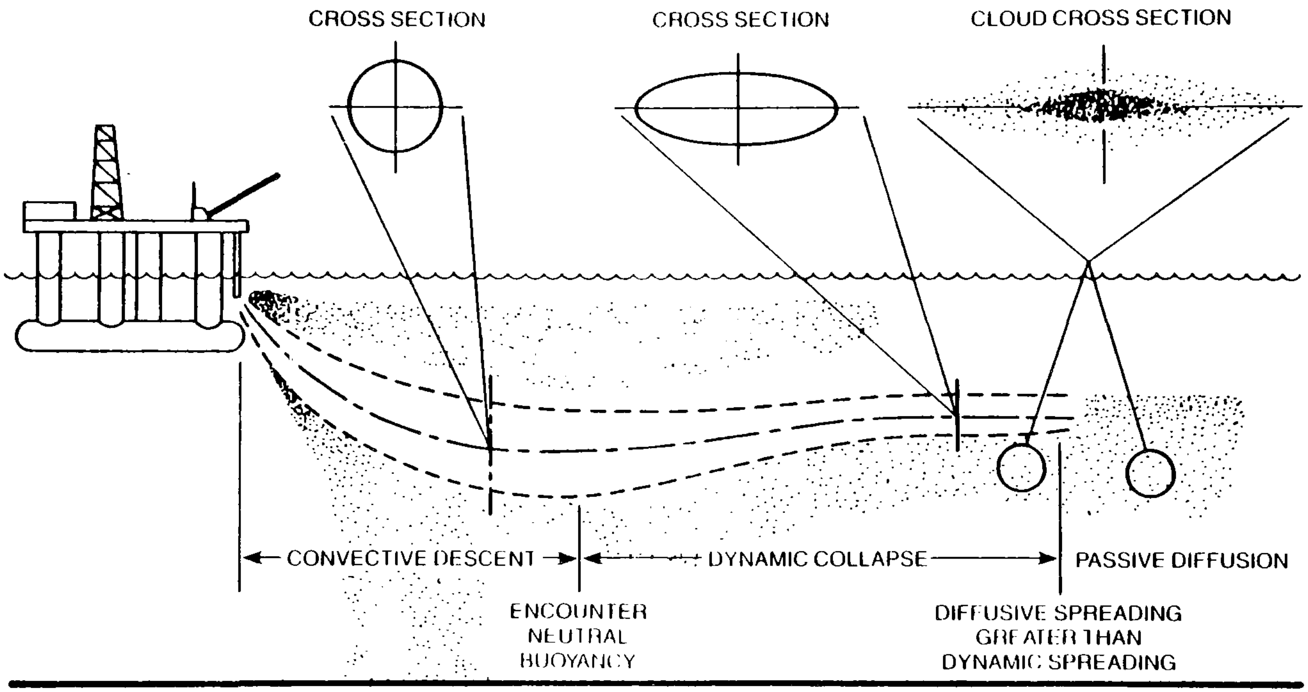
[e] The effluent was probably not measured and therefore a large dilution was obtained.

## OFFSHORE OPERATORS COMMITTEE MODEL

### Model Description

A complete description of model formulations, concepts, required inputs, output options, and model limitations is given in the user's manual by Brandsma et al. (1983, pp. 5-1 - 5-2), however, important details of the formulation will be reviewed here. The OOC model was developed to describe the fate of offshore drilling mud discharges. The model simulates the effluent plume (commonly known as the lower plume) through three phases: the jet phase (convective descent), dynamic collapse, and passive diffusion as shown in Figure 1. The model also simulates an upper plume, which appears to form when particles of mud separate from the main plume during the convective descent phase. The upper plume may represent up to 10 percent of the discharged mud. For the runs presented here, 10 percent of the discharged mud was separated by the model (referred to as forced separation) in a linear fashion over the depth of the convective descent.

Inputs to the model include data from four categories: drilling mud characteristics, discharge conditions, ambient characteristics and model options. These inputs are summarized in Table 2. Drilling mud characteristics consist of mud bulk density, discrete particle classes, concentration, density, and settling velocity for each particle class. Discharge conditions of interest include discharge rate, duration, orientation of the discharge, and rig type and position. Density profile, current velocity and distribution, and wave height and period are important ambient conditions. Model options include input options and output format control. Input conditions used in this report assume that the drilling rig is a jackup with a submerged discharge pipe. The concentration of suspended solids in the drilling mud is 1,441,000 mg/l unless stated otherwise. All model runs assume a density gradient of less than approximately $1x10^{-4}$ $g/cm^3$ per meter depth (increasing with depth). The model currently does not accurately simulate discharges from a gravel island. The current velocity profiles used are uniform distributions (over the depth) with a sharp decrease in velocity near the seafloor. Model runs represent somewhat artificial conditions because of the representation of current speed and direction. For purposes




REFERENCE: Brandsma and Sauer, 1983.

Figure 1. Idealized jet discharge described by OOC model.

TABLE 2. SUMMARY OF OOC MODEL INPUTS

| Category | Variable | Typical Value[a] |
| --- | --- | --- |
| Discharge Conditions | Rate | 100-1,000 bbl/h |
| | Duration | 1,800-3,600 sec |
| | Angle (from horizontal) | $90^{o}$ |
| | Depth | 0.3 m (1.0 ft) |
| | Nozzle radius | 0.1 m (0.33 ft) |
| | Rig type | Jackup |
| | Rig length | 70.1 m (230 ft) |
| | Rig width | 61.0 m (200 ft) |
| | Forced separation of fine particles | yes |
| Drilling Mud Characteristics | Bulk density | 2.09 $g/cm^3$ (17.4 lb/gal) |
| | Initial solids concentration | 1,441,000 mg/l |
| | Tracer concentration | 100 mg/l |
| Receiving Water Characteristics | Current velocity | 2-30 cm/sec ( 0.066-0.984 ft/sec ) |
| | Wave height | 0.61 m (2 ft) |
| | Wave period | 12 sec |
| | Density gradient ($\Delta\sigma_t$/m depth) | <0.10 |

[a] Typical values used for all model runs unless otherwise specified.

of the model simulation, ocean currents were specified at a constant direction and a constant speed for the entire simulation. In reality, current speed and direction are quite variable. As a result, predicted dilution may be conservatively low while predicted solids accumulation rates are conservatively high. Also, the bottom area receiving deposits is under-predicted. Typical drilling rig and discharge characteristics used include a rig length of 70 m (230 ft), a rig width of 61 m (200 ft), a discharge nozzle radius of 10.2 cm (4 in), a vertical angle of discharge ($90^{o}$) and a 0.3 m (1.0 ft) discharge depth (below the surface).

Outputs from the model include concentrations of particulate and dissolved mud components at various time steps shown in tabular and graphical form. Depth profiles of the concentrations of particulate and dissolved components for given time steps (Table 3) enable the calculation of minimum or depth-averaged dilution at selected points downstream of the source. A solids mass distribution summary (Table 4) shows the weight of solids in each plume phase, the amount of solids on the bottom, and the spatial deposition pattern (Table 5).

It should be noted that the model has not been completely verified with actual field data. Comparison of model results to field data for a 275 bbl/h discharge in 23 m (76 ft) of water showed that the model "...reproduces several observed features of drill mud discharges" (Brandsma et al., 1980, p. 598). No field data sets are currently available to further verify the model for the extreme range of water depths for which it has been run here (5 m to 120 m). It can only be stated that the model results appear to be reasonable and provide an estimate of the expected fate of discharged drilling muds. Numerical values provided by the model should not be considered to be of high precision. It is presently not possible to establish confidence limits to model results.

Ecomar recently completed a new field study to collect data to verify the OOC model. The study was designed to describe both particulate and dissolved fraction water column concentrations and bottom accumulation of solids. The discharge was located off Huntington Beach, California,

TABLE 3. EXAMPLE SPOT PROFILE RESULTS AT 1,000 AND 2,000 SEC AFTER START OF DISCHARGE (FROM OOC MODEL)

SPOT PROFILES OF COMBINED SOLIDS CONCENTRATIONS (MG/LITER OF SAMPLE) TIME(SEC) - 1000.0

| DISTANCE | 100.0 | 200.0 | 400.0 | 600.0 | 500.0 | 700.0 | 800.0 | 1000.0 | 1100.0 | 1300.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| BEARING | 240.0 | 240.0 | 260.0 | 260.0 | 280.0 | 280.0 | 300.0 | 300.0 | 320.0 | 320.0 |
| X-COORD. | 1050.0 | 1100.0 | 1069.5 | 1104.2 | 913.2 | 878.5 | 600.0 | 500.0 | 157.4 | 4.1 |
| Z-COORD. | 2713.4 | 2626.8 | 2406.1 | 2209.1 | 2307.6 | 2110.6 | 2107.2 | 1934.0 | 2092.9 | 1964.4 |
| W. DEPTH | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 |
| DEPTH | | | | | | | | | | |
| 0.0 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.3 | 0.33 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6.7 | 2.48 | 0.58 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 10.0 | 12.85 | 3.54 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 13.3 | 46.63 | 14.99 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 16.6 | 115.85 | 43.72 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 20.0 | 192.48 | 87.53 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 23.3 | 216.47 | 120.91 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 26.6 | 179.88 | 118.11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 30.0 | 131.38 | 85.25 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 33.3 | 99.12 | 47.22 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 36.6 | 85.66 | 19.94 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 39.9 | 99.00 | 6.09 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 43.3 | 148.05 | 1.26 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 46.6 | 228.83 | 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 49.9 | 327.31 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 53.3 | 423.77 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 56.6 | 495.01 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 59.9 | 521.53 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 63.3 | 495.17 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 66.6 | 423.68 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 69.9 | 326.57 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 73.2 | 226.44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 76.6 | 141.17 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 79.9 | 79.12 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

...MULTIPLY DISPLAYED VALUES BY 1.000

SPOT PROFILES OF COMBINED SOLIDS CONCENTRATIONS (MG/LITER OF SAMPLE) TIME(SEC) 2000.0

| DISTANCE | 100.0 | 200.0 | 400.0 | 600.0 | 500.0 | 700.0 | 800.0 | 1000.0 | 1100.0 | 1300.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| BEARING | 240.0 | 240.0 | 260.0 | 260.0 | 280.0 | 280.0 | 300.0 | 300.0 | 320.0 | 320.0 |
| X-COORD. | 1050.0 | 1100.0 | 1069.5 | 1104.2 | 913.2 | 878.5 | 600.0 | 500.0 | 157.4 | 4.1 |
| Z-COORD. | 2713.4 | 2626.8 | 2406.1 | 2209.1 | 2307.6 | 2110.6 | 2107.2 | 1934.0 | 2092.9 | 1964.4 |
| W. DEPTH | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 |
| DEPTH | | | | | | | | | | |
| 0.0 | 0.0 | 0.00 | 0.95 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.3 | 0.0 | 0.00 | 3.44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6.7 | 0.0 | 0.00 | 9.35 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 10.0 | 0.0 | 0.00 | 19.10 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 13.3 | 0.0 | 0.01 | 29.27 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 16.6 | 0.0 | 0.04 | 33.52 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 20.0 | 0.0 | 0.30 | 28.64 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 23.3 | 0.0 | 1.20 | 18.46 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 26.6 | 0.0 | 3.12 | 10.15 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 30.0 | 0.0 | 5.29 | 8.00 | 0.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 33.3 | 0.0 | 5.75 | 10.92 | 0.10 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 36.6 | 0.0 | 3.98 | 13.79 | 0.19 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 39.9 | 0.0 | 1.75 | 12.19 | 0.22 | 1.31 | 0.01 | 0.0 | 0.0 | 0.0 | 0.0 |
| 43.3 | 0.0 | 0.49 | 7.18 | 0.16 | 12.09 | 0.04 | 0.0 | 0.0 | 0.0 | 0.0 |
| 46.6 | 0.0 | 0.07 | 2.77 | 0.08 | 44.37 | 0.09 | 0.0 | 0.0 | 0.0 | 0.0 |
| 49.9 | 0.0 | 0.0 | 0.70 | 0.03 | 70.93 | 0.12 | 0.0 | 0.0 | 0.0 | 0.0 |
| 53.3 | 0.0 | 0.0 | 0.11 | 0.0 | 48.14 | 0.10 | 0.0 | 0.0 | 0.0 | 0.0 |
| 56.6 | 0.0 | 0.0 | 0.0 | 0.0 | 13.45 | 0.04 | 0.0 | 0.0 | 0.0 | 0.0 |
| 59.9 | 0.0 | 0.0 | 0.0 | 0.0 | 4.09 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| 63.3 | 0.0 | 0.0 | 0.0 | 0.0 | 2.52 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| 66.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.45 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| 69.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.01 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| 73.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| 76.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 79.9 | 6.47 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

...MULTIPLY DISPLAYED VALUES BY 1.000

Source: Brandsma et al. (1983).

TABLE 4. EXAMPLE SUMMARY TABLE OF MASS DISTRIBUTION OF SOLIDS (FROM OOC MODEL)

SUMMARY OF MASS DISTRIBUTION (LBS)

| CLASS NAME | SOL1 | SOL2 | SOL3 | SOL4 | SOL5 | SOL6 | TOTL |
|---|---|---|---|---|---|---|---|
| SOL DENS G/CC | 3.9590 | 3.9590 | 3.9590 | 3.9590 | 3.9590 | 3.9590 | |
| CONC VOL FRAC | 0.03640 | 0.03640 | 0.04368 | 0.07280 | 0.13830 | 0.03640 | |
| SET VELO FT/S | 0.021600 | 0.006820 | 0.002780 | 0.001430 | 0.000758 | 0.000427 | |
| TOTAL LBS | 12639. | 12639. | 15167. | 25278. | 48021. | 12639. | 126382. |
| TIME(SEC) = | 1000.0 | | | | | | |
| TO BE DISCHG.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN DYN PLUME.. | 1324. | 3410. | 5101. | 8953. | 16836. | 1873. | 37497. |
| IN PASS DIFF.. | 219. | 1941. | 5068. | 10492. | 26066. | 10572. | 54358. |
| ON BOTTOM..... | 11096. | 7289. | 5001. | 5835. | 5120. | 195. | 34536. |
| TIME(SEC) = | 2000.0 | | | | | | |
| TO BE DISCHG.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN DYN PLUME.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN PASS DIFF.. | 44. | 1691. | 3399. | 5403. | 20521. | 12278. | 43336. |
| ON BOTTOM..... | 12593. | 10947. | 11767. | 19873. | 27498. | 363. | 83040. |
| TIME(SEC) = | 3000.0 | | | | | | |
| TO BE DISCHG.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN DYN PLUME.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN PASS DIFF.. | 2. | 1008. | 2425. | 3305. | 13173. | 12217. | 32129. |
| ON BOTTOM..... | 12634. | 11628. | 12739. | 21969. | 34844. | 423. | 94238. |
| TIME(SEC) = | 5000.0 | | | | | | |
| TO BE DISCHG.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN DYN PLUME.. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| IN PASS DIFF.. | 0. | 151. | 1372. | 2075. | 10241. | 12085. | 25924. |
| ON BOTTOM..... | 12635. | 12481. | 13789. | 23194. | 37772. | 555. | 100425. |

NOTE: COMPARISON OF VALUES IN TABLE WITH THOSE IN THE PLANVIEWS MAY NOT BE EXACT DUE TO COMPUTER ROUND-OFF ERROR.

Source: Brandsma et al. (1983).

TABLE 5. EXAMPLE PLAN VIEW OF COMBINED SOLIDS ON THE BOTTOM AT 5,000 SEC AFTER START OF DISCHARGE (FROM THE OOC MODEL)

TOTAL ACCUMULATED SOLID MASS (LBS/GRID SQR) ON BOTTOM    TIME(SEC) = 5000.0
RIG LOCATION: M = 1000.0 FT, N = 2800.0 FT    GRID SPACING = 100.0 FT
...MULTIPLY DISPLAYED VALUES BY 100.0    (LEGEND... + = .LT. .01  0 = .LT. .0001)

| M N= | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | + | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | .09 | .02 | .02 | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | .01 | .14 | .24 | .33 | .61 | .05 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | .01 | .35 | 3.4 | 8.1 | 5.9 | 1.8 | .12 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | .03 | 1.4 | 18 | 60 | 39 | 2.5 | .25 | .01 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .10 | 1.6 | 5.7 | 214 | 222 | 7.7 | .20 | + | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .03 | .50 | 1.8 | 197 | 209 (RIG LOCATION) | + | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .05 | .57 | .05 | + | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Source: Brandsma et al. (1983).

at a water depth of 18.3 m (60 ft). A report is expected at the end of the year (Sauer, T., 4 April 1984, personal communication).

The model has considerable flexibility in simulating the many processes that affect dilution and deposition of drilling mud discharges; however, the model has certain limitations including (Brandsma et al. 1983, p. 5-2):

- The model does not account for the effects of flocculation of mud solids in the water column. It is assumed that the settling velocity distribution entered into the program by the user reflects the flocculated state of the solids.

- The algorithm used in the model to simulate the forced separation of fine material near the discharge source (during the jet phase) has no theoretical basis. It was developed to simulate field and laboratory observations.

- Results of wake intensity studies are used in the model formulation to describe the effects of a turbulent wake on the discharge plume. However, the relationship of rig structure and ambient velocities to wake intensity is not yet completely understood. The model accounts for the wake effect by using random fluctuations of the position, and size increases of effluent "clouds" when the "clouds" are within the wake zone. The size of the wake zone is determined by the rig structure and the ambient velocities.

- The model cannot simulate the situation where the plume descends vertically and encounters the bottom (shallow, low velocity waters). As ambient current velocities are reduced, the plume trajectory becomes nearly vertical and difficulties in producing a stable simulation arise. Increasing the ambient current speeds slightly or changing the angle of the pipe from vertical will help to produce a stable simulation.

In addition, the model does not account for solids resuspension or biological uptake.

The real value of the OOC model is its potential for use as a comparative tool. The effects of changes in the various input parameters may be assessed to determine which variables are the most important. This has been the focus of this modeling effort.

Model Results

For this report, the OOC model was run for 20 test cases with inputs as summarized in Table 6. These cases cover a variety of conditions including variation in water depth, discharge rate, current velocity, density stratification, predilution, and mud bulk density (initial solids concentration). Tabulated model results (minimum dilutions with distance from the source) for these test cases are provided in Appendix A.

Minimum dilution and distance from the discharge from representative test cases were plotted to determine relationships between dilution and discharge rate, current velocity, water depth, density stratification, predilution and mud bulk density. To determine the effect of water depth on initial dilution, the results of cases 3, 5, 6, 11, 13, 15, and 16 [water depths ranging from 5 to 120 m (16 to 394 ft)] were compared. For demonstration, Figure 2 shows the minimum solids dilution with distance from the discharge and Figure 3 shows the minimum dissolved fraction dilution with distance from the discharge for representative cases 3, 5, 13, and 15. These data indicate that the minimum solids dilution at distances greater than 80 m (262 ft) from the discharge is generally greater for the shallow water case (minimum solids dilution increases as water depth decreases). Within 80 m (262 ft) of the discharge source, this relationship is reversed; minimum solids dilution increases as water depth increases.

Another interesting observation is the slope of these dilution curves (Figure 2). Minimum solids dilutions for shallow water cases increase much more rapidly than deeper water cases. As water depth increases, the minimum solids dilution curve becomes more level. These results indicate

TABLE 6. SUMMARY OF OOC MODEL INPUTS FOR TEST CASES[a]

| Case Number | Water Depth (m) | Discharge Rate (bbl/h) | Surface Current (cm/sec)[b] | Density Stratification, $\Delta\sigma_t$ (Bottom to Surface) | Other |
|---|---|---|---|---|---|
| 1 | 40 | 1,000 | 2 | 3.9 | Predilution 9:1[c] |
| 2 | 40 | 1,000 | 10 | 3.9 | Predilution 9:1[c] |
| 3 | 40 | 1,000 | 10 | 3.9 | |
| 4 | 40 | 100 | 10 | 3.9 | |
| 5 | 5 | 1,000 | 10 | 0.1 | |
| 6 | 10 | 1,000 | 10 | 0.7 | |
| 7 | 10 | 1,000 | 10 | 0.7 | Predilution 9:1[c] |
| 8 | 10 | 100 | 10 | 0.7 | |
| 9 | 10 | 1,000 | 10 | 0.7 | Mud bulk density = 9 lb/gal |
| 10 | 15 | 1,000 | 2 | 1.07 | |
| 11 | 15 | 1,000 | 10 | 1.07 | |
| 12 | 15 | 1,000 | 30 | 1.07 | |
| 13 | 20 | 1,000 | 10 | 1.00 | |
| 14 | 40 | 1,000 | 10 | 0.5 | Minimum stratification (40 |
| 15 | 70 | 1,000 | 10 | 2.5 | |
| 16 | 120 | 1,000 | 10 | 0.98 | |
| 17 | 120 | 1,000 | 32 | 1.30 | |
| 18 | 5 | 250 | 10 | 0.1 | |
| 19 | 15 | 250 | 2 | 1.07 | |
| 20 | 15 | 250 | 10 | 1.07 | |

[a] All cases use a 2.09 g/cm$^3$ (17.4 lb/gal) mud unless otherwise specified (initial sol concentration 1,441,000 mg/l).

[b] Uniform velocity distribution with depth was assumed, with a sharp decrease in veloc near the bottom.

[c] Nine parts water with 1 part mud.

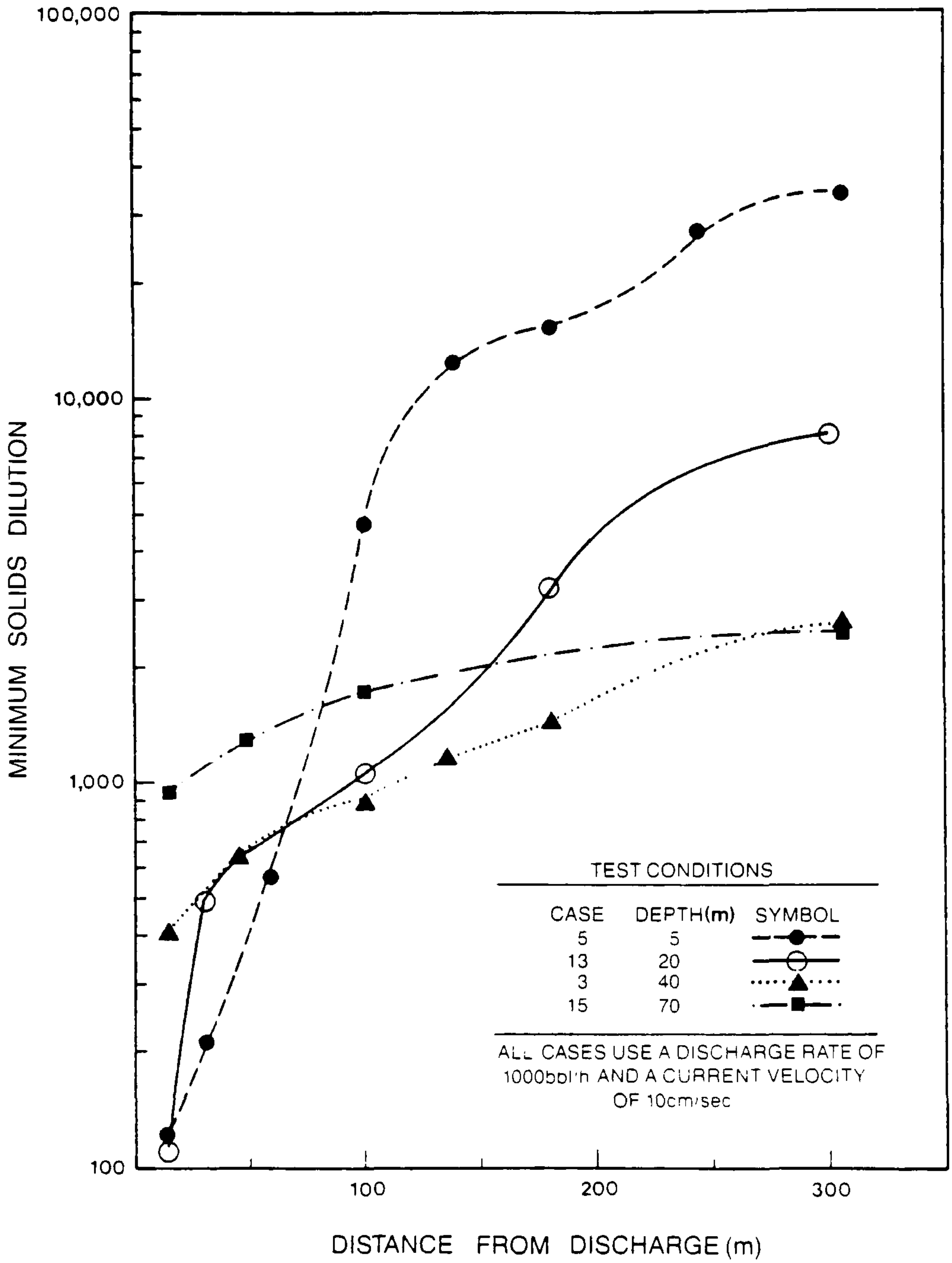



Figure 2. Minimum solids dilution versus distance from the discharge for different water depths.

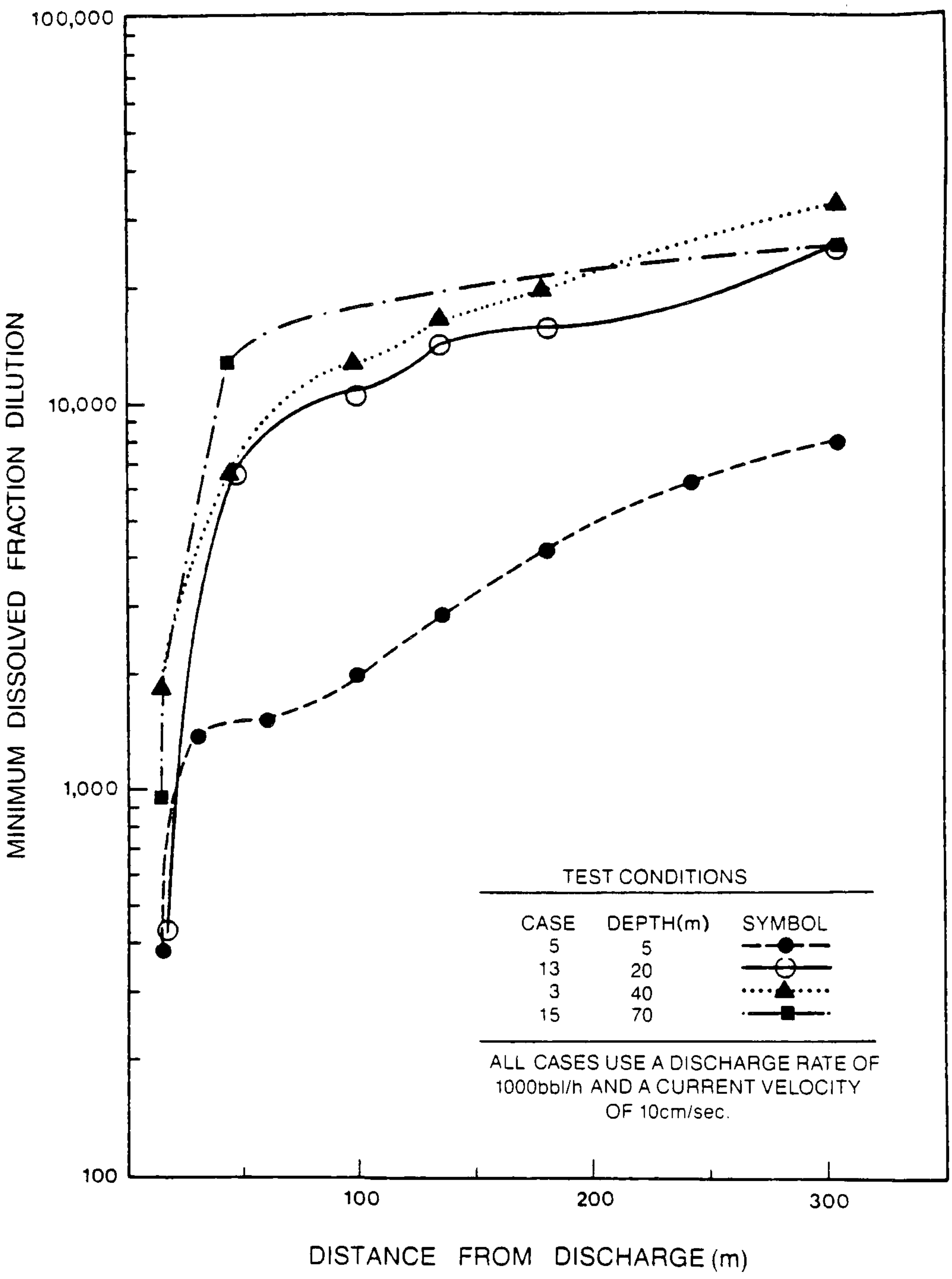



Figure 3. Minimum dissolved fraction dilution versus distance from the discharge for different water depths.

that rapid settling of solids out of the water column causing increased dilutions is the dominant process influencing solids dilution in shallow waters.

The minimum dissolved fraction dilutions, on the other hand, exhibit a very straightforward relationship to water depth (Figure 3). As water depth increases, dissolved fraction dilutions increase for all distances from the source. As water depth increases, the corresponding increase in water volume determines the dissolved fraction dilution.

A relationship between minimum dilutions and drilling effluent discharge rate may be determined by comparing the results of cases 3 and 4, and 6 and 8. Figure 4 shows this relationship for the minimum solids dilution for cases 3 and 4. These data indicate that as discharge rate increases, the minimum solids dilution decreases. The minimum dissolved fraction dilutions exhibit the same relationship. A similar result is found for cases 6 and 8.

Cases 1 and 2; and 10, 11, and 12 were compared to describe the relationship between initial dilution and current velocity. Figure 5 shows this relationship for solids dilution and Figure 6 presents the results for the dissolved fraction dilutions for representative cases 10, 11, and 12. As indicated by Figure 5, minimum solids dilution achieved at a given distance from the source decreases as current velocity increases. A similar, but not as clear, relationship holds for the dissolved fraction dilutions (Figure 6). Case 10, with the lowest current velocity, shows higher dissolved fraction dilutions at most distances. However, case 11 (10 cm/sec current) and 12 (30 cm/sec current) show similar dissolved fraction dilutions even though the current velocities are significantly different. A reason for these results is that a drilling effluent plume in a higher current environment takes less time to travel a specific distance, therefore allowing less time for dispersion to occur. To determine the behavior of drilling effluent plumes in high velocity environments, travel time should be considered. Figure 7 shows the relationship between travel time and minimum solids dilution. These results indicate that for a given travel time, solids dilutions are higher for the higher velocity cases. Therefore, in receiving

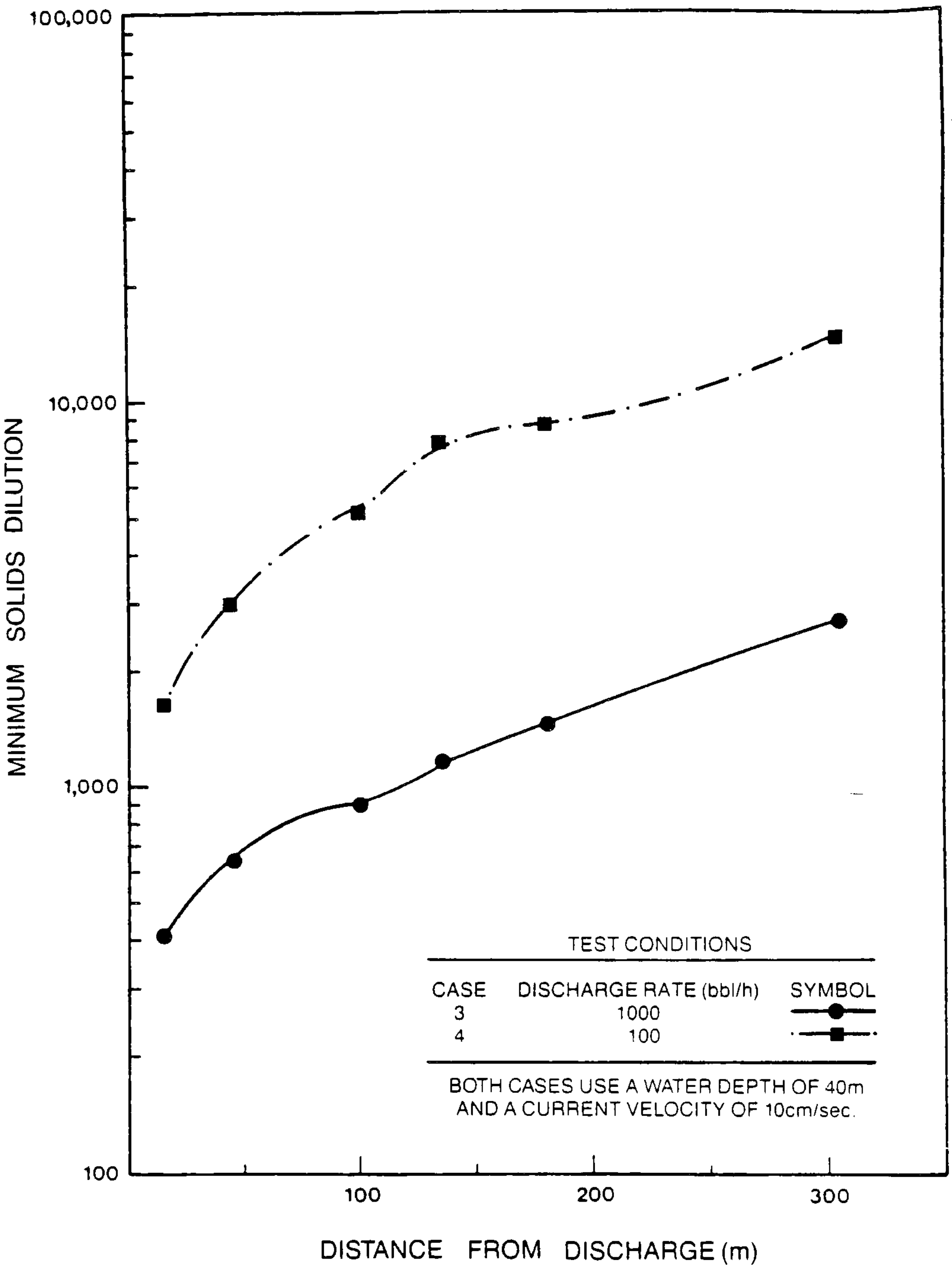



Figure 4. Minimum solids dilution versus distance from the discharge for different discharge rates.

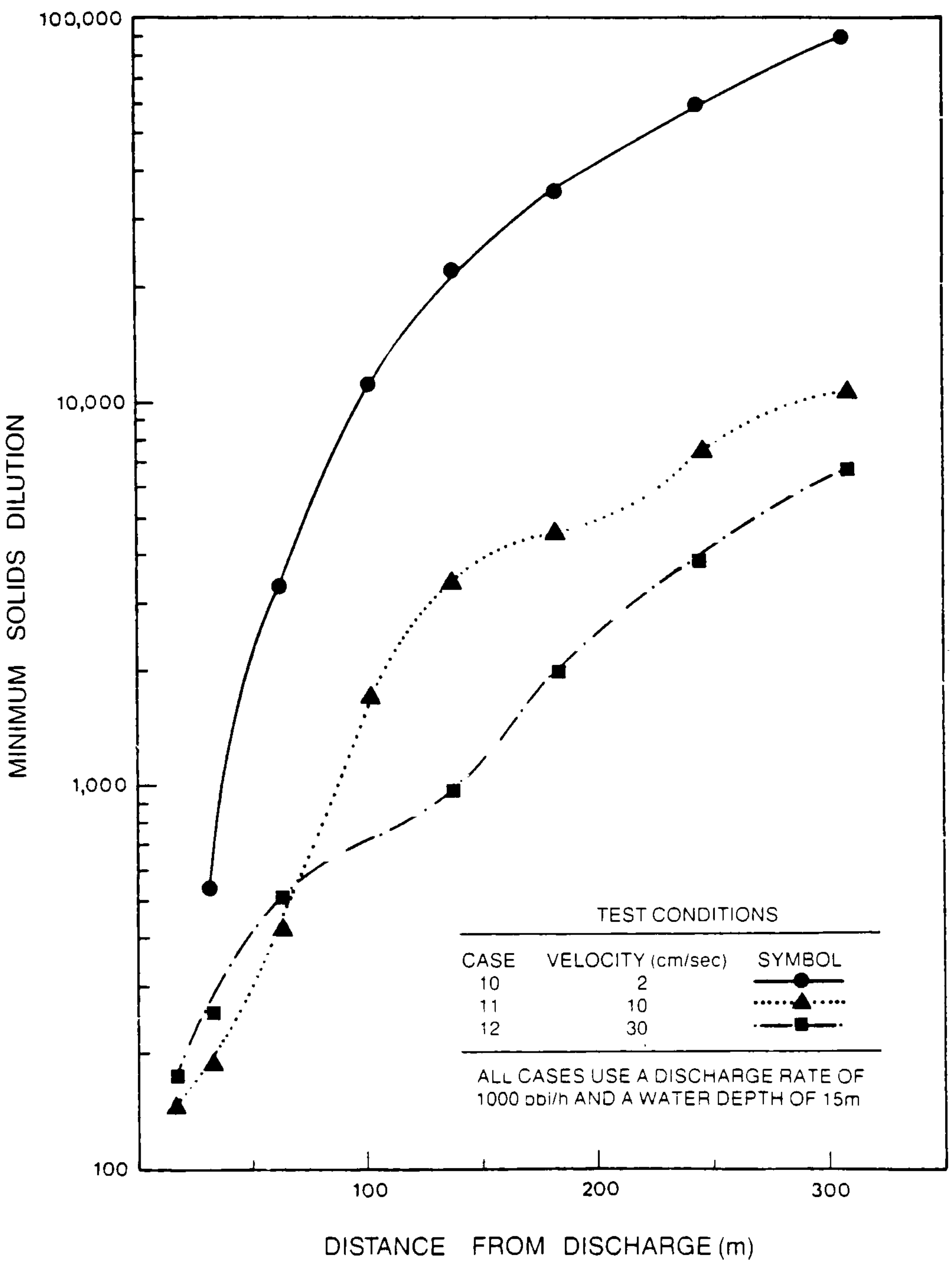



Figure 5. Minimum solids dilution versus distance from the discharge for different current velocities.

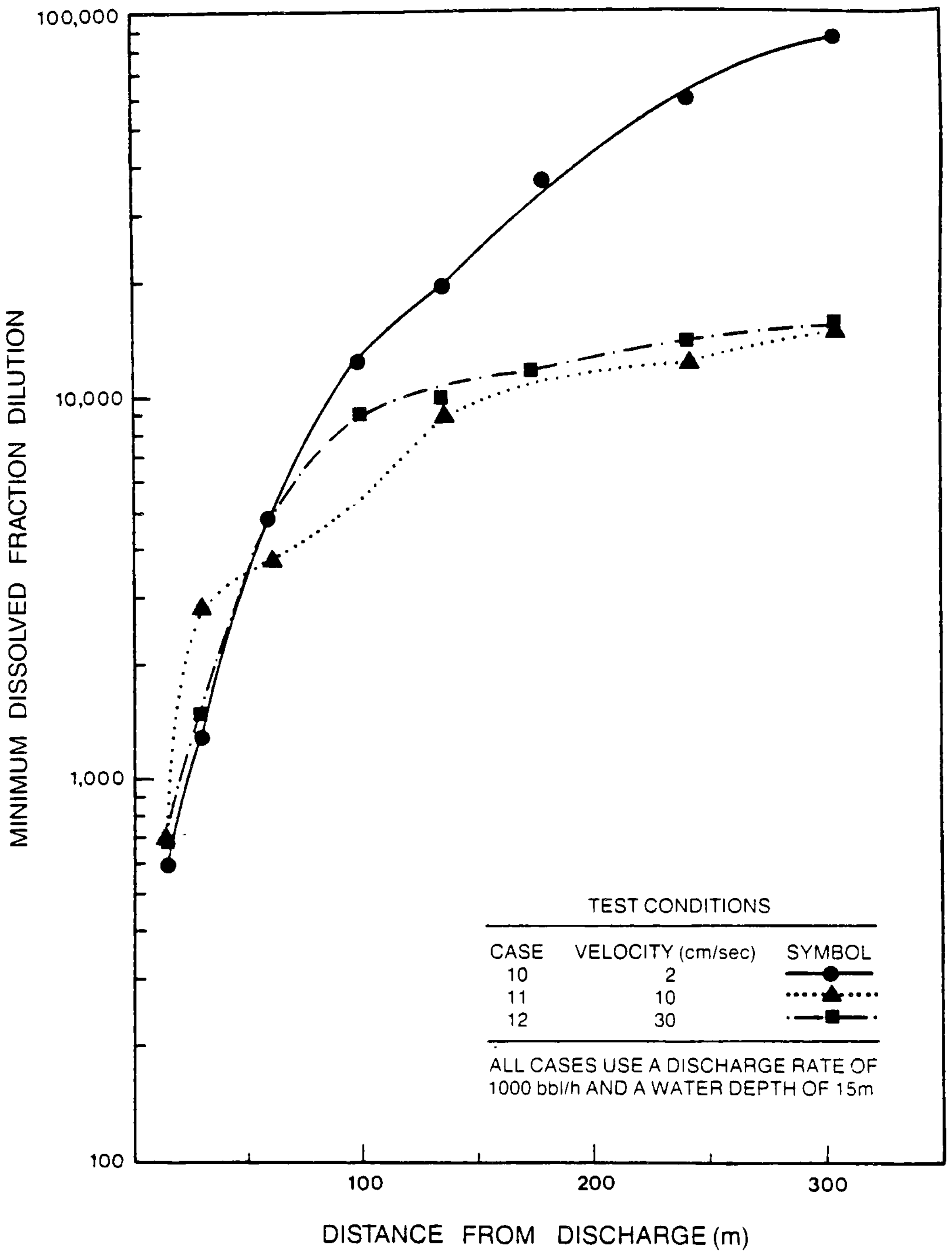



Figure 6. Minimum dissolved fraction dilutions versus distance from the discharge for different current velocities.

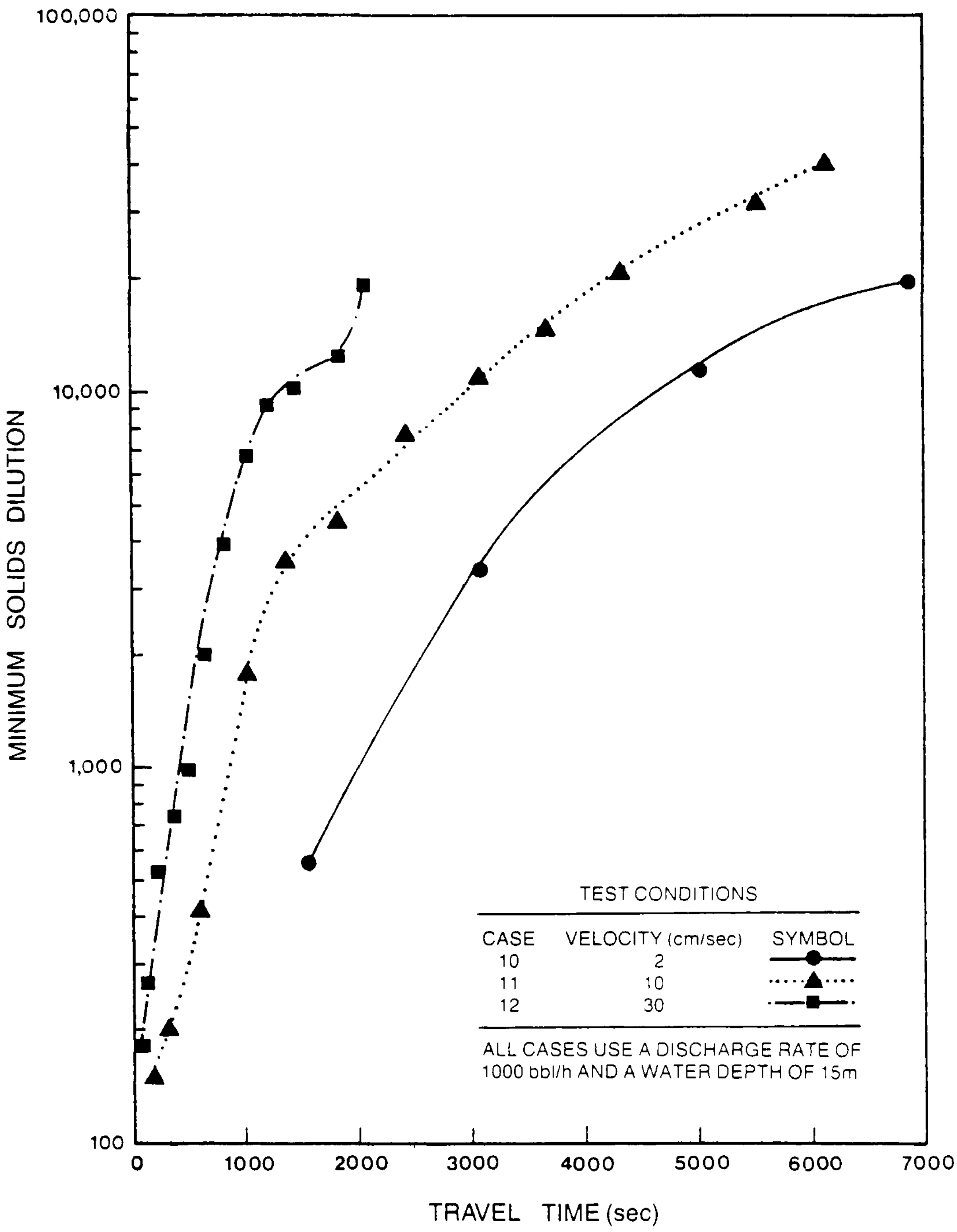



Figure 7. Minimum solids dilutions versus travel time for different current velocities.

waters with high current velocities, the effluent is more rapidly mixed over a larger area than in low velocity environments.

To determine the effects of density stratification (linear distribution with depth) on minimum drilling mud dilutions, results of cases 3 and 14 were plotted in Figure 8. Case 3 has approximately eight times the [illegible] of case 14, however, both minimum solids and dissolved fraction dilutions are similar for the two cases. Therefore, density stratification of the magnitude considered in these test cases does not significantly influence drilling mud dilution. It should be noted that a sharp increase in density (due to a thermocline or pycnocline) with depth could trap the effluent plume higher in the water column, limiting solids settling and dissolved fraction dilution. The exact position (depth) of this inflection would be very important in determining the magnitude of the dilutions achieved under these conditions.

Predilution of drilling mud is another factor that can influence the final concentration of suspended solids in the water column following initial dilution. Predilution is defined as the process of mixing drilling mud and water to dilute the mud prior to discharge. In a case where predilution is used, the total dilution observed at some distance from the discharge is a combination of dilution by the receiving water and predilution. Figure 9 shows the relationship between minimum solids dilution and predilution for cases 2 and 4. These two cases [40 m (131 ft) depth] give roughly identical total solids and dissolved fraction dilutions with distance. These results [40 m (131 ft)] indicate that discharging 100 bbl/h of mud prediluted with 9 parts of water (total discharge rate of 1,000 bbl/h) is the same as discharging 100 bbl/h of straight drilling mud with respect to dilution. A similar relationship was observed for solids dilutions in 10 m (33 ft) of water (cases 7 and 8). Total solids dilutions were identical for these two cases but the dissolved fraction dilutions for case 8 (no predilution) were consistently higher (approximately 50 percent higher) than case 7 (predilution) (Figure 10). These results indicate that predilution or lowering the discharge rate by the appropriate amount results in roughly identical solids dilutions with distance from the discharge for waters 10 to 40 m (33 to 131 ft) deep. The relationship holds for

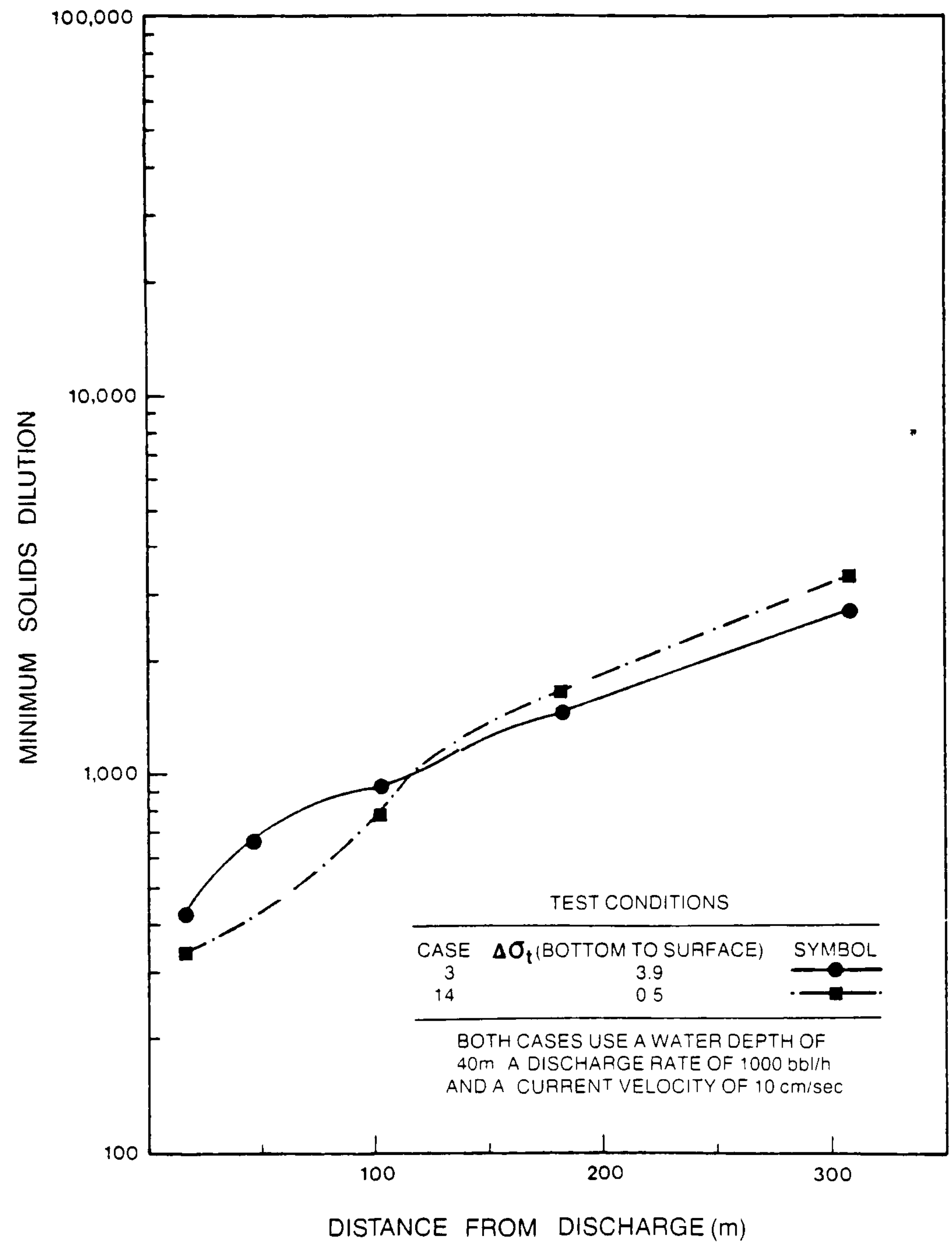



Figure 8. Minimum solids dilution versus distance from the discharge for different degrees of density stratification.

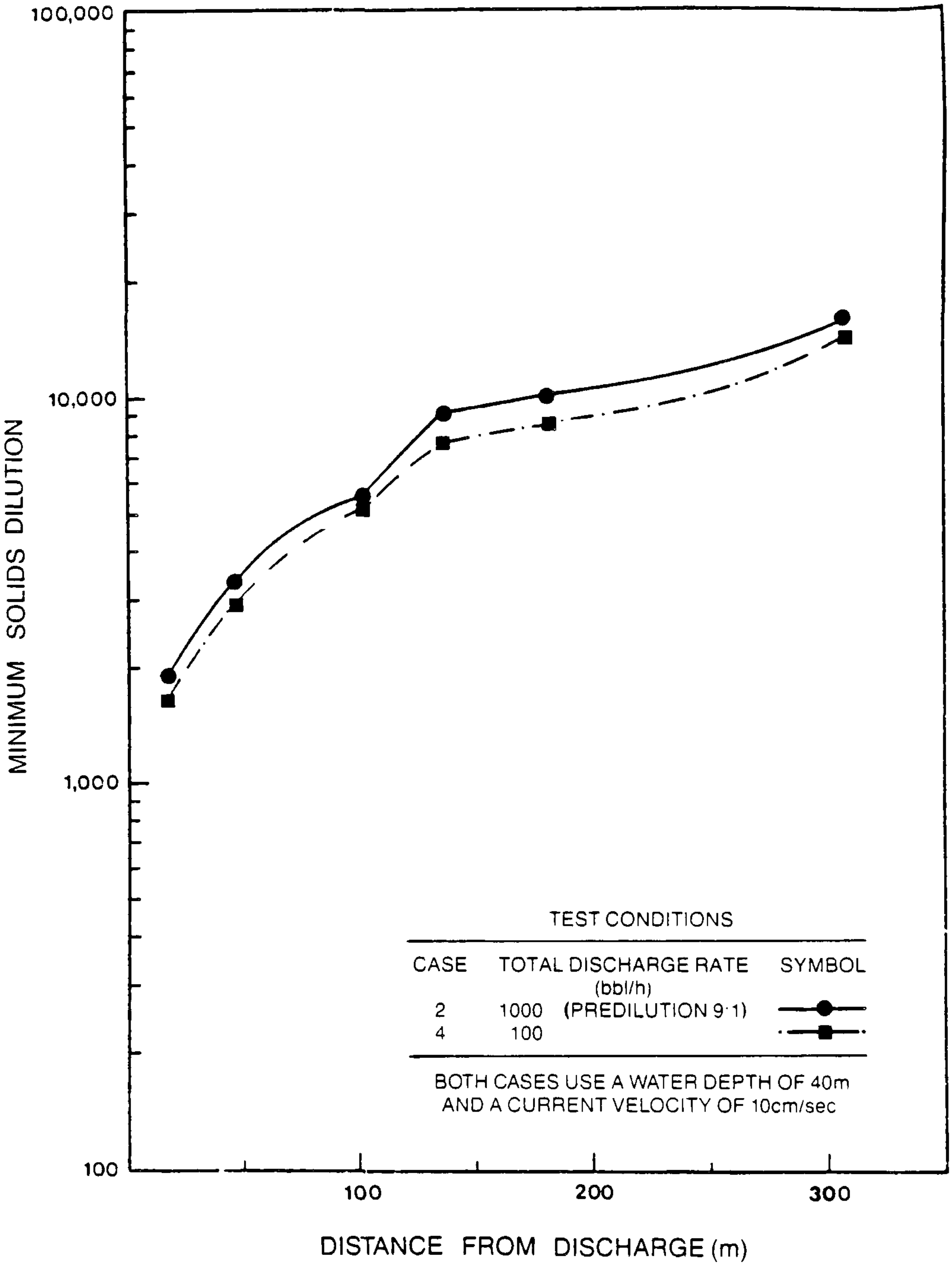



Figure 9. Minimum solids dilution versus distance from the discharge for predilution and no predilution at 40m

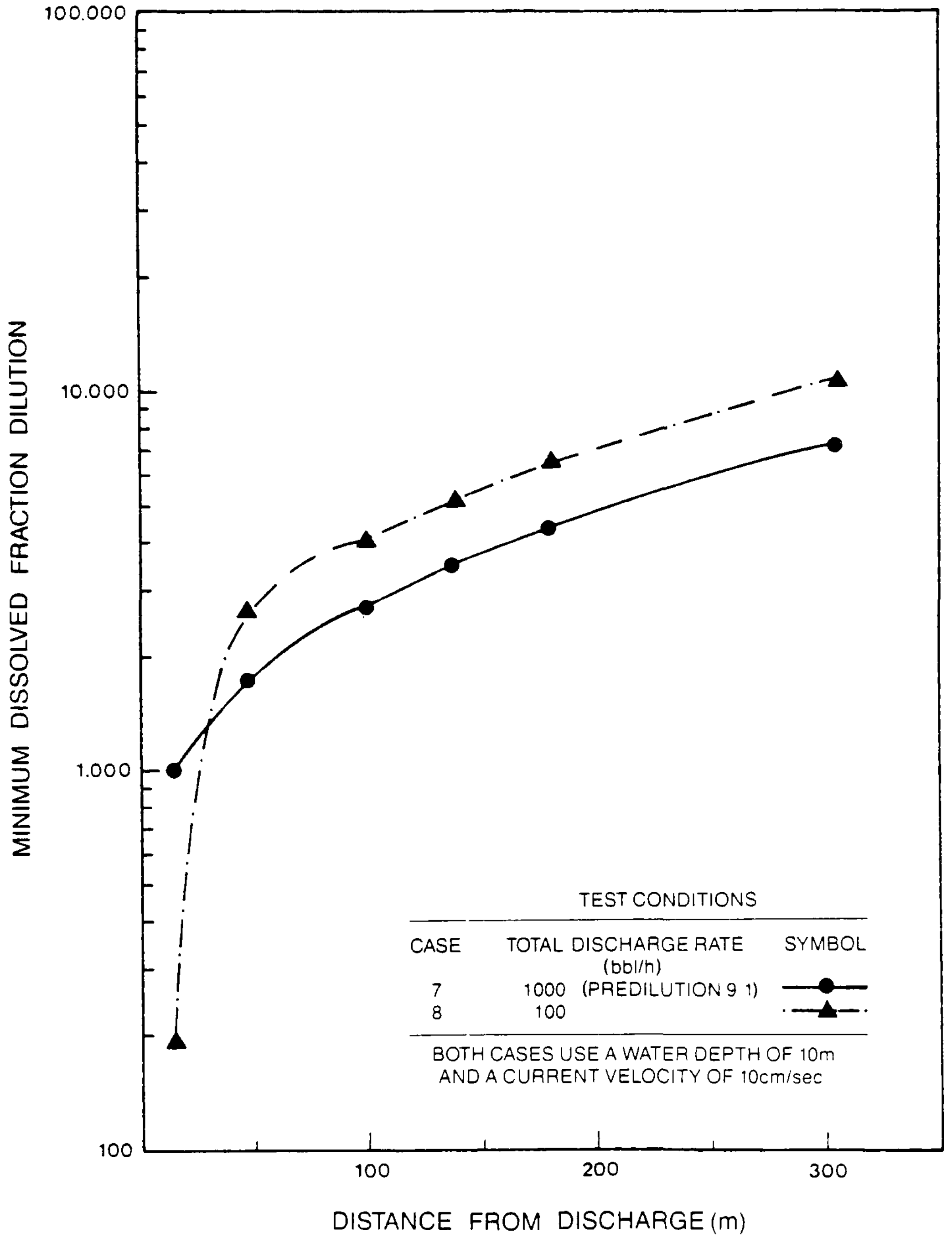



Figure 10. Minimum dissolved fraction dilution versus distance from the discharge for predilution and no predilution at 10m.

dissolved fraction dilutions for the deeper [40 m (131 ft)] case. No data on predilution are available for waters less than 10 m (33 ft) deep. However, similar relationships are expected to apply to these cases.

The initial solids concentration of the mud greatly influences the final solids concentration in the water column and the magnitude of dilution achieved by the receiving water. Results of cases 6 and 9 were compared to determine the relationship between mud bulk density (initial solids concentration) and dilution (similar to predilution). For case 9, a mud bulk density of 9 lb/gal was represented by assuming the same solids density and particle size distribution (fall velocity) as the 17.4 lb/gal mud but using a lower initial concentration of solids in the mud. Figure 11 shows the minimum solids dilution with distance from the discharge for these two cases. Higher solids and dissolved fraction dilutions are achieved for case 6 (higher mud bulk density of 17.4 lb/gal). However, lower water column concentrations of suspended solids (Figure 12) are achieved in the lower mud bulk density case (case 9). These results indicate that the concentration of suspended solids in the receiving water is a result of both the dilution and the initial solids concentration of the mud. A less concentrated discharge (case 9) is not diluted by the receiving water as rapidly as a concentrated discharge (case 6) but the less concentrated discharge results in lower final receiving water solids concentrations.

## Summary

The effects of various factors such as water depth, discharge rate, current velocity, density stratification, and initial mud solids concentration on particulate and dissolved fraction dilutions of drilling muds may be described by comparing the results of the 17 test cases (OOC model) described above. Results of these model runs support the following conclusions:

- Within 80 m (262 ft) of the discharge and with a 10 cm/sec current, particulate dilution increases as water depth increases. However, at distances greater than approximately 80 m (262 ft), particulate dilution decreases as water depth

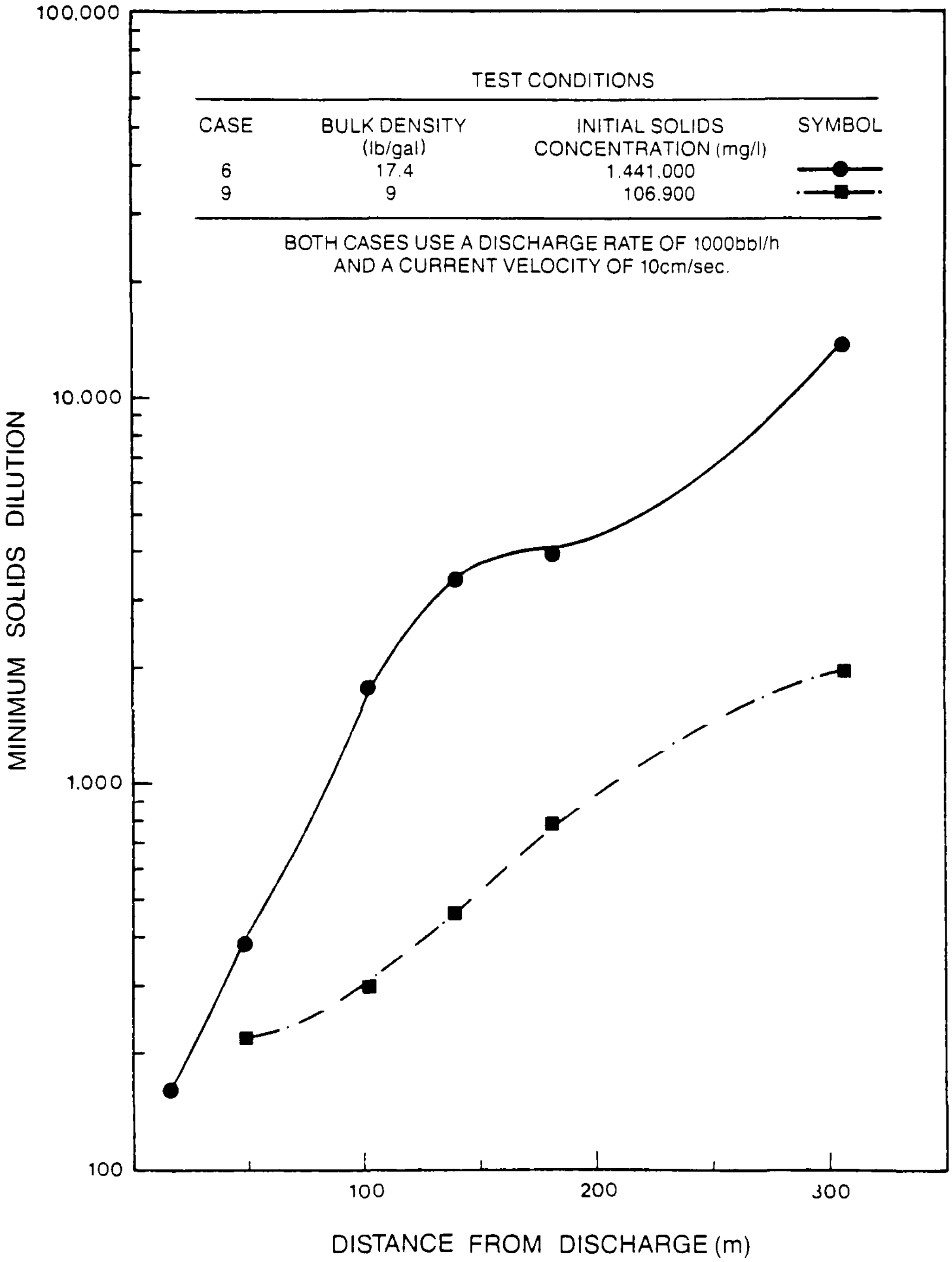



Figure 11. Minimum solids dilution versus distance from the discharge for different bulk mud density discharges at 10m.

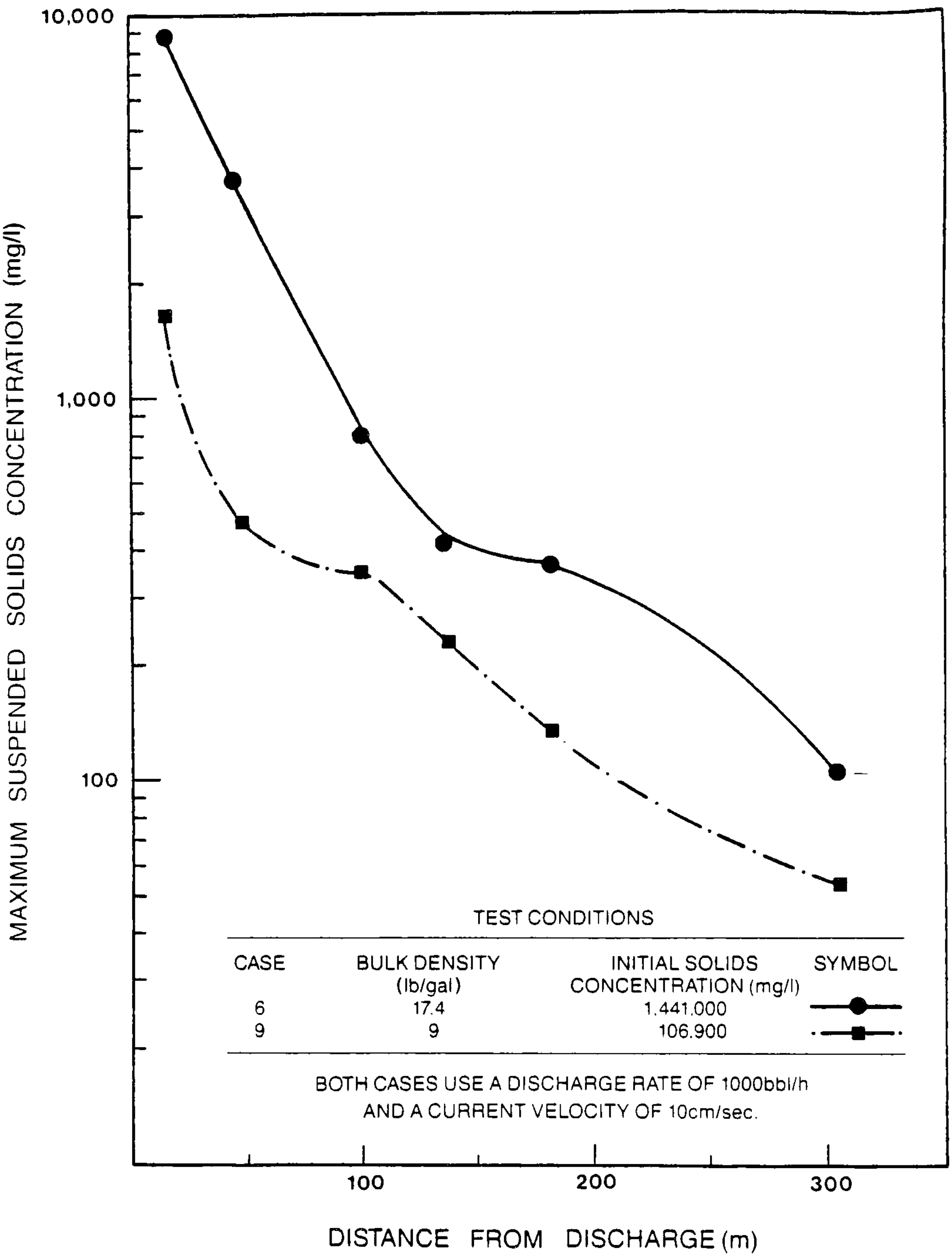



Figure 12. Maximum suspended solids concentration versus distance from the discharge for different bulk mud density discharges at 10m.

increases. Dissolved fraction dilution increases as water depth increases for all distances.

- Both particulate and dissolved fraction dilutions decrease as discharge rate increases.

- Particulate dilution at a given distance from the source decreases as current velocity increases. However, for a given travel time, larger particulate dilutions are obtained in the higher velocity case. No direct relationship between dissolved fraction dilution and current velocity could be determined. The largest dissolved fraction dilutions were obtained in the low velocity case, however.

- Density stratification of the type and magnitude considered in this report did not significantly affect either particulate or dissolved fraction dilutions.

- Predilution of drilling mud has the same effect on solids dilution as reducing the discharge rate by the appropriate amount (as long as the mud discharge rates are equal). This relationship holds for dissolved fraction dilutions in deeper water [40 m (131 ft)], but in shallow water [10 m (33 ft)], slightly lower dissolved fraction dilutions were obtained for the predilution case. There appears to be no practical advantage to predilution in waters deeper than 10 m (33 ft).

- The initial solids concentration of the mud influences the magnitude of dilution of both particulate and dissolved fractions. As mud solids concentration (or mud bulk density) increases, dilutions of both particulate and dissolved fractions increase. However, lower water column concentrations of suspended solids are achieved for the low mud density case (lower initial solids concentration).

Sensitivity Analysis

Multiple regression analysis was used to investigate the relationship between predicted suspended solids concentrations at 100 m (328 ft) and selected model input parameters. An analysis was conducted with both the predicted depth-averaged and maximum suspended solids concentrations at 100 m (328 ft) from the discharge as the dependent variables, and current velocity, discharge depth, and discharge rate as the independent variables. These analyses were conducted with a sample size of 14.

The relative influence of the individual independent variables on the total explainable variation ($R^2$) in the multiple regression analysis was also measured. The contribution of the correlation between each independent variable and the predicted suspended solids concentrations was assessed by weighting the individual correlation coefficients by the standardized partial regression coefficient (often called the beta weights). The results of these analyses indicate that there is no significant linear relationship between the predicted suspended solids concentrations and the selected independent parameters. Using the depth-averaged solids concentrations at 100 m (328 ft) from the discharge as the dependent variable, the regression analysis gave an $R^2$ value of 0.52. Of this total explained variation, water depth accounted for 3.1 percent, current velocity accounted for 20.4 percent, and discharge rate accounted for 76.5 percent. Using the maximum suspended solids concentration at 100 m (328 ft) from the discharge as the dependent variable, the regression analysis gave an $R^2$ value of 0.43. Of this total explained variation, water depth accounted for 6.2 percent, current velocity accounted for 42.1 percent, and discharge rate accounted for 51.7 percent.

The results of these regression analyses indicate that nonlinear relationships between independent variables and criterion variables account for 48 to 57 percent of the total variation. However, discharge rate was shown to be the dominant influence on the explained variability in suspended solids concentration.

## EPA MODEL DESCRIPTION

The EPA model, developed and described by Yearsley (1984, pp. 1-16), simulates the discharge of drilling muds to relatively shallow waters. The model is applicable near the edge of the mixing zone and beyond for shallow discharges with low densimetric Froude numbers. Under such conditions several assumptions greatly simplify the computation. These assumptions include the omission of the convective descent and dynamic collapse phases, the immediate and uniform vertical mixing of solids upon discharge, and the subsequent dominance of horizontal diffusion, advection, and particle settling in the dilution process. The rationale for the omission of the convective descent and dynamic collapse phases is that they generally occur within 100 m (328 ft) of the point of discharge. In recognition of this fact, the 100 m distance is often established as a mixing boundary. Outside of the mixing zone of shallow discharges, vertical mixing is sufficient to provide a uniform vertical distribution of solids. The EPA model formulation assumes horizontal mixing occurs under isotropic turbulence. In contrast to the OOC model, no upper and lower plume separation is implicitly included in the EPA model.

In comparison to the OOC model, input and output of the EPA model are greatly simplified. Inputs to the model include data from three categories: drilling mud characteristics, ambient characteristics, and model options. Drilling mud characteristics consist of the source strength (discharge flow rate multiplied by drilling mud concentration), the number of discrete particle classes, and the distribution and settling velocities of the particle classes. Ambient conditions are defined by the current velocity, water depth, coefficient of eddy diffusivity, and background suspended solids concentrations. Model options permit the specification of the simulation duration, the number of time periods, the integration time increments, and the distances from the discharge at which the drilling mud concentrations are to be determined. Output from the model consists of a tabular presentation of drilling mud concentrations at the preselected distances and times. Concentrations of solids are depth-averaged values computed along the plume centerline in the direction of the current.

Limitations of the EPA model include an invariant water depth, and constant discharge rate, and a unidirectional current of constant speed. The distribution of cuttings is not incorporated into the EPA model. Unlike the OOC model, dilution of the dissolved fraction is not computed by the EPA model, nor is there any simulation of seabottom sediment accumulation. Dissolved constituents are, in the short-term, conserved within the water column, as no settling occurs, and thus dilution of dissolved solids is always expected to be smaller than the suspended solids dilution predicted by the EPA model. The EPA model has not undergone extensive verification with field data. Comparisons made by Yearsley (1984, pp. 14-15) indicated that the model generally predicts higher concentrations than those measured in the field. Therefore, the dilutions predicted by the model tend to be conservatively high. Near the discharge, however, maximum measured concentrations were much higher than the depth-averaged results of the model. This is a consequence of the model assumption that the drilling mud is uniformly mixed throughout the water column. Thus, the EPA model should not be used to predict drilling mud concentrations close to the source [within 100 m (328 ft)].

# III. SOLIDS DEPOSITION

## FIELD STUDIES

There have been no comprehensive field studies of bottom deposition (areal extent and depth) of drilling mud discharges. Many studies involve simple observation of the presence or absence of piles of drilling materials near the source. Table 7 summarizes the findings of available deposition studies.

There are several problems with interpretation and comparison of available field study results of bottom deposition. Many studies were not designed to fully describe bottom deposition patterns and characteristics. Sampling time, frequency, location and procedures, and quantities measured often differed among studies. In addition, the oceanographic and discharge conditions varied widely from study to study and during each study. These factors make it difficult to interpret results and determine the influence of different factors on the bottom deposition characteristics. Detailed discussion of available field studies is included in Appendix D. Problems with available field data include poor study design, difficulty in measuring deposition rates and sediment accumulation, variability of oceanographic conditions during the tests, and small discharge volumes studied.

General conclusions supported by these field studies include:

- Energy dynamics of the system strongly influenced bottom deposition patterns. For example, no visible accumulation of solids was observed near discharge sites in Cook Inlet but deposited solids in the low energy mid-Atlantic remained on the bottom for several years.

TABLE 7. SUMMARY OF RESULTS OF DEPOSITION STUDIES

| Site | Reference | Sampling Method | Length of Deposition Area (m) | Other |
|---|---|---|---|---|
| Palawan Island, Philippines[a] | Hudson et al. (1982) | Diver observation | 20 | No visible cuttings pile |
| Mid-Atlantic[a] | EG&G Environmental Consultants (1982) | Sediment samples, television monitoring, side-scan sonar | 100 | Elevated barium levels out to 1.6 km from discharge |
| Georges Bank[a] | Bothner et al. (1983) | Sediment samples | 500 | |
| Canadian Beaufort | Crippen et al. (1980) | Sediment samples | -- | Elevated metals concentrations within 45 m from discharge |
| Gulf of Mexico | Tillery and Thomas (1980) | Sediment samples | -- | Decreasing gradient of metals concentration with distance from the discharge |
| Reindeer Island | Northern Technical Services (1981) | Settling pans | 30 | Maximum deposition of 173 $mg/cm^2$ at 6 m from discharge |
| Tern Island | Northern Technical Services (1983) | Sediment samples | -- | No accumulation observed |
| Norton Sound | Ecomar (1983) | Sediment traps | 300 | Accumulations ranged from 2 to 1,740 $g/m^2$. Maximum at 12 m from discharge |
| Tanner Bank | Ecomar (1978) | Sediment traps | 125 | Maximum deposition rate of 67 $g/m^2$/day at 64 m from discharge |
| Cook Inlet[a] | Houghton et al. (1980) | Sediment samples, sediment traps, television monitoring | -- | No visible accumulation. Cuttings deposition ranged from $5.24 \times 10^{-3}$ $g/m^2/h$ to 1.25 $g/m^2/h$ within 100 m of discharge. |

[a] Results for cuttings discharges only.

- Drilling effluents were generally deposited near the discharge [within 100 to 1,000 m (328 ft to 3,281 ft)]. Deposition patterns were determined by oceanographic conditions during the study such as current velocity and water depth, and discharge conditions such as discharge rate, volume, and duration.

- Barium was the most common metal found in elevated levels in sediments near drilling rigs. Other metals found in elevated levels in sediments near drilling rigs included cadmium, chromium, copper, lead, mercury, and zinc.

OOC MODEL RESULTS

Bottom deposition characteristics were predicted by the OOC model for 20 cases listed in Table 6. Tabulated model results (deposition) for these test cases are provided in Appendix B. The OOC model was used to determine the relationship between bottom deposition and water depth, discharge rate, current velocity, density stratification, predilution, and mud bulk density (initial solids concentration).

Cumulative percent deposited solids versus distance from the discharge was plotted to determine these relationships. These plots show the pattern of solids accumulation including the areal extent of deposition. Figure 13 shows how the deposition pattern changes for mud discharges in various water depths. For the 5 m (16 ft) depth, solids were deposited within approximately 100 m (328 ft) of the discharge. Ninety percent of the deposited solids settled within 15 m (50 ft). Maximum deposition was much greater for this shallow water case than for the deeper cases. A majority of deposited solids (90 percent) accumulated within 183 m (600 ft) for the 40 m (131 ft) case and within 1,036 m (3,400 ft) for the 70 m (230 ft). Therefore, as water depth increases, deposition area increases and deposition thickness decreases for a given mud discharge. In addition, the location of maximum deposition thickness moves farther downcurrent as water depth increases.

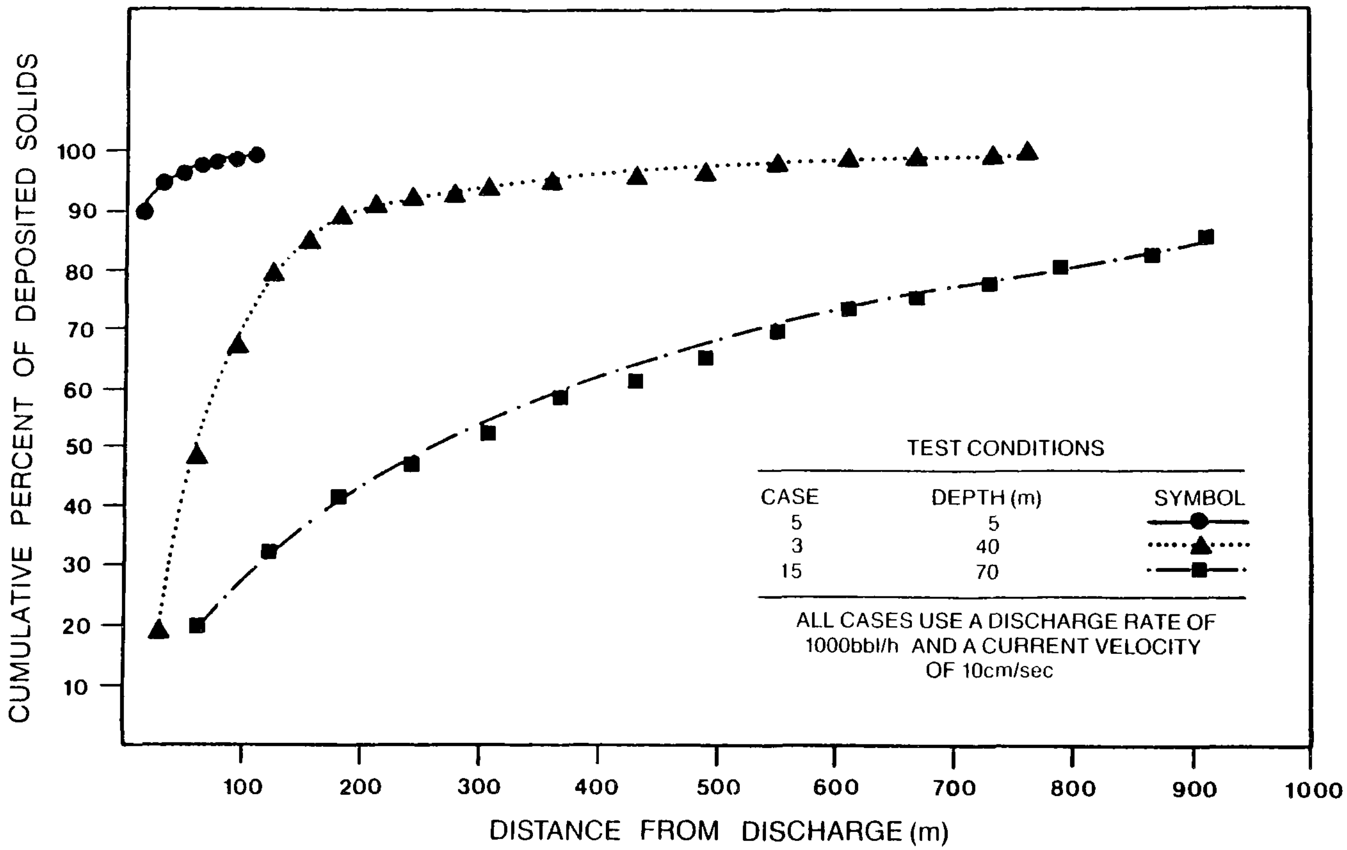



Figure 13. Cumulative percent of deposited solids versus distance from the source for different water depths.

Figure 14 shows the relationship between solids deposition and ambient current velocity. As expected, cases with higher current velocities result in deposition of a lesser amount over a greater area. Therefore, as current velocity increases, deposition area increases and deposition thickness decreases. In addition, the location of maximum deposition moves farther downcurrent as ambient velocity increases.

The relationship between bottom deposition and discharge rate is not as clearly defined as those discussed previously. Figure 15 shows the bottom deposition patterns for cases 3 (1,000 bbl/h discharge rate) and 4 (100 bbl/h discharge rate). Although the discharge rates differ by a factor of 10, the deposition patterns are quite similar. The lower discharge rate (case 4) scenario gives a slightly larger deposition area and lower deposition thickness. In addition, the maximum deposition occurs within 31 m (100 ft) of the source for the low discharge rate scenario and within 61 m (200 ft) of the source for the higher discharge rate case.

Figure 16 shows the relationship between initial bulk density of the mud (initial solids concentration) and solids deposition. This plot shows that the deposition area is greater than double for the less concentrated (lower initial solids concentration), lower density discharge. Maximum deposition thickness is less (approximately half) for the lower density discharge but the location of maximum deposition [31 m (100 ft)] is the same for both cases. Therefore, as solids concentration increases, deposition area decreases while deposition thickness increases.

The solids deposition results for deeper water cases [greater than 40 m (131 ft)] indicate that drilling solids settle in discrete zones (or distances from the discharge) with no (or little) accumulation in between these zones. This effect is a consequence of using discrete particle classes (settling velocities) to represent a continuous distribution. As water depth increases [depths greater than 40 m (131 ft)], individual particle classes spend more time in the water column and become segregated due to the different settling velocities as they settle to the bottom. Use of a greater number of solids classes will alleviate this phenomenon.

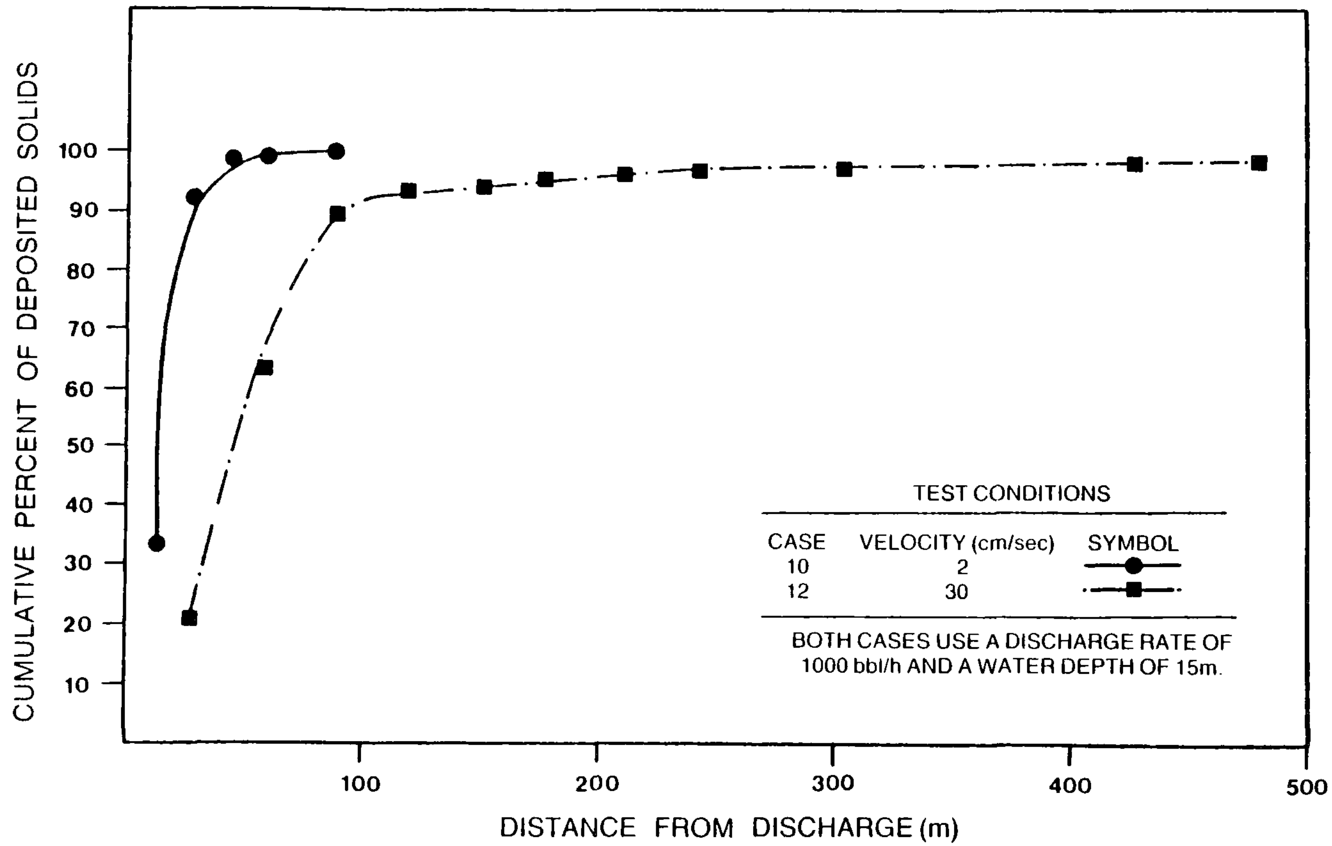



Figure 14. Cumulative percent of deposited solids versus distance from the source for different current velocities.

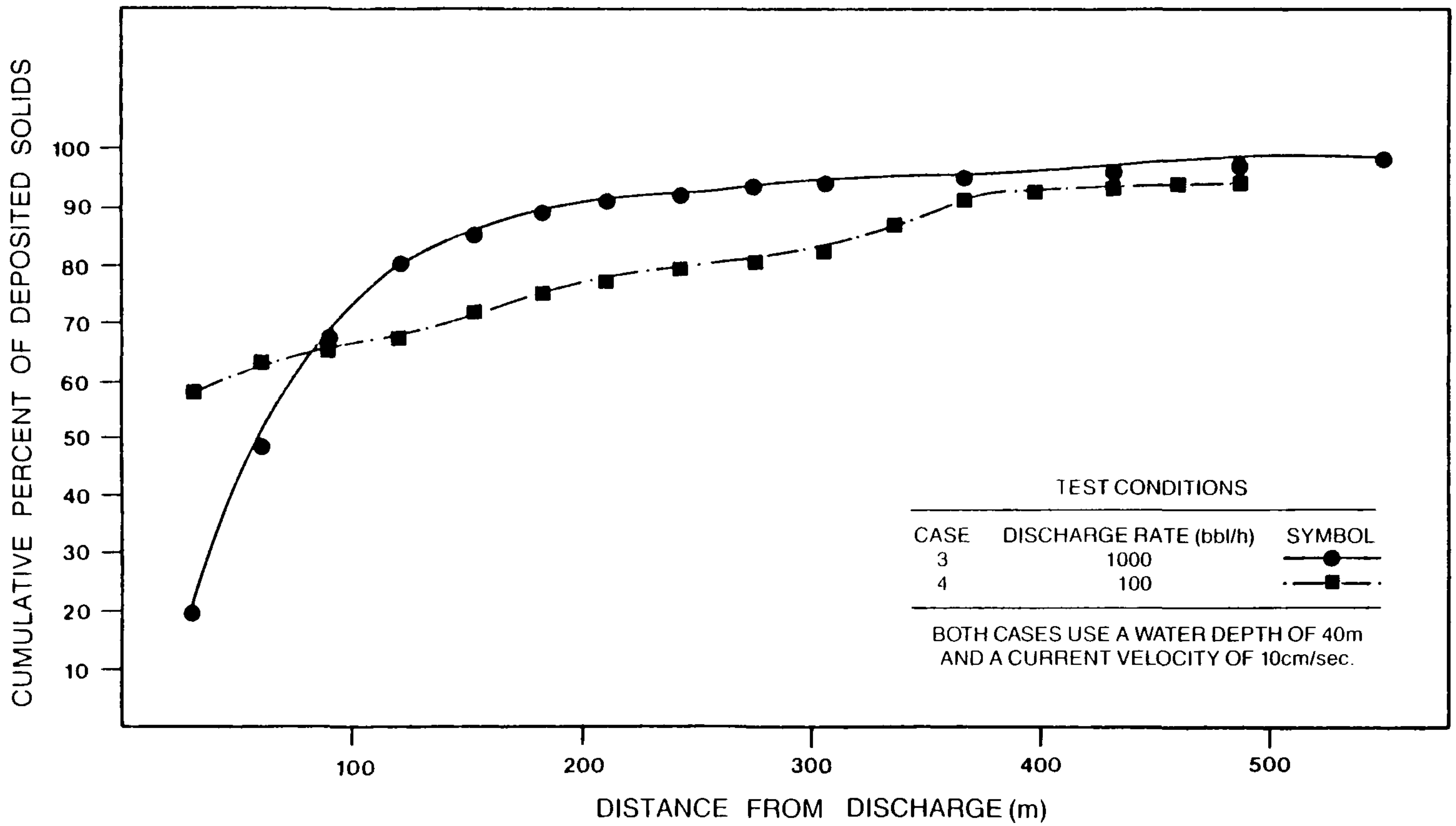



Figure 15. Cumulative percent of deposited solids versus distance from the source for different discharge rates.

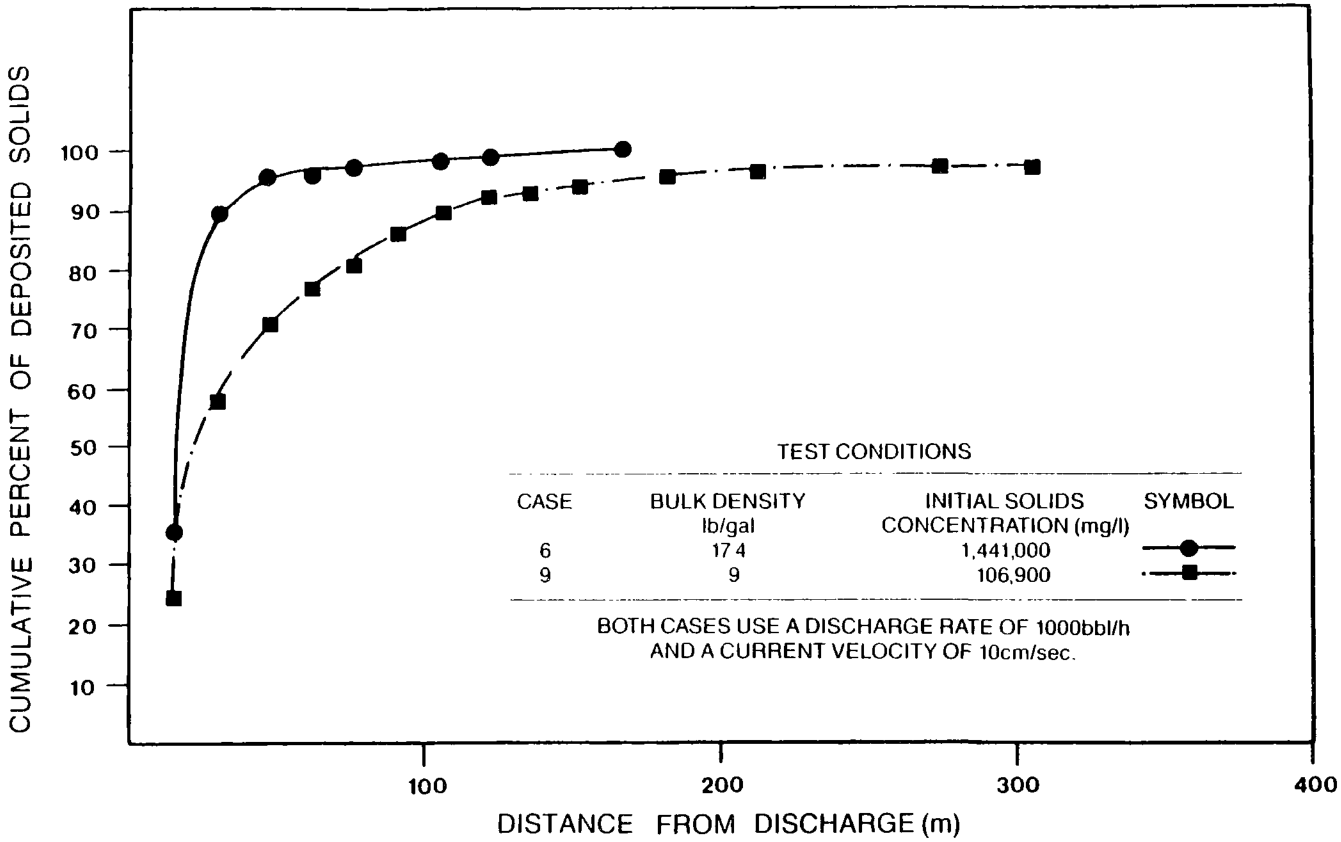



Figure 16. Cumulative percent of deposited solids versus distance from the source for different bulk mud densities.

Deposition area and thickness are not significantly affected by the variation considered in discharge rate, density stratification, or predilution (change in initial solids concentration).

Summary

The effects of various factors such as water depth, discharge rate, current velocity, density stratification, predilution, and initial mud solids concentration on drilling mud deposition patterns may be determined by comparing the OOC model results discussed above. Results of these model runs support the following conclusions:

- As water depth or current velocity increases, deposition area increases and deposition thickness decreases. The location of maximum deposition moves downcurrent as water depth or current velocity increases.

- As initial mud solids concentration increases, deposition area decreases and deposition thickness increases. The location of maximum deposition is not affected by variation in the initial mud solids concentration (bulk mud density).

- Solids deposition patterns were not significantly affected by variation in the mud discharge rate or density stratification. Deposition characteristics of the predilution case (case 2) were also similar to the reduced total discharge rate case (case 4).

# IV. FACTORS TO CONSIDER IN EVALUATING DISCHARGE LIMITATIONS

The most direct method to ensure that drilling mud discharges comply with developed guidelines involves regulation of discharge characteristics and discharge location. Drilling mud discharges can be closely regulated or completely prohibited in or near "sensitive" environmental areas including depositional areas, areas of low net circulation, or shallow waters. Discharge characteristics that may be regulated include drilling mud type, mud toxicity, initial solids concentration, discharge rate, and depth. First, discharge guidelines must be developed and then, drilling mud dilutions must be predicted for specific cases to determine compliance of possible discharge alternatives. To determine discharge guidelines, drilling mud composition and toxicity must be considered.

## MUD COMPOSITION

Eight generic mud types have been evaluated during permit development in EPA. Table 8 lists the basic components of each mud and their maximum authorized concentrations. Each mud differs in its basic components, and a single mud type can vary substantially in composition. For example, the amount of barite in seawater/lignosulfonate mud can vary from 25-450 lb/bbl.

The presence of potentially toxic trace elements in drilling muds and cuttings is of primary concern. Metals including lead, zinc, mercury, arsenic, and cadmium can be present as impurities in barite; chromium is present in chrome lignosulfonates and chrome-treated lignite (Kramer et al., 1980, p. 789; Crippen et al., 1980, pp. 639-640). According to Ayers et al. (1980b, p. 389; Ecomar 1978, as cited by Petrazzuolo 1981, p. 3-3), drill pipe dope (15 percent copper, 7 percent lead) and drill collar dope (35 percent zinc, 20 percent lead, 7 percent copper) may also contribute trace metals to the muds and cuttings discharge.

# TABLE 8. APPROVED DRILLING MUD TYPES

| COMPONENTS | MAXIMUM AUTHORIZED CONCENTRATION (pounds per barrel) |
|---|---|
| **Seawater/Freshwater/Potassium/Polymer Mud** | |
| KCL | 50 |
| Starch | 12 |
| Cellulose polymer | 5 |
| XC polymer | 2 |
| Drilled solids | 100 |
| Caustic | 3 |
| Barite | 450 |
| Seawater or freshwater | As needed |
| **Seawater/Lignosulfonate Mud** | |
| Attapulgite or Bentonite | 50 |
| Lignosulfonate | 15 |
| Lignite | 10 |
| Caustic | 5 |
| Barite | 450 |
| Drilled solids | 100 |
| Soda ash/Sodium bicarbonate | 2 |
| Cellulose polymer | 5 |
| Seawater | As needed |
| **Lime Mud** | |
| Lime | 20 |
| Bentonite | 50 |
| Lignosulfonate | 15 |
| Lignite | 10 |
| Caustic | 5 |
| Barite | 180 |
| Drilled solids | 100 |
| Soda ash/Sodium bicarbonate | 2 |
| Seawater or freshwater | As needed |
| **Nondispersed Mud** | |
| Bentonite | 15 |
| Acrylic polymer | 2 |
| Barite | 180 |
| Drilled solids | 70 |
| Seawater or freshwater | As needed |

| COMPONENTS | MAXIMUM AUTHORIZED CONCENTRATION (pounds per barrel) |
|---|---|
| **Spud Mud** | |
| Lime | 1 |
| Attapulgite or Bentonite | 50 |
| Caustic | 2 |
| Barite | 50 |
| Soda ash/Sodium bicarbonate | 2 |
| Seawater | As needed |
| **Seawater/Freshwater Gel Mud** | |
| Lime | 2 |
| Attapulgite or Bentonite | 50 |
| Caustic | 3 |
| Barite | 50 |
| Drilled solids | 100 |
| Soda ash/Sodium bicarbonate | 2 |
| Cellulose polymer | 2 |
| Seawater or freshwater | As needed |
| **Lightly Treated Lignosulfonate Freshwater/Seawater Mud** | |
| Lime | 2 |
| Bentonite | 50 |
| Lignosulfonate | 6 |
| Lignite | 4 |
| Caustic | 3 |
| Barite | 180 |
| Drilled solids | 100 |
| Soda ash/Sodium bicarbonate | 2 |
| Cellulose polymer | 2 |
| Seawater to freshwater ratio | 1:1-approximately |
| **Lignosulfonate Freshwater Mud** | |
| Lime | 2 |
| Bentonite | 50 |
| Lignosulfonate | 15 |
| Lignite | 10 |
| Caustic | 5 |
| Barite | 450 |
| Drilled solids | 100 |
| Cellulose polymer | 2 |
| Soda ash/Sodium bicarbonate | 2 |
| Freshwater | As needed |

Muds representative of generic muds 2 through 8 were analyzed for trace metals as part of the mid-Atlantic bioassay program. While these muds are "representative," the observed trace metal concentrations do not represent the maximum concentrations that could occur. An estimate of trace metal concentrations expected to occur in the drilling muds and cuttings discharged from exploratory drilling operations is made here for subsequent impact evaluation. Ideally, conservative values could be selected from a large number of chemical analyses of muds and cuttings. This is not possible, however, because only limited data are available on the trace metal content of drilling muds and cuttings. Data from several sources were combined to produce the expected maximum trace metal concentrations in drilling mud presented in Table 9.

It should be noted that the concentrations presented in Table 10 represent a whole mud analysis that includes constituents both in the dissolved and particulate state. In the short term (over a few hours), dissolved metals and their toxicity are of primary concern. Results of analyses for dissolved pollutants associated with drilling muds are more limited than whole mud analyses data.

The partitioning of metals between the solid and liquid phase in drilling muds prior to discharge is expected to vary substantially from the partitioning observed in seawater. The pH of drilling mud is generally about 10 while the pH of seawater is approximately 8. Since pH is an important factor controlling adsorption, observations at the pH of seawater are most appropriate as an indicator of partitioning after discharge.

No detailed studies have been conducted to quantify the receiving water concentrations of soluble metals associated with drilling muds. Ayers et al. (1980a, p. 355) analyzed the filtrate of samples collected near the discharge in the Gulf of Mexico for chromium. These samples contained high solids concentrations before filtering. Concentrations of chromium were below the 20 ppb detection limit of the analytical method used for all filtrate samples.

TABLE 9. MAXIMUM TRACE METAL CONCENTRATIONS MEASURED IN DRILLING MUD DISCHARGES

| Metal | Concentration (ppm) | Reference |
|---|---|---|
| Arsenic | 24 | a |
| Barium | 398,800 | b |
| Cadmium | 2.1[c] | b |
| Chromium | 1,300 | d |
| Copper | 88 | d |
| Lead | 820 | a |
| Mercury | 1.53[c] | b |
| Nickel | 88 | d |
| Vanadium | 235 | d |
| Zinc | 1,350[c] | b |

[a] Crippen et al. (1980, p. 649). Reported as ug/g drilling fluid.

[b] Data derived from end-of-well chemical analyses reported to EPA Region X in discharge monitoring reports (mg/kg dry weight basis).

[c] Higher concentrations of cadmium, mercury, and zinc were measured by Crippen et al. (1980, p. 649) but are not used here because the barite used in Crippen's study is not representative of drilling muds used on the Alaskan outer continental shelf.

[d] Northern Technical Services (1981, p. 91) (ppm drilling fluid) and Northern Technical Services (1982, p. 91) (mg/kg solid phase).

TABLE 10. SOLUBLE AND SOLIDS METAL CONCENTRATIONS IN DREDGED MATERIALS DUMPED AT SEA, 1978 AND 1979

| Metal | Average Concentration Solid Phase mg/kg | Average Concentration Liquid Phase[a] mg/l | Dissolved Constituent Concentration Ratio[b] |
|---|---|---|---|
| Arsenic | 4.0 | 0.0049 | 0.0012 |
| Cadmium | 1.2 | 0.0016 | 0.0013 |
| Chromium | 33.0 | 0.0048 | 0.0001 |
| Copper | 30.4 | 0.0027 | 0.0001 |
| Mercury | 0.3 | 0.0003 | 0.0010 |
| Nickel | 15.0 | 0.0068 | 0.0005 |
| Lead | 29.6 | 0.0068 | 0.0002 |
| Zinc | 68.8 | 0.0325 | 0.0005 |

[a] From results of elutriate test.

[b] Liquid phase:solid phase (mg/l:mg/kg).

Source: Bigham et al. (1982, pp. 292-294).

In the absence of detailed information on the partitioning of metals between the dissolved and particulate phases of drilling muds and cuttings, the metals partitioning characteristics of dredged material are used here to develop estimates of dissolved metals concentrations associated with drilling muds and cuttings. This is believed to be a reasonable approach because of the physical similarities of the two materials. Dredged materials are naturally-occurring sediments, sometimes contaminated, that are mechanically or hydraulically picked up and transported to another site for disposal. Dredged sediments are up to 80 percent water, and contain variable proportions of sand, silt, and clay size particles, with organic matter concentrations usually ranging from near 0 to 10 percent. The important similarity to drilling muds and cuttings is that the majority of the bulk metals are incorporated into the crystalline lattice of inorganic particles.

Table 10 presents concentrations of metals observed in the solid and dissolved fraction of samples of dredged material dumped at sea in 1978 and 1979 (Bigham et al., 1982, pp. 292-294). The data represent approximately 50 separate analyses of sediments from the East and Gulf Coasts. The data in Table 10 indicate that the partitioning varies from one metal to the next but, in general, the dissolved fraction in mg/l is approximately 0.1% of the solid fraction in mg/kg.

## Marine Water Quality Criteria

Table 11 summarizes the estimated maximum trace metal concentrations of the whole mud and the dissolved fraction and also lists the federal marine water quality criteria. Using the dissolved fraction concentrations, a minimum dilution of only 72:1 would be needed to comply with the federal 24-h saltwater criteria. State criteria for specific sites should also be considered. Therefore, it does not appear that dilution of the dissolved fraction of discharged drilling muds will be a limiting factor at the edge of the 100 m (328 ft) mixing zone.

TABLE 11. TRACE METAL CONCENTRATIONS OF THE WHOLE MUD AND DISSOLVED FRACTION AND FEDERAL MARINE WATER QUALITY STANDARDS

| Metal | Concentration | | Federal Saltwater Criteria[b] (ug/l) | |
|---|---|---|---|---|
| | Whole Mud (mg/kg) | Dissolved Fraction[a] (mg/l) | Maximum Allowable | 24-h Criteria |
| Arsenic | 24 | 0.024 | 508 | No criteria |
| Barium | 398,800 | 399 | No criteria | No criteria |
| Cadmium | 2.1 | 0.0021 | 59 | 4.5 |
| Chromium | 1,300 | 1.3 | 1,260 (hexavalent) | 18 (hexavalent) |
| Copper | 88 | 0.088 | 23 | 4.0 |
| Lead | 820 | 0.82 | 668 | 25[c] |
| Mercury | 1.53 | 0.00153 | 3.7 | 0.1 |
| Nickel | 88 | 0.088 | 140 | 7.1 |
| Vanadium | 235 | 0.235 | No criteria | No criteria |
| Zinc | 1,350 | 1.35 | 170 | 58 |

[a] Estimated as 0.001 times the whole mud concentration (see Table 10).

[b] From 45 Federal Register 79318.

[c] Chronic toxicity criteria.

## TOXICITY OF DRILLING MUDS

Section 125.123(d)(1) of the Ocean Discharge Criteria requires, if a determination regarding unreasonable degradation cannot be made, that the discharge must pass certain bioassay-based requirements. Although this requirement does not apply to all cases of ocean discharge of drilling mud and cuttings, the procedure may be applied to all cases as an approximate guideline and also provide a means of comparing potential impacts of exploratory drilling between different general permit areas.

The bioassay-based requirements are based upon the limiting permissible concentrations (LPC) concept of the Ocean Dumping Regulations. The application of the LPC concept to drilling mud discharges can be summarized as follows. The results of acute bioassay tests of various drilling muds provide a mud concentration which causes mortality to 50 percent of the organisms tested. This concentration, referred to as the $LC_{50}$ (lethal concentration), is also specific to the duration of the test which is commonly 96 hours. Bioassay tests applicable to Alaska marine organisms range from 48- to 144-h duration. Since the $LC_{50}$ is the point where half the test organisms died, the LPC value is obtained by applying a safety factor (0.01) to the $LC_{50}$ value[1]. In other words, the LPC value is one one-hundredth of the $LC_{50}$ and is designed to preclude both acute and chronic toxicity impacts.

The mixing zone extends 100 m (328 ft) in all directions from the discharge point[2]. The concentration of muds 100 m (328 ft) from the discharge is determined with an appropriate dispersion model or based upon results of field studies. This concentration should then be less than the specified guideline concentration.

Drilling muds are usually discharged intermittently in large quantities (roughly 1,000 bbl) when the mud system is changed, although small quantities may be discharged steadily with cuttings from solids control equipment

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[1]The regulations allow the use of other than 0.01 if applicable (40 Federal Register 65954 and 42 Federal Register 2481).
[2]The regulations allow that the mixing zone may be defined by the boundary of the zone of initial dilution as calculated by an approved plume model (40 Federal Register 65953).

(Ayers et al. 1980a). Large-scale discharges during mud change-over may occur at rates up to approximately 1,000 bbl/hr. It would appear, therefore, that measures of acute toxicity ($LC_{50}$) would be of greater concern for drilling mud discharges because exposure to drilling muds in the water column are not chronic (LPC) in the usual sense of the term. Therefore, a representative minimum $LC_{50}$ will be selected as the guideline for the allowable drilling mud solids concentration at 100 m (328 ft) from the discharge.

A variety of Alaskan marine organisms have been exposed to drilling mud in laboratory or field experiments. Most of these studies (Environmental Protection Service 1975; EG&G Marine Research Laboratory 1976; EG&G Bionomics 1976a, 1976b; Tornberg et al. 1980; Gerber et al. 1980; Houghton et al. 1980; Neff et al. 1980; Crawford and Gates 1981; Northern Technical Services 1981; Carls and Rice 1984) have addressed short-term acute effects in a "screening" sense in the laboratory. Carls and Rice (1984) obtained the lowest $LC_{50}$ values for an Alaskan species (600 ppm vol:vol for dock shrimp larvae, *Pandalus danae*), however, it is suspected that the mud was treated with a chromium-rich special additive that has since been reformulated to exclude chromium (Hulse, M., 1983, personal communication). The Carls and Rice (1984) $LC_{50}$ data may not represent those expected on the Alaskan outer continental shelf. More likely representative lowest $LC_{50}$ values are 1,100 mg/l (3,000 ppm vol:vol) noted for pink salmon fry, *Oncorhynchus gorbuscha*, by Houghton et al. (1980).

While the $LC_{50}$-type analysis is generally reasonable, some problems arise in its application to drilling mud discharges. First, the duration of high rate discharges is much less than the test period of the bioassay. Bulk discharges of mud generally do not exceed 1,000 bbl. At a discharge rate of 1,000 bbl/h, the period of discharge does not exceed 1 h. This period represents only from 2.1 to 0.7 percent of the bioassay period for Alaska organisms (48 to 144 h). It appears, therefore, that some adjustment should be made to the $LC_{50}$-type analysis to account for the difference in exposure time.

Unfortunately, no standard method is available to adjust an $LC_{50}$ value to reflect shorter exposure times. Results of most applicable bioassay tests do not report the mortalities observed at times less than the full duration of the test. Where these data are available, large differences occur between the exposure time-mortality relationship for different organisms. Thus, any adjustment to the $LC_{50}$-type analysis must be somewhat artificial and judgmental.

A second exposure time-related problem occurs with the $LC_{50}$ analysis. When concentrations of solids discharged from a fixed point are observed at another field point (100 m) downstream, the downstream concentration will be related to the current velocity. For a 2 cm/sec current, which may represent under-ice conditions in the Beaufort Sea, the time required to travel 100 m is 5,000 sec or 83 min. For a 10 cm/sec current, which may represent moderate-energy open water currents, the travel time decreases to 1,000 sec or 17 min. At high current velocities around 30 cm/sec which occur in Cook Inlet and elsewhere in Alaska, the travel time to 100 m is further reduced to 333 sec or 6 min. If these travel times are now compared to the exposure times used in the bioassays (48 to 144 h), the 100 m distance from the discharge appears extremely conservative for higher current regimes. Since impacts to water column organisms are related to exposure time, as indicated by bioassay tests, the regulatory procedure used to evaluate these impacts should also take exposure time into account. At the same time it should be realized that the mixing zone concept is still useful for purposes of impact analysis and monitoring purposes.

The $LC_{50}$ mixing zone concept could be very flexible if bioassay data were available for shorter exposure times. For example, an exposure time of one hour would be a closer, but still conservative, approximation of actual exposure times. In the absence of these bioassay data, the only remaining flexibility is in the size of the mixing zone and the safety factor. Therefore, using the minimum $LC_{50}$ for 48- to 144-h duration bioassays as a receiving water suspended solids guideline will result in a conservative value for typical drilling mud discharges of 1-h or less duration.

Based on the bioassay results discussed above (Alaskan species), the lowest representative $LC_{50}$ for generic muds is 1,100 mg/l. If the initial drilling mud solids concentration is conservatively assumed to be 1,441,000 mg/l (highest concentration used in the field studies summarized in Table 1), the 1,100 mg/l criteria may be represented as a minimum particulate dilution of approximately 1,300:1 at the edge of the 100 m (328 ft) mixing zone.

## BOTTOM DEPOSITION

No studies have been conducted to determine the magnitude or duration of solids accumulation on the seafloor that will adversely affect benthic biota. Table 12 summarizes the results of a few major field investigations on environmental fate and effects of drilling fluids and cuttings discharges. The results of most studies show that drilling solids accumulations generally occur within 1,000 m of the discharge site. Only two of the eight studies summarized showed some impact to benthic biota near the discharge site, however, impacts were observed only in a limited area. These studies support the following general conclusions:

- Solids accumulation is directly influenced by the oceanographic conditions at the drilling site and the quantity of material discharged. High energy environments tend to disperse drilling effluents over a large area and may resuspend or transport the solids out of the study area.

- Elevated levels of trace metals (especially barium) are commonly present in sediments near drilling rigs. However, there is no direct correlation between elevated levels of trace metals in sediments and impacts to the biota.

- Impacts on benthic biota are limited to areas directly adjacent to the discharge site.

TABLE 12. SUMMARY OF MAJOR FIELD INVESTIGATIONS OF THE ENVIRONMENTAL FATE AND EFFECTS OF DRILLING FLUIDS AND CUTTINGS DISCHARGED TO THE ENVIRONMENT

| Location | Objectives | Physical Characteristics | Results | References |
|---|---|---|---|---|
| East Flower Garden Bank, NW Gulf of Mexico | Fate of drilling fluids shunted to 10 m above bottom; effects on coral reef 2,100 m away | Drilling at 129 m water depth; coral zone at 20-50 m and NW of drill site; bottom currents toward WSW drill site | Drill fluids and cuttings distributed to 1,000 m from discharge | Gettleson (1978) |
| Palawan Island, Philippines | Effects of drilling discharges on coral reefs | Drilling directly on reef at 26 m; two wells drilled 3 m apart; 3 cm/sec currents to the north | 70-90 percent reduction in some species of living corals within 115 by 85 m area; epifauna associated with corals affected to 40 m; no drill cuttings pile. Cuttings present within 20 m of the wells. | Hudson et al. (1982) |
| Lower Cook Inlet, AK | Fate of drilling discharges and effects on benthic communities | Drilling at 62 m water depth, 4.6-5.3 m tides, mean maximal tide currents 42-104 cm/sec between bottom and surface. Discharge rate varied from 20 to 1,200 bbl/h. | Little accumulation of mud and cuttings on bottom; no effects on benthos attributable to discharges; cuttings deposition rate ranged from $5.24 \times 10^3$ to $3.2 \times 10^{-2}$ $g/h/m^2$ with distance from discharge. | Dames & Moore (1978)<br>Houghton et al. (1980)<br>Lees and Houghton (1980) |
| Mid-Atlantic OCS | Fate of drilling discharges; effects on benthic community; bioaccumulation of metals | Drilling at 120 m water depth; bottom currents < 10 cm/sec 62 percent of time, sediments 20 percent silt/clay. Discharge rates were 275 and 500 bbl/h. | Visible cuttings piles within 100 m elevated Ba in sediments to 1.6 km; abundance of predatory demersal spp. increased; large decrease in abundance of benthic infauna near rig with some bioaccumulation of Ba and possibly Cr by benthic infauna. | EG&G Environmental Consultants (1982) |
| Georges Bank, North-Atlantic OCS | Fate of drilling discharges; effects on benthic community; bioaccumulation of metals | Rigs at 80 and 140 m monitored; residual bottom current 3.5 cm/sec. Frequent severe storms; sediments < 1 percent silt/clay | Evidence of cuttings within 500 m of rigs; elevated Ba in bulk sediments to 2 km; no effects on benthos attributable to drilling; no bioaccumulation. | Battelle/W.H.O.I. (1983)<br>Bothner et al. (1983)<br>Payne et al. (1982) |
| U.S. Beaufort Sea, AK | Effects of above-ice and below-ice disposal of drilling mud and cuttings on benthic communities; bioavailability of metals | Water depth 5-8 m; ice cover most of year with bottom scour in shallower areas. Near-bottom currents were 4 to 5 cm/sec. Discharge rates were 1,510 and 21 bbl/h. | 0.5-6 cm fluid and cuttings on bottom but carried away quickly; no effects attributable to discharges on benthos; possible uptake of Ba by macroalgae and Cu by amphipods; maximum deposition of 173 $mg/cm^2$ at 6 m from the discharge. Little deposition at distances greater than 30 m from the discharge. | Northern Technical Services (1981) |
| Canadian Beaufort Sea | Metals from drilling discharges in sediments and benthos | Drilling from artificial island; rapid seasonal erosion ad ice scour | Elevated levels of Hg, Pb, Zn, Cd, As, and Cr in sediments near discharge (within 45 m) with elevated Hg to 1,800 m; no correlation between metals in sediments and biota; coarse grained material from island observed out to 300 m. | Crippen et al. (1980) |
| Central Gulf of Mexico | Distribution of metals in sediments and biota in oil production fields | Shallow water, high suspended sediment load. Study sites located in less than 18 to 92 m depth. Current velocities ranged from 0 to 20 cm/sec. Discharge rates varied from 275 to 1,000 bbl/h. | Decreasing concentration gradients of Ba, Cd, Cr, Cu, Pb, and Zn in sediments around some rigs. Metals not elevated in commercial species of shrimp and fish. | Tillery and Thomas (1980) |

## SUMMARY OF OOC MODEL RESULTS

Minimum solids dilutions at 100 m (328 ft) from the discharge as predicted by the OOC model are summarized in Table 13 for each case. Results of OOC model runs discussed in this report showed that the density stratification considered did not significantly affect dilution. Particulate dilution was shown to increase as discharge rate or current velocity decreased. The relationship between particulate dilution and water depth was not as clear. In waters shallower than 20 m (66 ft), particulate dilution generally increased as water depth decreased. However, in water 40 to 70 m (131 to 230 ft) deep, the opposite is true. This indicates that care should be taken when using the OOC model predictions for shallow water. The model cannot accurately simulate discharges to shallow, low velocity waters where the plume descends vertically and encounters the bottom.

## EPA MODEL RESULTS

Results of EPA model simulations are shown in Figure 17 for a 10 cm/sec (0.33 ft/sec) ambient current speed and Figure 18 for a 2 cm/sec (0.07 ft/sec) ambient current speed, for water depths from 2 to 20 m (7 to 66 ft), and discharge rates (Q) from 250 to 1,000 bbl/h. These results show that the depth-averaged solids dilution increases linearly as water depth increases. Solids dilution [at 100 m (328 ft)] generally increases as discharge rate decreases or current velocity increases [except for the highest discharge rate (1,000 bbl/h) case. The EPA model gives much lower solids dilutions (more conservative) than those predicted by the OOC model for comparable cases (see Table 14).

## EFFECTS OF ICE COVER ON DRILLING MUD DILUTION

The presence of ice cover generally affects drilling mud dilution and solids deposition by eliminating wind-driven current velocities and decreasing the total water depth available for dilution. Currents and circulation should not be altered substantially by the presence of drift ice. However, the presence of pack ice will eliminate wind driven circulation

TABLE 13. SUMMARY OF MINIMUM SOLIDS DILUTIONS PREDICTED BY THE OOC MODEL AT 100 m (328 ft) FROM THE DISCHARGE[a]

| Case Number | Water Depth (m) | Discharge Rate (bbl/h) | Surface Current (cm/sec)[b] | Density Stratification, $\Delta\sigma_t$ (Bottom to Surface) | Minimum Solids Dilution at 100 m (328 ft) | Comments |
|---|---|---|---|---|---|---|
| 1 | 40 | 1,000 | 2 | 3.9 | 2,015[c] | Predilution 9:1[d] |
| 2 | 40 | 1,000 | 10 | 3.9 | 532[e] | Predilution 9:1[d] |
| 3 | 40 | 1,000 | 10 | 3.9 | 905 | |
| 4 | 40 | 100 | 10 | 3.9 | 5,246 | |
| 5 | 5 | 1,000 | 10 | 0.1 | 4,810 | |
| 6 | 10 | 1,000 | 10 | 0.7 | 1,785 | |
| 7 | 10 | 1,000 | 10 | 0.7 | 360[f] | Predilution 9:1[d] |
| 8 | 10 | 100 | 10 | 0.7 | 3,859 | |
| 9 | 10 | 1,000 | 10 | 0.7 | 299 | Mud bulk density = 9 lb/gal |
| 10 | 15 | 1,000 | 2 | 1.07 | 11,407 | |
| 11 | 15 | 1,000 | 10 | 1.07 | 1,748 | |
| 12 | 15 | 1,000 | 30 | 1.07 | 752 | |
| 13 | 20 | 1,000 | 10 | 1.00 | 1,092 | |
| 14 | 40 | 1,000 | 10 | 0.5 | 731 | Minimum stratification (40 m) |
| 15 | 70 | 1,000 | 10 | 2.5 | 1,803 | |
| 16 | 120 | 1,000 | 10 | 0.98 | 1,437 | |
| 17 | 120 | 1,000 | 32 | 1.30 | 5,793 | |
| 18 | 5 | 250 | 10 | 0.1 | 6,109 | |
| 19 | 15 | 250 | 2 | 1.07 | 8,873 | |
| 20 | 15 | 250 | 10 | 1.07 | 2,558 | |

[a] All cases use a 2.09 g/cm$^3$ (17.4 lb/gal) mud unless otherwise specified (initial solids concentration 1,441,000 mg/l).
[b] Uniform velocity distribution with depth was assumed, with a sharp decrease in velocity near the bottom.
[c] Dilution due to the receiving water only. Total dilution is 20,150:1.
[d] Nine parts water with 1 part mud.
[e] Dilution due to the receiving water only. Total dilution is 5,320:1.
[f] Dilution due to the receiving water only. Total dilution is 3,600:1.

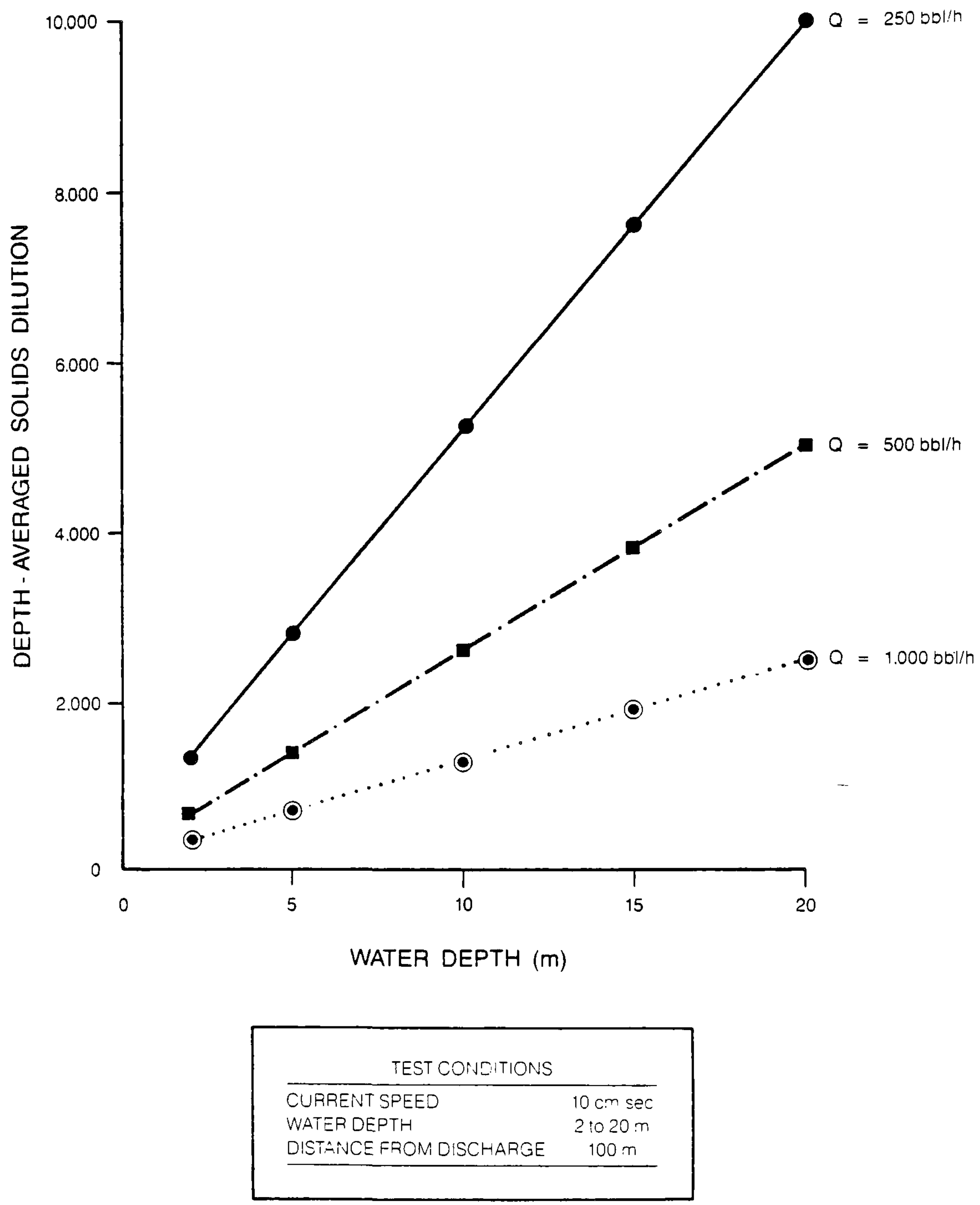


Figure 17. Depth-averaged solids dilution at 100 meters from discharge predicted by the EPA model for 10 cm/sec current speed.

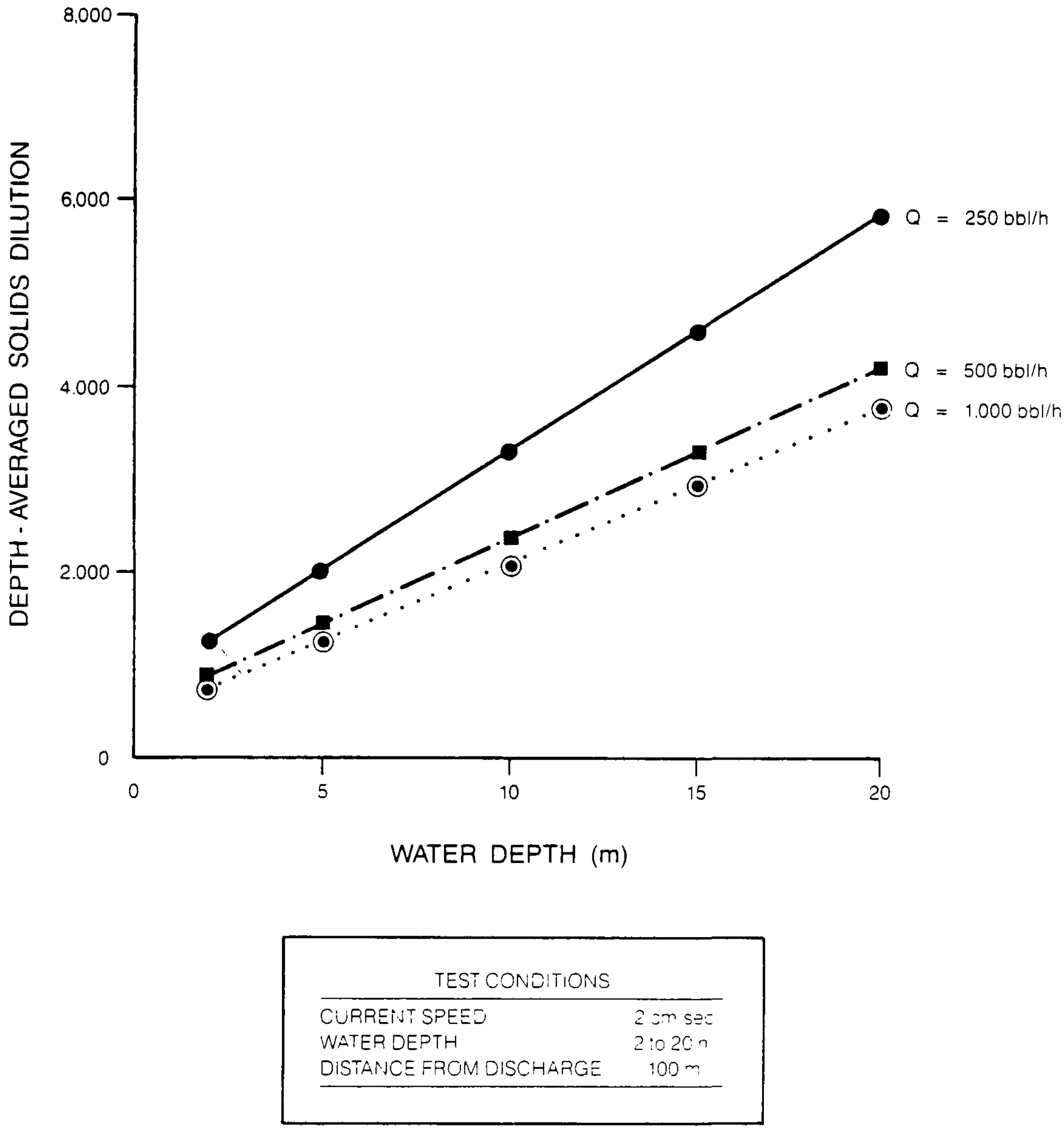


Figure 18. Depth-averaged solids dilution at 100 meters from discharge predicted by the EPA model for 2 cm/sec current speed.

TABLE 14. COMPARISON OF DEPTH-AVERAGED SOLIDS DILUTIONS AT 100 m (328 ft) FROM THE DISCHARGE FOR THE OOC AND EPA MODELS

| Water Depth (m) | Current Speed (cm/sec) | Discharge Rate (bbl/h) | Depth-Averaged Solids Dilution at 100 m (328 ft) from the Discharge EPA Model | OOC Model |
|---|---|---|---|---|
| 5 | 10 | 250 | 2,831 | 20,121 |
| 5 | 10 | 1,000 | 708 | 14,948 |
| 10 | 10 | 1,000 | 1,310 | 5,190 |
| 15 | 2 | 250 | 4,649 | 29,349 |
| 15 | 2 | 1,000 | 2,984 | 23,517 |
| 15 | 10 | 250 | 7,625 | 13,040 |
| 15 | 10 | 1,000 | 1,906 | 5,661 |
| 20 | 10 | 1,000 | 2,502 | 4,674 |

over ice covered areas and dampen wave activity. In addition, tidal currents may be reduced beneath ice cover. The frictional force of the ice cover on the water surface also acts to decrease current speeds. All of these effects will reduce circulation (current velocities) and result in decreased dispersion and increased near-field deposition of drilling mud discharges.

Available monitoring data from SOHIO's Mukluk Well No. 1 (SOHIO, 1984) were evaluated to determine current velocities under ice in Harrison Bay of the Beaufort Sea. Currents were monitored at a depth of approximately 12.2 m (40 ft) in 14.0 m (46 ft) of water from September 20, 1983, through February 16, 1984. Ice conditions varied throughout the monitoring period. By mid-October there were a few inches of ice cover and by the first of November there was a solid ice cover approximately 0.3 m (1 ft) thick. By January there was a 1.8 m (6 ft) thick layer of ice with ice ridges up to 6.1 m (20 ft) thick which lasted through June (Wagner, M., 8 August 1984, personal communication). Current velocities ranged from 1.5 to 39.7 cm/sec with monthly average speeds decreasing steadily from 11.9 cm/sec in September to 2.5 cm/sec in February. These data indicate that as the ice cover grew thicker and more stable, the current velocity decreased (see Figure 19), and that a current velocity of 2 cm/sec, as used in the modeling efforts, is representative of under-ice current velocities in shallow Alaskan waters.

Under these conditions (2 cm/sec current velocity), the EPA model predicted depth-averaged particulate dilutions at 100 m (328 ft) from the discharge point ranging from 741 to 3,812:1 for the maximum discharge rate (1,000 bbl/h) and water depths ranging from 2 to 20 m (7 to 66 ft) (see Figures 17 and 18). These dilutions are much lower than those predicted by the OOC model (Table 14), but the OOC model results are less reliable in shallow, low velocity waters.

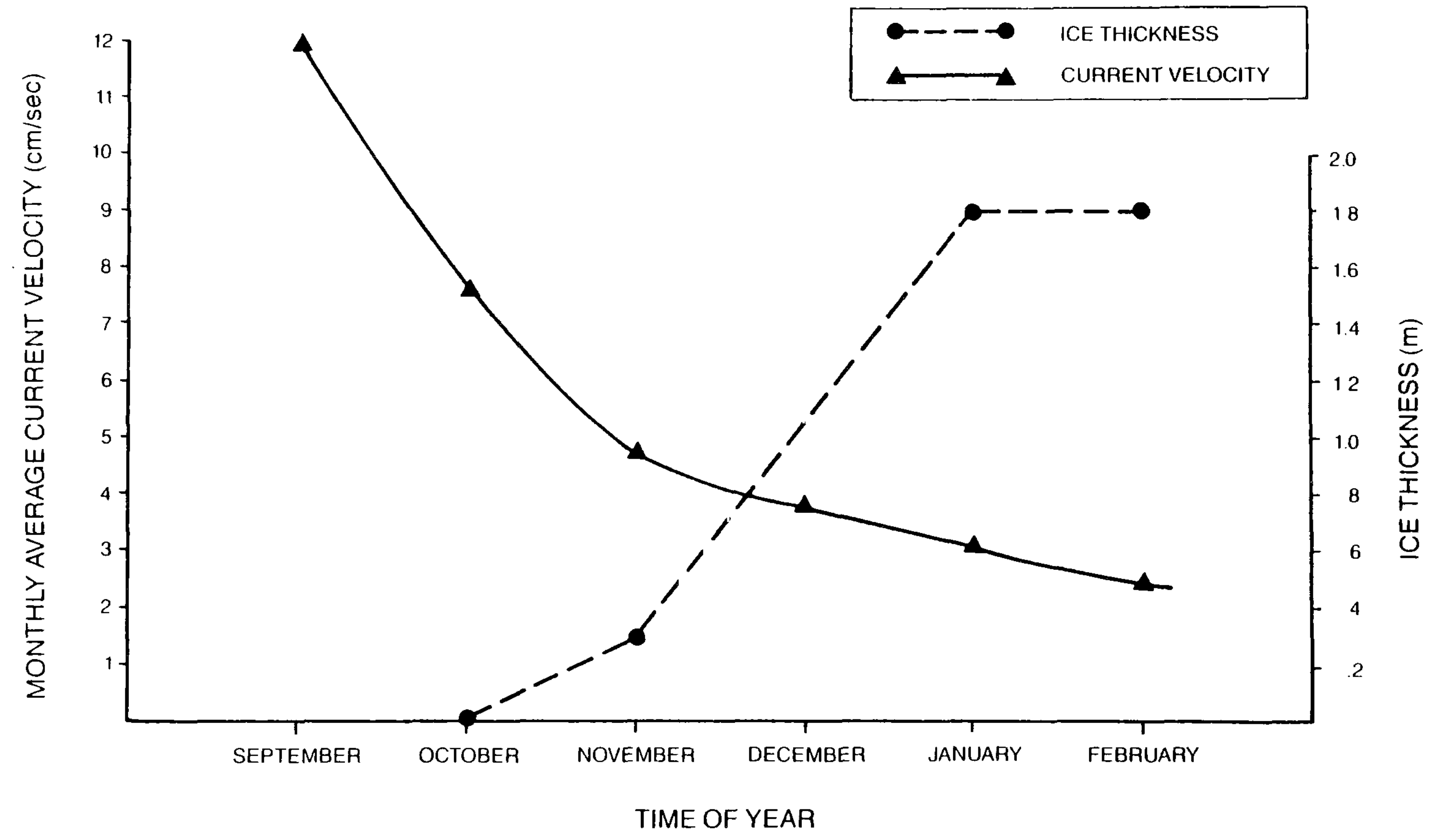


Figure 19. The relationship between ice cover, current velocity, and time of year.

# V. RECOMMENDATIONS

## RECOMMENDED DISCHARGE REGULATIONS

Data presented in this report indicated that varying the discharge rate significantly affected both the dissolved and particulate dilutions, but did not substantially affect the solids deposition area or thickness. Dissolved fraction dilution does not appear to be a limiting factor at the edge of the 100 m (328 ft) mixing zone. As discharge rate increased (in the range of 100 to 1,000 bbl/h), the dilution decreased. Therefore, specifying a maximum allowable discharge rate would ensure that the drilling effluent would undergo a minimum specified dilution (or not exceed a maximum specified receiving water concentration) at the edge of a mixing zone. Predilution of drilling muds involves mixing seawater with drilling mud prior to discharge to decrease the initial solids concentration. Results discussed in this report showed that for a given volume of mud discharged, predilution and lowering the discharge rate had a similar effect on dilution. Predilution (9:1) with a high discharge rate (1,000 bbl/h) and no predilution with a low discharge rate (100 bbl/h) both resulted in similar effluent dilutions with distance from the source. Therefore, there seems to be no practical advantage to predilution of drilling mud discharges and recommendations made in this report will be in terms of a maximum allowable discharge rate for a given water depth.

Maximum allowable discharge rates were determined using the results from the EPA model simulations (2 and 10 cm/sec current velocities) for water depths less than 20 m (66 ft) and the results from the OOC model simulations (10 cm/sec current velocity) for water depths from 20 to 120 m (66 to 394 ft). Neither model is applicable for water depths less than 2 m (6.6 ft). For shallow waters [less than 20 m (66 ft) deep], EPA model results (see Figures 17 and 18) indicate that particulate dilutions at

100 m (328 ft) from the source are less than the recommended 1,300:1 dilution for the following cases:

- A discharge rate of 1,000 bbl/h (or greater) and water depths between 2 and 5 m (6.6 and 16 ft).

- A discharge rate of 250 bbl/h (or greater) and a water depth of 2 m (6.6 ft).

For deeper waters [20 to 120 m (66 to 394 ft) deep], the OOC model results (see Table 13) indicate that particulate dilution at 100 m (328 ft) from the source are less than the recommended 1,300:1 dilution for the following case:

- A discharge rate of 1,000 bbl/h (or greater) and water depths between 20 and 40 m (66 to 131 ft).

Based on these results, a maximum discharge rate of 250 bbl/h is recommended for water depths from 2 to 5 m (7 to 16 ft). For water depths between 5 and 20 m (16 and 66 ft), the discharge rate should not exceed 500 bbl/h. The recommended maximum discharge rate for water depths from 20 to 40 m (66 to 131 ft) is 750 bbl/h. A maximum discharge rate of 1,000 bbl/h is recommended for water depths between 40 and 120 m (131 to 394 ft). The deepest case considered in this analysis was 120 m (394 ft).

Model results discussed in this report indicate that ambient current speed directly affects dilution of both the dissolved and particulate fractions of drilling mud discharges. The EPA model generally predicted higher solids dilutions in waters with higher current speeds (except for the 1,000 bbl/h discharge rate). The OOC model predicted lower dilutions in waters with higher current speeds. These results indicate that in shallow waters [less than 20 m (66 ft) deep], the recommended discharge rates could be increased as ambient current speed increased and still meet the recommended 1,300:1 dilution. Similarly, for deeper waters [20 to 120 m (66 to 394 ft) deep], the recommended discharge rates could be decreased as ambient current velocity increased. The degree to which these rates could be increased or decreased cannot be determined from the available data since changing the discharge rate will also affect dilution.

## OOC MODEL SIMULATIONS

The input variables of primary interest to the regulation of discharges (water depth, current velocity, and discharge rate) have been considered in this report. Many site specific input variables available in the OOC model format have not been evaluated. Future simulations using this model may incorporate these parameters to assess the effect of these variables on drilling mud dilution and solids deposition. Discharge characteristics of interest for future simulations include rig type (jackup versus semisubmersible), discharge nozzle radius and orientations, shunting of discharges, and use of denser (or finer) solids in the drilling mud (different particle size distributions). Oceanographic characteristics not evaluated in detail for this report include variation of density stratification profiles with time, sea-state conditions, change in water depth within the model grid, layered vertical current velocity distribution, and density stratification involving a strong gradient such as a pycnocline or thermocline. OOC model simulations incorporating these parameters will add to our understanding of the processes affecting drilling mud dilution and bottom deposition.

To augment the data gathered from the simulations presented in this report, it would be helpful to conduct more OOC model simulations using water depths between 15 and 70 m (49 and 230 ft) and discharge rates between 100 and 1,000 bbl/h. These runs will help fill in some of the information gaps and better define the water depth ranges and associated discharge rate limits. Simulations using water depths of several hundred meters will help define the potential for dilution of mud discharges in the deeper waters of many lease sale areas.

## FIELD STUDIES

Neither the OOC or EPA mud dispersion models have been adequately verified in the field. Several field data sets have been collected (see Table 1 and Appendix C and D) but none have provided information in adequate detail for meaningful model calibration. The OOC model is considered to provide reasonable results, but this opinion is based on the structure of the model and comparison of model results to laboratory data of Fan (1967), Koester (1976), and Davis (1983) (see MMS, 1983) and not on comparison to field data. Collection of an adequate data set and comparison to model results is strongly recommended to properly verify both models.

For Alaskan waters, model verification is most needed for shallow-water cases; from 2 to about 40 m (7 to 131 ft). In deeper waters, dilutions are generally large enough to alleviate concern. A verification study in waters between 10 and 20 m (33 to 66 ft) would probably be most practical and useful.

It is not necessary that the verification study be performed in Alaskan waters. In fact, from a logistical point of view, the chance of a field test being successful would be greater in Gulf of Mexico or California waters.

The field verification study should provide an approximate mass balance of drilling mud discharged under steady-state conditions and over distances between about 50 to about 200 m (164 to 656 ft) downcurrent of the discharge. The steady-state condition means that mud should still be discharging when the leading edge of the mud cloud reaches 200 m (656 ft) downcurrent of the discharge. If the average current speed were 10 cm/sec (0.33 ft/sec), plume sampling would commence following about 30 minutes of discharge. Mud discharge should continue at a constant rate throughout the sampling. Field data collection should allow for verification of predicted water column dilutions and bottom deposition.

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# APPENDIX A

## MINIMUM DILUTIONS AS PREDICTED BY THE OOC MODEL

TABLE A-1. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 1*

| Distance from Discharge (m) | (ft) | Minimum Dilution** Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 165 | 200 |
| 45.7 | 150 | 565 | 635 |
| 100.0 | 328 | 2,015 | 2,170 |
| 137.2 | 450 | 3,520 | 3,745 |
| 182.9 | 600 | 6,030 | 6,240 |
| 243.8 | 800 | 9,575 | 9,625 |
| 304.8 | 1,000 | 14,645 | 14,310 |
| 426.7 | 1,400 | 29,290 | 26,450 |

*MODEL INPUTS: Water Depth = 40 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 2 cm/sec
Forced Separation.

**Dilutions are due to receiving water only. To obtain total dilution (to include predilution) multiply all dilutions by 10.

TABLE A-2. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 2*

| Distance from Discharge (m) | (ft) | Minimum Dilution** Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 190 | 262 |
| 45.7 | 150 | 337 | 383 |
| 100.0 | 328 | 532 | 726 |
| 137.2 | 450 | 973 | 1,041 |
| 182.9 | 600 | 1,014 | 1,311 |
| 304.8 | 1,000 | 1,566 | 2,045 |
| 609.6 | 2,000 | 4,008 | 4,810 |
| 914.4 | 3,000 | 7,307 | 7,294 |

*MODEL INPUTS: Water Depth = 40 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 10 cm/sec
Forced Separation.

**Dilutions are due to receiving water only. To obtain total dilution (to include predilution) multiply all dilutions by 10.

TABLE A-3. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 3*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 417 | 185 |
| 45.7 | 150 | 654 | 679 |
| 100.0 | 328 | 905 | 1,285 |
| 137.2 | 450 | 1,176 | 1,672 |
| 182.9 | 600 | 1,469 | 1,949 |
| 304.8 | 1,000 | 2,689 | 3,180 |
| 609.6 | 2,000 | 13,528 | 12,557 |
| 914.4 | 3,000 | 18,098 | 10,992 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-4. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 4*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 1,642 | 1,911 |
| 45.7 | 150 | 2,950 | 4,177 |
| 100.0 | 328 | 5,246 | 7,423 |
| 137.2 | 450 | 7,869 | 10,503 |
| 182.9 | 600 | 8,577 | 9,610 |
| 304.8 | 1,000 | 14,472 | 15,997 |
| 609.6 | 2,000 | 42,445 | 37,685 |
| 914.4 | 3,000 | 79,525 | 59,393 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 100 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-5. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 5*

| Distance from Discharge (m) | Distance from Discharge (ft) | Minimum Dilution Particulate | Minimum Dilution Dissolved |
|---|---|---|---|
| 15.2 | 50 | 120 | 39 |
| 30.5 | 100 | 215 | 141 |
| 61.0 | 200 | 571 | 152 |
| 100.0 | 328 | 4,810 | 200 |
| 137.2 | 450 | 12,566 | 290 |
| 182.9 | 600 | 15,711 | 421 |
| 243.8 | 800 | 27,664 | 617 |
| 304.8 | 1,000 | 34,131 | 789 |
| 457.2 | 1,500 | 69,379 | 1,425 |
| 609.6 | 2,000 | 107,537 | 1,957 |

*MODEL INPUTS: Water Depth = 5 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-6. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 6*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 163 | 52 |
| 45.7 | 150 | 391 | 318 |
| 100.0 | 328 | 1,785 | 536 |
| 137.2 | 450 | 3,445 | 755 |
| 182.9 | 600 | 3,964 | 848 |
| 304.8 | 1,000 | 14,059 | 1,445 |
| 609.6 | 2,000 | 78,486 | 6,803 |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-7. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 7*

| Distance from Discharge (m) | (ft) | Minimum Dilution** Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 71 | 110 |
| 45.7 | 150 | 193 | 176 |
| 100.0 | 328 | 360 | 267 |
| 137.2 | 450 | 678 | 340 |
| 182.9 | 600 | 823 | 437 |
| 304.8 | 1,000 | 1,919 | 723 |
| 609.6 | 2,000 | 9,279 | 1,708 |
| 914.4 | 3,000 | 30,530 | 2,556 |

*MODEL INPUTS: Water Depth = 10 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 10 cm/sec
Forced Separation.

**Dilutions are due to receiving water only. To obtain total dilution (to include predilution) multiply all dilutions by 10.

TABLE A-8. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 8*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 685 | 196 |
| 45.7 | 150 | 1,871 | 2,674 |
| 100.0 | 328 | 3,859 | 4,049 |
| 137.2 | 450 | 6,535 | 5,181 |
| 182.9 | 600 | 9,152 | 6,623 |
| 304.8 | 1,000 | 21,880 | 10,989 |
| 609.6 | 2,000 | 113,554 | 26,302 |
| 914.4 | 3,000 | 354,054 | 39,017 |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 100 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-9. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 9*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 66 | 68 |
| 45.7 | 150 | 230 | 110 |
| 100.0 | 328 | 299 | 168 |
| 137.2 | 450 | 471 | 238 |
| 182.9 | 600 | 808 | 290 |
| 304.8 | 1,000 | 1,994 | 518 |
| 609.6 | 2,000 | 10,809 | 2,483 |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Bulk Mud Density = 9 lb/gal
Initial Solids Concentration = 106,900 mg/l
Forced Separation.

TABLE A-10. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 10*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 67 | 61 |
| 30.5 | 100 | 559 | 127 |
| 61.0 | 200 | 3,405 | 478 |
| 100.0 | 328 | 11,407 | 1,218 |
| 137.2 | 450 | 20,247 | 1,930 |
| 182.9 | 600 | 36,288 | 3,612 |
| 243.8 | 800 | 60,142 | 5,826 |
| 304.8 | 1,000 | 90,175 | 8,547 |
| 365.8 | 1,200 | 131,478 | 11,787 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 2 cm/sec
Forced Separation.

TABLE A-11. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 11*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 150 | 72 |
| 30.5 | 100 | 197 | 280 |
| 61.0 | 200 | 437 | 371 |
| 100.0 | 328 | 1,748 | 526 |
| 137.2 | 450 | 3,521 | 875 |
| 182.9 | 600 | 4,595 | 853 |
| 243.8 | 800 | 7,741 | 1,209 |
| 304.8 | 1,000 | 10,933 | 1,460 |
| 365.8 | 1,200 | 14,494 | 1,905 |
| 426.7 | 1,400 | 20,875 | 2,179 |
| 548.7 | 1,800 | 32,058 | 3,120 |
| 609.6 | 2,000 | 40,868 | 3,458 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-12. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 12*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 186 | 68 |
| 30.5 | 100 | 268 | 147 |
| 61.0 | 200 | 535 | -- |
| 100.0 | 328 | 752 | 903 |
| 137.2 | 450 | 1,007 | 1,003 |
| 182.9 | 600 | 2,053 | 1,142 |
| 243.8 | 800 | 3,979 | 1,351 |
| 304.8 | 1,000 | 6,806 | 1,484 |
| 365.8 | 1,200 | 9,461 | 1,869 |
| 426.7 | 1,400 | 10,264 | 1,934 |
| 548.7 | 1,800 | 12,608 | 2,439 |
| 609.6 | 2,000 | 18,817 | 2,688 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 30 cm/sec
Forced Separation.

TABLE A-13. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 13*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 115 | 43 |
| 45.7 | 150 | 513 | 682 |
| 100.0 | 328 | 1,092 | 1,082 |
| 137.2 | 450 | 3,289 | 1,458 |
| 182.9 | 600 | -- | 1,587 |
| 304.8 | 1,000 | 8,215 | 2,571 |
| 609.6 | 2,000 | 40,937 | 10,870 |
| 914.4 | 3,000 | 99,379 | -- |

*MODEL INPUTS: Water Depth = 20 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-14. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 14*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 333 | 202 |
| 45.7 | 150 | 345 | 797 |
| 100.0 | 328 | 731 | 1,186 |
| 137.2 | 450 | 1,225 | 1,548 |
| 182.9 | 600 | 1,618 | 1,835 |
| 304.8 | 1,000 | 3,312 | 2,980 |
| 609.6 | 2,000 | 19,497 | 13,580 |
| 914.4 | 3,000 | 19,071 | 10,412 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Minimal stratification [$\Delta\sigma_t$(bottom to surface)] = 0.5.
Forced Separation

TABLE A-15. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 15*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 972 | 1,547 |
| 45.7 | 150 | 1,305 | 2,073 |
| 100.0 | 328 | 1,803 | 2,702 |
| 304.8 | 1,000 | 2,511 | 3,625 |
| 609.6 | 2,000 | 11,217 | 15,593 |
| 914.4 | 3,000 | 11,697 | 14,626 |

*MODEL INPUTS: Water Depth = 70 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-16. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 16*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 100.0 | 328 | 1,437 | 2,503 |
| 137.2 | 450 | 1,695 | 2,700 |
| 182.9 | 600 | 2,397 | 3,567 |
| 304.8 | 1,000 | 5,443 | 7,289 |
| 426.7 | 1,400 | 10,892 | 13,567 |
| 548.6 | 1,800 | 16,510 | 18,788 |
| 609.6 | 2,000 | 23,325 | 25,714 |

*MODEL INPUTS: Water Depth = 120 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-17. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 17*

| Distance from Discharge | | Minimum Dilution | |
|---|---|---|---|
| (m) | (ft) | Particulate | Dissolved |
| 30.5 | 100 | 2,002 | 2,859 |
| 61.0 | 200 | 4,189 | 6,671 |
| 100.0 | 328 | 5,793 | 9,127 |
| 201.2 | 660 | 10,673 | 16,661 |
| 411.5 | 1,350 | 17,130 | 26,803 |
| 1,219.2 | 4,000 | 23,504 | 37,636 |
| 1,609.4 | 5,280 | 30,178 | 43,889 |
| 2,414.0 | 7,920 | 107,058 | 112,514 |

*MODEL INPUTS: Water Depth = 120 m
Discharge Rate = 1,000 bbl/h
Surface Current = 32 cm/sec
Forced Separation.

TABLE A-18. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 18*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 149 | 55 |
| 30.5 | 100 | 1,540 | 152 |
| 61.0 | 200 | 1,873 | 613 |
| 100.0 | 328 | 6,109 | 1,040 |
| 137.2 | 450 | 19.418 | 1,435 |
| 182.9 | 600 | 20,854 | 2,101 |
| 243.8 | 800 | 50,704 | 3,030 |
| 304.8 | 1,000 | 52,286 | 3,817 |

*MODEL INPUTS: Water Depth = 5 m
Discharge Rate = 250 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

TABLE A-19. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 19*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 345 | 188 |
| 30.5 | 100 | 876 | 430 |
| 61.0 | 200 | 3,333 | 1,073 |
| 100.0 | 328 | 8,873 | 2,239 |
| 137.2 | 450 | 16,347 | 3,293 |
| 182.9 | 600 | 27,448 | 4,608 |
| 213.4 | 700 | 38,213 | 5,798 |
| 243.8 | 800 | 50,122 | 6,672 |
| 274.3 | 900 | 64,330 | 8,021 |
| 304.8 | 1,000 | 83,585 | 9,415 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 250 bbl/h
Surface Current = 2 cm/sec
Forced Separation.

TABLE A-20. MINIMUM SOLIDS AND DISSOLVED FRACTION DILUTIONS PREDICTED BY THE OOC MODEL FOR CASE 20*

| Distance from Discharge (m) | (ft) | Minimum Dilution Particulate | Dissolved |
|---|---|---|---|
| 15.2 | 50 | 492 | 157 |
| 30.5 | 100 | 1,398 | 468 |
| 61.0 | 200 | 1,544 | 1,416 |
| 100.0 | 328 | 2,558 | 2,538 |
| 137.2 | 450 | 4,447 | 3,115 |
| 182.9 | 600 | 5,259 | 3,846 |
| 243.8 | 800 | 9,282 | 4,926 |
| 304.8 | 1,000 | 13,136 | 6,098 |
| 365.8 | 1,200 | 18,406 | 7,246 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 250 bbl/h
Surface Current = 10 cm/sec
Forced Separation.

# APPENDIX B

## SOLIDS DEPOSITION AS PREDICTED BY THE OOC MODEL

TABLE B-1. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 1*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 4,482 | 0.180 | 63 |
| 61.0 | 200 | 1,113 | 0.045 | 78 |
| 91.4 | 300 | 395 | 0.016 | 84 |
| 121.9 | 400 | 195 | 0.008 | 86 |
| 152.4 | 500 | 127 | 0.005 | 88 |
| 182.9 | 600 | 132 | 0.005 | 90 |
| 213.4 | 700 | 112 | 0.004 | 92 |
| 243.8 | 800 | 103 | 0.004 | 93 |
| 274.3 | 900 | 93 | 0.004 | 94 |
| 304.8 | 1,000 | 83 | 0.003 | 95 |
| 335.3 | 1,100 | 73 | 0.003 | 96 |
| 365.8 | 1,200 | 68 | 0.003 | 97 |
| 396.2 | 1,300 | 59 | 0.002 | 98 |
| 426.7 | 1,400 | 45 | 0.002 | 99 |
| 457.2 | 1,500 | 32 | 0.001 | 99 |

*MODEL INPUTS: Water Depth = 40 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 2 cm/sec
Total Solids Discharge = 22,907 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 24,000 sec (400 min).

TABLE B-2. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 2*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 1,343 | 0.054 | 57 |
| 61.0 | 200 | 33 | 0.001 | 59 |
| 91.4 | 300 | 54 | 0.002 | 61 |
| 121.9 | 400 | 137 | 0.005 | 67 |
| 152.4 | 500 | 83 | 0.003 | 70 |
| 182.9 | 600 | 78 | 0.003 | 74 |
| 213.4 | 700 | 59 | 0.002 | 76 |
| 243.8 | 800 | 63 | 0.003 | 79 |
| 274.3 | 900 | 63 | 0.003 | 82 |
| 304.8 | 1,000 | 73 | 0.003 | 85 |
| 365.8 | 1,200 | 98 | 0.003 | 92 |
| 426.7 | 1,400 | 41 | 0.002 | 96 |
| 487.7 | 1,600 | 19 | 0.001 | 98 |
| 548.6 | 1,800 | 18 | 0.001 | ∿100 |
| 609.6 | 2,000 | 16 | 0.001 | |

*MODEL INPUTS: Water Depth = 40 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 10 cm/sec
Total Solids Discharge = 22,925 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-3. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 3*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 15.2 | 0.609 | 20 |
| 61.0 | 200 | 21.9 | 0.877 | 49 |
| 91.4 | 300 | 13.4 | 0.535 | 67 |
| 121.9 | 400 | 9.9 | 0.398 | 80 |
| 152.4 | 500 | 3.8 | 0.150 | 85 |
| 182.9 | 600 | 2.7 | 0.109 | 89 |
| 213.4 | 700 | 1.6 | 0.062 | 91 |
| 243.8 | 800 | 1.1 | 0.045 | 92 |
| 274.3 | 900 | 0.8 | 0.033 | 93 |
| 304.8 | 1,000 | 0.6 | 0.023 | 94 |
| 365.8 | 1,200 | 0.4 | 0.015 | 95 |
| 426.7 | 1,400 | 0.4 | 0.015 | 96 |
| 487.7 | 1,600 | 0.3 | 0.012 | 97 |
| 548.6 | 1,800 | 0.3 | 0.011 | 98 |
| 609.6 | 2,000 | 0.2 | 0.009 | 99 |
| 670.6 | 2,200 | 0.2 | 0.007 | 99 |
| 731.5 | 2,400 | 0.2 | 0.006 | 99 |
| 762.0 | 2,500 | 0.1 | 0.006 | ∿100 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,621 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-4. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 4*

| Distance from Discharge (m) | (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 1,546 | 0.062 | 58 |
| 61.0 | 200 | 132 | 0.005 | 63 |
| 91.4 | 300 | 59 | 0.002 | 65 |
| 121.9 | 400 | 54 | 0.002 | 67 |
| 152.4 | 500 | 112 | 0.004 | 71 |
| 182.9 | 600 | 98 | 0.004 | 75 |
| 213.4 | 700 | 63 | 0.003 | 77 |
| 243.8 | 800 | 32 | 0.001 | 79 |
| 274.3 | 900 | 43 | 0.002 | 80 |
| 304.8 | 1,000 | 59 | 0.002 | 82 |
| 335.3 | 1,100 | 132 | 0.005 | 87 |
| 365.8 | 1,200 | 88 | 0.004 | 91 |
| 396.2 | 1,300 | 48 | 0.002 | 92 |
| 426.7 | 1,400 | 22 | 0.001 | 93 |
| 457.2 | 1,500 | 12 | ~0.000 | 94 |
| 487.7 | 1,600 | 12 | | 94 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 100 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 22,927 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-5. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 5*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 439.00 | 17.600 | 90 |
| 30.5 | 100 | 27.00 | 1.100 | 95 |
| 45.7 | 150 | 7.80 | 0.312 | 97 |
| 61.0 | 200 | 6.10 | 0.242 | 98 |
| 76.2 | 250 | 5.50 | 0.219 | 99 |
| 91.4 | 300 | 1.30 | 0.051 | 99 |
| 106.7 | 350 | 0.60 | 0.023 | ∿100 |
| 121.9 | 400 | 0.50 | 0.019 | |
| 137.2 | 450 | 0.30 | 0.012 | |
| 152.4 | 500 | 0.30 | 0.011 | |
| 182.9 | 600 | 0.06 | 0.002 | |
| 213.4 | 700 | 0.08 | 0.003 | |
| 243.8 | 800 | 0.04 | 0.002 | |
| 274.3 | 900 | 0.04 | 0.002 | |
| 304.8 | 1,000 | 0.02 | 0.001 | |

*MODEL INPUTS: Water Depth = 5 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,586 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-6. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 6*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 168.0 | 6.70 | 36 |
| 30.5 | 100 | 254.0 | 10.20 | 90 |
| 45.7 | 150 | 21.0 | 0.86 | 95 |
| 61.0 | 200 | 6.6 | 0.27 | 96 |
| 76.2 | 250 | 3.9 | 0.16 | 97 |
| 91.4 | 300 | 2.7 | 0.11 | 97 |
| 106.7 | 350 | 2.7 | 0.11 | 98 |
| 121.9 | 400 | 2.7 | 0.11 | 99 |
| 137.2 | 450 | 2.2 | 0.09 | 99 |
| 152.4 | 500 | 1.3 | 0.05 | 99 |
| 167.6 | 550 | 1.0 | 0.04 | ∿100 |
| 182.9 | 600 | 0.5 | 0.02 | |
| 198.1 | 650 | 0.2 | 0.01 | |
| 213.4 | 700 | 0.1 | 0.01 | |
| 228.6 | 750 | 0.1 | ∿0.00 | |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,567 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 8,000 sec (133 min).

TABLE B-7. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 7*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 27.0 | 1.078 | 31 |
| 30.5 | 100 | 26.0 | 1.031 | 60 |
| 45.7 | 150 | 8.6 | 0.344 | 70 |
| 61.0 | 200 | 13.0 | 0.508 | 84 |
| 76.2 | 250 | 5.1 | 0.203 | 90 |
| 91.4 | 300 | 1.4 | 0.057 | 92 |
| 106.7 | 350 | 0.9 | 0.035 | 93 |
| 121.9 | 400 | 0.9 | 0.035 | 94 |
| 137.2 | 450 | 0.9 | 0.034 | 95 |
| 152.4 | 500 | 0.8 | 0.032 | 96 |
| 182.9 | 600 | 0.2 | 0.009 | 97 |
| 213.4 | 700 | 0.2 | 0.008 | 97 |
| 243.8 | 800 | 0.2 | 0.009 | 98 |
| 274.3 | 900 | 0.2 | 0.006 | 98 |
| 304.8 | 1,000 | 0.1 | 0.004 | 98 |

*MODEL INPUTS: Water Depth = 10 m
Total Discharge Rate = 1,000 bbl/h
Mud Discharge Rate = 100 bbl/h
Predilution 9:1
Surface Current = 10 cm/sec
Total Solids Discharge = 22,898 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-8. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 8*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 28.0 | 1.140 | 32 |
| 30.5 | 100 | 27.0 | 1.078 | 63 |
| 45.7 | 150 | 14.0 | 0.570 | 79 |
| 61.0 | 200 | 8.2 | 0.328 | 88 |
| 76.2 | 250 | 3.1 | 0.125 | 92 |
| 91.4 | 300 | 0.9 | 0.037 | 93 |
| 106.7 | 350 | 1.1 | 0.042 | 94 |
| 121.9 | 400 | 0.9 | 0.035 | 95 |
| 137.2 | 450 | 0.8 | 0.031 | 96 |
| 152.4 | 500 | 0.7 | 0.027 | 96 |
| 182.9 | 600 | 0.2 | 0.009 | 97 |
| 213.4 | 700 | 0.2 | 0.008 | 98 |
| 243.8 | 800 | 0.2 | 0.007 | 98 |
| 274.3 | 900 | 0.1 | 0.005 | 98 |
| 304.8 | 1,000 | 0.1 | 0.005 | 99 |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 100 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 22,901 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-9. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 9*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 8.10 | 0.323 | 25 |
| 30.5 | 100 | 10.40 | 0.417 | 58 |
| 45.7 | 150 | 4.20 | 0.166 | 71 |
| 61.0 | 200 | 1.70 | 0.066 | 77 |
| 76.2 | 250 | 1.40 | 0.055 | 81 |
| 91.4 | 300 | 1.60 | 0.064 | 86 |
| 106.7 | 350 | 1.40 | 0.057 | 90 |
| 121.9 | 400 | 0.60 | 0.025 | 92 |
| 137.2 | 450 | 0.30 | 0.012 | 93 |
| 152.4 | 500 | 0.10 | 0.005 | 94 |
| 182.9 | 600 | 0.10 | 0.005 | 95 |
| 213.4 | 700 | 0.10 | 0.006 | 96 |
| 243.8 | 800 | 0.09 | 0.004 | 96 |
| 274.3 | 900 | 0.08 | 0.003 | 97 |
| 304.8 | 1,000 | 0.10 | 0.004 | 97 |

*MODEL INPUTS: Water Depth = 10 m
Discharge Rate = 1,000 bbl/h
Bulk Mud Density = 9 lb/gal
Surface Current = 10 cm/sec
Total Solids Discharge = 8,505 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 8,000 sec (133 min).

TABLE B-10. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 10*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 129.00 | 5.200 | 34 |
| 30.5 | 100 | 221.00 | 8.800 | 92 |
| 45.7 | 150 | 25.00 | 1.000 | 99 |
| 61.0 | 200 | 1.10 | 0.044 | 99 |
| 76.2 | 250 | 0.40 | 0.016 | 99 |
| 91.4 | 300 | 0.30 | 0.012 | ∿100 |
| 106.7 | 350 | 0.20 | 0.008 | |
| 121.9 | 400 | 0.20 | 0.008 | |
| 137.2 | 450 | 0.20 | 0.008 | |
| 152.4 | 500 | 0.10 | 0.004 | |
| 182.9 | 600 | 0.10 | 0.004 | |
| 213.4 | 700 | 0.10 | 0.004 | |
| 243.8 | 800 | 0.08 | 0.003 | |
| 274.3 | 900 | 0.06 | 0.002 | |
| 304.8 | 1,000 | 0.06 | 0.002 | |
| 335.3 | 1,100 | 0.04 | 0.002 | |
| 365.8 | 1,200 | 0.02 | 0.001 | |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 2 cm/sec
Total Solids Discharge = 114,433 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 20,000 sec (333 min).

TABLE B-11. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 11*

| Distance from Discharge (m) | (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 76.0 | 3.031 | 20 |
| 30.5 | 100 | 159.0 | 6.358 | 62 |
| 45.7 | 150 | 105.0 | 4.218 | 90 |
| 61.0 | 200 | 15.0 | 0.568 | 93 |
| 76.2 | 250 | 5.1 | 0.203 | 95 |
| 91.4 | 300 | 7.4 | 0.297 | 97 |
| 106.7 | 350 | 5.1 | 0.203 | 98 |
| 121.9 | 400 | 2.0 | 0.078 | 99 |
| 137.2 | 450 | 0.8 | 0.033 | 99 |
| 152.4 | 500 | 0.4 | 0.017 | 99 |
| 182.9 | 600 | 0.3 | 0.011 | 99 |
| 213.4 | 700 | 0.2 | 0.007 | 99 |
| 243.8 | 800 | 0.1 | 0.004 | 99 |
| 274.3 | 900 | 0.1 | 0.004 | 99 |
| 304.8 | 1,000 | 0.1 | 0.004 | 99 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,555 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-12. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 12*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 28.00 | 0.953 | 21 |
| 61.0 | 200 | 48.00 | 1.925 | 63 |
| 91.4 | 300 | 30.00 | 1.197 | 89 |
| 121.9 | 400 | 4.50 | 0.180 | 93 |
| 152.4 | 500 | 1.40 | 0.057 | 94 |
| 182.9 | 600 | 0.80 | 0.031 | 95 |
| 213.4 | 700 | 1.30 | 0.051 | 96 |
| 243.8 | 800 | 1.00 | 0.039 | 97 |
| 274.3 | 900 | 0.70 | 0.027 | 97 |
| 304.8 | 1,000 | 0.50 | 0.021 | 98 |
| 365.8 | 1,200 | 0.20 | 0.008 | 98 |
| 426.7 | 1,400 | 0.08 | 0.003 | 99 |
| 487.7 | 1,600 | 0.05 | 0.002 | 99 |
| 548.6 | 1,800 | 0.05 | 0.002 | 99 |
| 609.6 | 2,000 | 0.05 | 0.002 | 99 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 1,000 bbl/h
Surface Current = 30 cm/sec
Total Solids Discharge = 114,556 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

## TABLE B-13. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 13*

| Distance from Discharge (m) | (ft) | Maximum Deposition (kg/m$^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 55.00 | 2.210 | 49 |
| 61.0 | 200 | 43.00 | 1.740 | 88 |
| 91.4 | 300 | 5.40 | 0.210 | 93 |
| 121.9 | 400 | 3.00 | 0.121 | 96 |
| 152.4 | 500 | 1.90 | 0.074 | 97 |
| 182.9 | 600 | 0.70 | 0.027 | 98 |
| 213.4 | 700 | 0.40 | 0.016 | 98 |
| 243.8 | 800 | 0.30 | 0.012 | 99 |
| 274.3 | 900 | 0.20 | 0.008 | 99 |
| 304.8 | 1,000 | 0.20 | 0.006 | 99 |
| 335.3 | 1,100 | 0.20 | 0.006 | 99 |
| 365.8 | 1,200 | 0.10 | 0.005 | 99 |
| 396.2 | 1,300 | 0.09 | 0.004 | 99 |
| 426.7 | 1,400 | 0.09 | 0.004 | 99 |
| 457.2 | 1,500 | 0.08 | 0.003 | ~100 |

*MODEL INPUTS: Water Depth = 20 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,551 kg
Forced Separation.

**Assuming an in-place density of 2.5 g/cm$^3$.
***After 10,000 sec (167 min).

TABLE B-14. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 14*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 30.5 | 100 | 16.2 | 0.646 | 20 |
| 61.0 | 200 | 35.2 | 1.410 | 65 |
| 91.4 | 300 | 12.9 | 0.517 | 81 |
| 121.9 | 400 | 6.7 | 0.269 | 89 |
| 152.4 | 500 | 2.8 | 0.113 | 93 |
| 182.9 | 600 | 1.5 | 0.060 | 95 |
| 213.4 | 700 | 0.8 | 0.031 | 96 |
| 243.8 | 800 | 0.4 | 0.018 | 96 |
| 274.3 | 900 | 0.4 | 0.014 | 97 |
| 304.8 | 1,000 | 0.2 | 0.010 | 97 |
| 365.8 | 1,200 | 0.2 | 0.007 | 98 |
| 426.7 | 1,400 | 0.2 | 0.006 | 98 |
| 487.7 | 1,600 | 0.2 | 0.007 | 98 |
| 548.6 | 1,800 | 0.1 | 0.006 | 99 |
| 609.6 | 2,000 | 0.1 | 0.004 | 99 |
| 670.6 | 2,200 | 0.1 | 0.003 | 99 |
| 731.5 | 2,400 | 0.1 | 0.003 | ~100 |

*MODEL INPUTS: Water Depth = 40 m
Discharge Rate = 1,000 bbl/h
Minimum Stratification ($\Delta\sigma_t$ surface to bottom) = 0.5
Surface Current = 10 cm/sec
Total Solids Discharge = 114,539 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-15. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 15*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 61.0 | 200 | 878 | 0.035 | 20 |
| 121.9 | 400 | 603 | 0.024 | 33 |
| 182.9 | 600 | 410 | 0.016 | 42 |
| 243.8 | 800 | 264 | 0.011 | 48 |
| 304.8 | 1,000 | 238 | 0.010 | 53 |
| 365.8 | 1,200 | 249 | 0.010 | 59 |
| 426.7 | 1,400 | 143 | 0.006 | 62 |
| 487.7 | 1,600 | 187 | 0.007 | 66 |
| 548.6 | 1,800 | 181 | 0.007 | 70 |
| 609.6 | 2,000 | 143 | 0.006 | 74 |
| 670.6 | 2,200 | 114 | 0.005 | 76 |
| 731.5 | 2,400 | 105 | 0.004 | 78 |
| 792.5 | 2,600 | 111 | 0.004 | 81 |
| 853.5 | 2,800 | 115 | 0.005 | 83 |
| 914.4 | 3,000 | 100 | 0.004 | 86 |

*MODEL INPUTS: Water Depth = 70 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,634 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 14,000 sec (233 min).

TABLE B-16. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 16*

| Distance from Discharge (m) | (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 61.0 | 200 | 330 | 0.013 | 4 |
| 121.9 | 400 | 1,001 | 0.040 | 17 |
| 182.9 | 600 | 3,015 | 0.121 | 57 |
| 243.8 | 800 | 647 | 0.026 | 65 |
| 304.8 | 1,000 | 415 | 0.017 | 71 |
| 365.8 | 1,200 | 354 | 0.014 | 75 |
| 426.7 | 1,400 | 317 | 0.013 | 80 |
| 487.7 | 1,600 | 305 | 0.012 | 84 |
| 548.6 | 1,800 | 244 | 0.010 | 87 |
| 609.6 | 2,000 | 195 | 0.008 | 89 |
| 731.5 | 2,400 | 146 | 0.006 | 93 |
| 853.5 | 2,800 | 134 | 0.005 | 97 |
| 975.4 | 3,200 | 74 | 0.003 | 99 |
| 1,097.3 | 3,600 | 12 | ∿0.000 | ∿100 |

*MODEL INPUTS: Water Depth = 120 m
Discharge Rate = 1,000 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,554 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 16,000 sec (267 min).

TABLE B-17. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 17*

| Distance from Discharge (m) | (ft) | Maximum Deposition ($g/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 152.4 | 500 | 0.0 | 0.000 | 0 |
| 304.8 | 1,000 | 0.0 | 0.000 | 0 |
| 457.2 | 1,500 | 0.0 | 0.000 | 0 |
| 609.6 | 2,000 | 0.1 | 0.000 | 0 |
| 762.0 | 2,500 | 1.4 | 0.000 | 0 |
| 914.4 | 3,000 | 5.8 | 0.000 | 2 |
| 1,066.8 | 3,500 | 17.0 | 0.001 | 6 |
| 1,219.2 | 4,000 | 14.0 | 0.001 | 10 |
| 1,371.6 | 4,500 | 4.3 | 0.000 | 11 |
| 1,524.0 | 5,000 | 1.3 | 0.000 | 11 |
| 1,676.4 | 5,500 | 1.3 | 0.000 | 12 |
| 1,828.8 | 6,000 | 1.8 | 0.000 | 12 |
| 2,133.6 | 7,000 | 6.4 | 0.000 | 15 |
| 2,438.4 | 8,000 | 21.0 | 0.001 | 23 |
| 2,743.2 | 9,000 | 41.0 | 0.002 | 43 |
| 3,048.0 | 10,000 | 51.0 | 0.002 | 67 |
| 3,200.4 | 10,500 | 63.0 | 0.003 | 84 |
| 3,352.8 | 11,000 | 37.0 | 0.001 | 93 |
| 3,657.6 | 12,000 | 3.5 | ∿0.000 | ∿100 |

*MODEL INPUTS: Water Depth = 120 m
Discharge Rate = 1,000 bbl/h
Surface Current = 32 cm/sec
Total Solids Discharge = 114,646 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 16,000 sec (267 min).

TABLE B-18. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 18*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 352.00 | 14.100 | 72 |
| 30.5 | 100 | 105.00 | 4.200 | 94 |
| 45.7 | 150 | 10.00 | 0.400 | 96 |
| 61.0 | 200 | 8.00 | 0.300 | 98 |
| 76.2 | 250 | 5.00 | 0.200 | 99 |
| 91.4 | 300 | 1.00 | 0.060 | 99 |
| 106.7 | 350 | 1.00 | 0.040 | 99 |
| 121.9 | 400 | 0.70 | 0.030 | 99 |
| 137.2 | 450 | 0.60 | 0.020 | 99 |
| 152.4 | 500 | 0.40 | 0.020 | ~100 |
| 182.9 | 600 | 0.20 | 0.010 | |
| 213.4 | 700 | 0.10 | 0.004 | |
| 243.8 | 800 | 0.08 | 0.003 | |
| 274.3 | 900 | 0.06 | 0.002 | |
| 304.8 | 1,000 | 0.04 | 0.002 | |

*MODEL INPUTS: Water Depth = 5 m
Discharge Rate = 250 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,652 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

TABLE B-19. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 19*

| Distance from Discharge (m) | (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 131.00 | 5.200 | 36 |
| 30.5 | 100 | 195.00 | 7.800 | 89 |
| 45.7 | 150 | 33.00 | 1.300 | 98 |
| 61.0 | 200 | 4.30 | 0.200 | 99 |
| 76.2 | 250 | 1.40 | 0.060 | 99 |
| 91.4 | 300 | 0.80 | 0.030 | 99 |
| 106.7 | 350 | 0.60 | 0.020 | ~100 |
| 121.9 | 400 | 0.40 | 0.020 | |
| 137.2 | 450 | 0.30 | 0.010 | |
| 152.4 | 500 | 0.30 | 0.010 | |
| 182.9 | 600 | 0.20 | 0.010 | |
| 213.4 | 700 | 0.10 | 0.004 | |
| 243.8 | 800 | 0.06 | 0.002 | |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 250 bbl/h
Surface Current = 2 cm/sec
Total Solids Discharge = 114,652 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 16,000 sec (267 min).

TABLE B-20. SOLIDS DEPOSITION FROM OOC MODEL FOR CASE 20*

| Distance from Discharge (m) | Distance from Discharge (ft) | Maximum Deposition ($kg/m^2$) | Maximum** Thickness of Deposited Mud (cm) | Cumulative*** Percent of Deposited Solids |
|---|---|---|---|---|
| 15.2 | 50 | 67.0 | 2.70 | 18 |
| 30.5 | 100 | 92.0 | 3.70 | 43 |
| 45.7 | 150 | 69.0 | 2.80 | 62 |
| 61.0 | 200 | 71.0 | 2.80 | 82 |
| 76.2 | 250 | 25.0 | 1.00 | 88 |
| 91.4 | 300 | 6.0 | 0.20 | 90 |
| 106.7 | 350 | 6.0 | 0.20 | 92 |
| 121.9 | 400 | 7.0 | 0.30 | 94 |
| 137.2 | 450 | 6.0 | 0.20 | 95 |
| 152.4 | 500 | 4.0 | 0.20 | 96 |
| 182.9 | 600 | 2.0 | 0.06 | 97 |
| 213.4 | 700 | 1.0 | 0.03 | 98 |
| 243.8 | 800 | 0.6 | 0.02 | 98 |
| 274.3 | 900 | 0.5 | 0.02 | 99 |
| 304.8 | 1,000 | 0.3 | 0.01 | 99 |

*MODEL INPUTS: Water Depth = 15 m
Discharge Rate = 250 bbl/h
Surface Current = 10 cm/sec
Total Solids Discharge = 114,652 kg
Forced Separation.

**Assuming an in-place density of 2.5 $g/cm^3$.
***After 10,000 sec (167 min).

# APPENDIX C

# FIELD OBSERVATIONS OF DRILLING MUD DILUTION

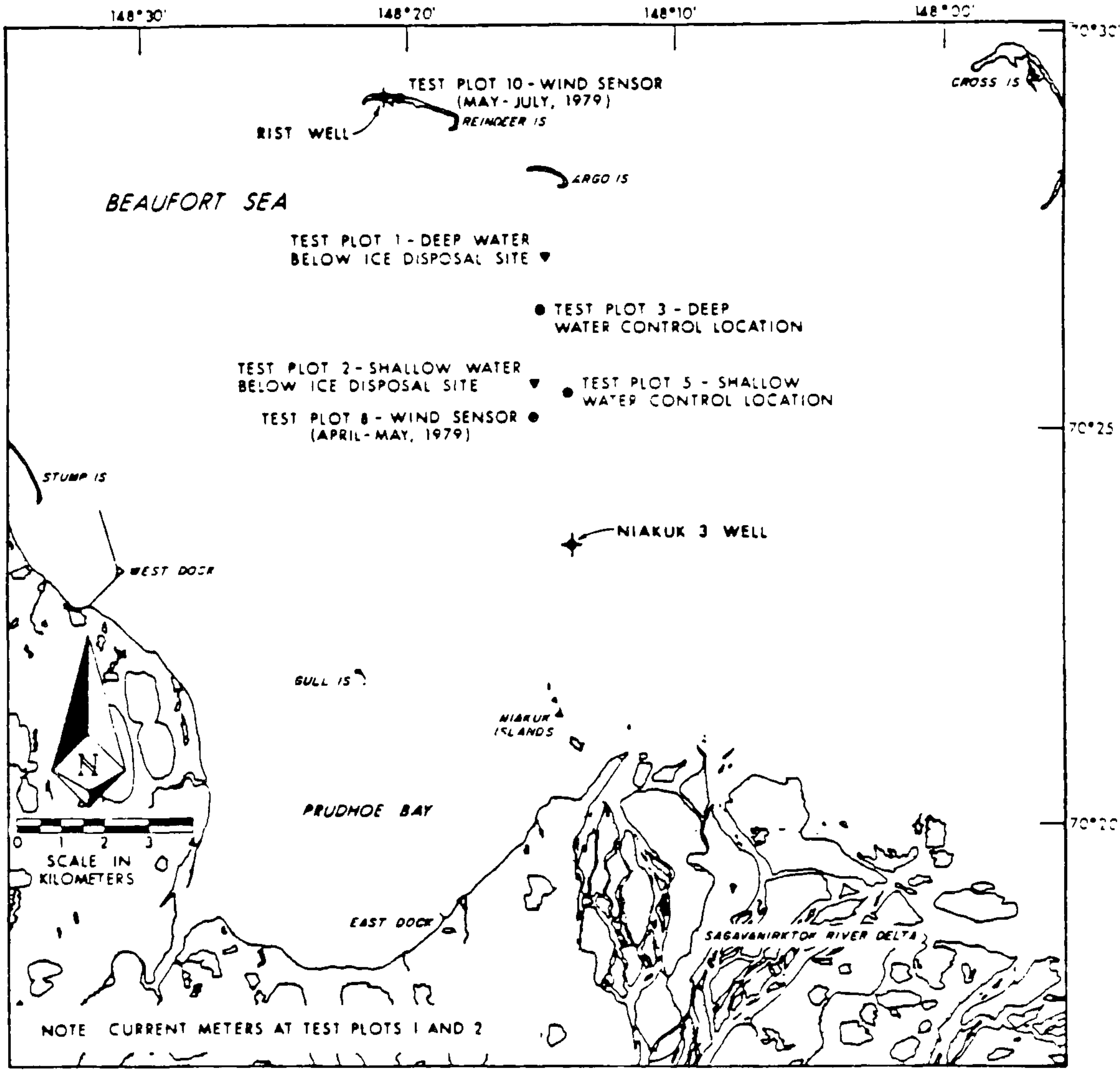
## SUMMARY OF FIELD OBSERVATIONS OF DRILLING MUD DILUTION

### SHALLOW WATER STUDIES

Northern Technical Services (1981, pp. 70-92) conducted two shallow water effluent disposal studies off Reindeer Island in the Beaufort Sea at locations shown in Figure C-1. A summary of the discharge conditions and effluent characteristics for both tests is given in Table C-1. Drilling effluent was mixed with Rhodamine WT dye and then discharged vertically through the sea ice from a 7.6 cm (3 in) diameter nozzle at Reynolds numbers ranging from $10^3$ to $10^5$ (Northern Technical Services 1981, p. 99). Dye concentrations were measured throughout the water column through augered holes along transects running parallel or perpendicular to the principal current direction. Water temperature and salinity profiles taken on April 20 showed a vertical density gradient of approximately $8 \times 10^{-5}$ g/cm$^3$ change per meter (density decreasing with depth). Profiles taken earlier (April 17 and 18) showed that density decreased slightly to 4.5 m (15 ft) depth and then increased with depth to the seafloor.

Results indicated that the effluent formed a circular jet which spread radially outward as a wall jet when it contacted the seafloor. Dye concentrations were not detected until a distance of 10 m (33 ft) from the discharge point for test case 2 and 50 to 60 m (164 to 197 ft) for test case 1 (Northern Technical Services 1981, p. 85). At distances less than these detection points, the height of rise of the wall jet above the seafloor was less than 0.5 m (1.6 ft). Because of sampling string configuration, it was not possible to monitor conditions within 0.5 m (1.6 ft) of the seafloor. As the wall jet expanded radially outward, it moved with the mean laminar current flow.

For test plot 1, current data indicated that velocities were less than the threshold of the meter [1.5 cm/sec (0.05 ft/sec)]. A higher discharge




REFERENCE: Nortec, 1981

Figure C-1. Location map of test plots for the below-ice disposal studies (Reindeer Island).

TABLE C-1. SUMMARY OF DISCHARGE CONDITIONS AND PHYSICAL CHARACTERISTICS OF DRILLING EFFLUENTS USED IN THE BELOW-ICE TEST DISCHARGES AT REINDEER ISLAND

| Location | Test Plot 1 | Test Plot 2 |
|---|---|---|
| Date of test | April 30, 1979 | April 22, 1979 |
| Time of discharge | 1854-1858 AST | 1730-2030 AST |
| Test fluid | Drilling mud | Reserve pit fluids |
| Volume discharged | $16.0 \times 10^3$ l (100 bbl) | $9.5 \times 10^3$ l (60 bbl) |
| Discharge rate | $4.0 \times 10^3$ lpm (1,510 bbl/h) | $5.7 \times 10^1$ lpm (21 bbl/h) |
| Discharge hose diameter | 7.6 cm | 7.6 cm |
| Discharge temperature | $23^o$ c | $19^o$ c |
| Density (at $20^o$ C) | 1.16 g/ml | 1.05 g/ml |
| Ice thickness | 1.8 m | 1.9 m |
| Water depth | 8.4 m | 5.5 m |
| Depth below discharge point | 7.6 m | 5.3 m |
| Average current speed | <1.5 cm/sec | 4.4 cm/sec |
| Depth of current meter | 6.7 m | 4.0 m |
| Discharge Reynolds number | $7.5 \times 10^5$ | $1.3 \times 10^3$ |

rate (1,500 bbl/h) and larger volume of mud (100 bbl) was discharged at this site than at test plot 2. Ambient conditions included water temperatures from -1.24 to -1.23° C and salinities from 32.26 to 32.44 ppt (Northern Technical Services 1981, p. 82). Minimum dilutions and percent transmittance for test plot 1 monitoring are shown in Table C-2. Results from this test plot do not follow expected plume behavior. Dye concentration increased with increasing distance from the discharge point and it is probable that the effluent plume was not sampled in several locations. Transmittance measurements indicated that separation of dye from suspended solids occurred before a distinct plume was observed in the water column [50 to 60 m (164 to 197 ft) from the discharge] (Northern Technical Services 1981, p. 85). Transmittance increased to ambient levels at 244 m (800 ft) downcurrent indicating that a majority of solids had been deposited within this distance.

Results of the measurements for test plot 2 are shown in Table C-3. Ambient sea water conditions for this case included water temperatures of approximately -1.28° C and salinities from 32.93 to 33.04 ppt. Dye concentration generally decreases with distance from the discharge. Transmittance indicates that there was some separation of solids from the dye plume during the study. It is assumed that the effluent plume was not captured in samples taken for distances of 1.5, 6.1, 30.5, and 61 m (5, 20, 100, and 200 ft). Results from test plot 2 were used to formulate an empirical relationship between concentration and distance from discharge.

Both of these studies measure the dilution of the dissolved fraction. Although the dissolved and solid fractions are related, the dilution of the dye will not accurately represent the solids dilution if separation of the two plumes occurs.

Northern Technical Services (1983, pp. 9-60) conducted another drilling effluent disposal study in the Beaufort Sea, Alaska (Tern Island). Case 1 conditions included a mud discharge rate of 84 bbl/h, a predilution of 30:1 with seawater and an average current velocity of 12 cm/sec (0.5 ft/sec) at 3.4 m (11 ft) above the seafloor. Case 2 conditions included a mud discharge rate of 34 bbl/h, predilution of 75:1 with seawater and an average

TABLE C-2. BELOW-ICE EFFLUENT DISCHARGE DILUTION FROM TEST PLOT 1 (8.4 m DEPTH)[a], REINDEER ISLAND

| Distance (m) | Depth of Observation (m) | Minimum Transmittance (%) | Maximum Dye Concentration C/Co | Minimum Dilution |
|---|---|---|---|---|
| 12.2 | 7.0 | 84 | $5.7 \times 10^{-5}$ | 17,544 |
| 18.3 | 7.0 | 80 | $1.4 \times 10^{-3}$ | 714 |
| 30.5 | 7.0 | 70 | $1.7 \times 10^{-3}$ | 588 |
| 61.0 | 6.0 | 85 | $8.9 \times 10^{-3}$ | 112 |
| 122.0 | 6.1-5.7 | 62-63 | $1.1 \times 10^{-2}$ | 91 |
| 244.0 | 5.9-6.1 | 82-84 | $1.2 \times 10^{-2}$ | 83 |
| Ambient | 2.0-7.5 | 80 | 0 | ---- |

[a] Average current speed of 1.2 cm/sec.

Source: Nortec (1981).

TABLE C-3. BELOW-ICE EFFLUENT DISCHARGE DILUTION FROM TEST PLOT 2 (5.5 m DEPTH)[a], REINDEER ISLAND

| Distance (m) | Depth of Observation (m) | Minimum Transmittance (%) | Maximum Dye Concentration C/Co | Minimum Dilution |
|---|---|---|---|---|
| 1.5 | 4.9 | 47 | $7.0x10^{-5}$ | 14,286 |
| 3.0 | 4.9 | 46 | $1.2x10^{-2}$ | 83 |
| 6.1 | 2.0-2.2 | 48-54 | $5.7x10^{-5}$ | 17,544 |
| 12.2 | 4.5 | 73 | $3.5x10^{-3}$ | 286 |
| 18.3 | 3.2-3.4 | 51-65 | $2.6x10^{-3}$ | 385 |
| 30.5 | 3.5 | 65 | $7.9x10^{-5}$ | 12,658 |
| 61.0 | 2.2-3.5 | 46-74 | $2.0x10^{-6}$ | 500,000 |
| Ambient | 2.6-5.0 | 92 | 0 | ---- |

[a] Average current speed of 4.4 cm/sec.

current of 11 cm/sec (0.36 ft/sec). Both discharges were made from a man-made gravel island in 6.7 m (22 ft) of water (Northern Technical Services 1983, p. 27).

Depths or number of measurements were not given so it is difficult to determine whether the plume was actually measured (profiles were taken for test 1). Tables C-4 and C-5 show the results for test 1 and test 2, respectively. Concentrations measured at 0 to 10 m (0 to 33 ft) from the discharge are well outside the calibration range of the optical turbidity sensor used to measure these values. Most of the measurements were made near the surface [0.5 to 1 m (1.6 to 3.3 ft) from the surface]. Profiles taken during test 1 showed that most of the effluent remained in the upper layers due, in part, to a thermocline at 4.5 to 5 m (15 to 16 ft) depth (Northern Technical Services 1983, p. 33). It is more likely that buoyancy of the effluent plume kept it near the surface. Water temperatures during the tests ranged from 0.5 to 1.5° C from bottom to surface and salinities ranged from 26.8 to 24.8 ppt (from test 1 profiles). Results show that dilutions of 167:1 and 300:1 were reached for test 1 and 2, respectively, by approximately 100 m (328 ft) downstream and that slightly greater dilutions are attained for test 2 and the lower discharge rate. Suspended solids concentrations were within 5 mg/l of background levels at 1,900 m (6,234 ft) and 500 m (1,640 ft) for test 1 and 2, respectively (Northern Technical Services 1983, p. 34). Only farfield measurements of suspended solids were given for test plot 2. As shown in Table C-5, these measurements are within typical background levels (less than 20 mg/l). The dilutions calculated for this test may be significantly higher if the correct ambient suspended solids concentrations were subtracted from the measured concentrations. It appears that background suspended solids concentrations were reached at approximately 210 m (689 ft) from the discharge.

Ecomar (1983, pp. 17-79) conducted drilling mud dispersion studies in Central Norton Sound in water depths of 12 to 13 m (39 to 43 ft). A total of 1,100 barrels of mud (bulk density of 10.19 lb/gal) was discharged at a rate of 1,060 bbl/h at 1 m (3.3 ft) below the surface through a 0.32 m (12.6 in) diameter pipe. Measured currents ranged from averages of 15 cm/sec (0.5 ft/sec) near the bottom to 77 cm/sec (0.5 to 2.5 ft/sec at 1 m (3.3 ft)

TABLE C-4. MAXIMUM DYE AND SUSPENDED SOLIDS CONCENTRATION FOR TEST 1[a], TERN ISLAND

| Down Stream Distance (m) | Maximum Concentration: Dye[b] (C/Co) | Maximum Concentration: Suspended Solids (mg/l) | Minimum Dilution: Dye | Minimum Dilution: Suspended[c] Solids |
|---|---|---|---|---|
| 10 | $1.72 \times 10^{-3}$ | 964 | 581 | 9 |
| 30 | $5.42 \times 10^{-4}$ | 271 | 1,845 | 33 |
| 60 | $3.59 \times 10^{-4}$ | 153 | 2,786 | 63 |
| 100 | $1.92 \times 10^{-4}$ | 70 | 5,208 | 167 |
| 350 | - | 18 | - | d |
| 480 | - | 10 | - | d |
| 730 | - | 10 | - | d |
| 940 | - | 7 | - | d |
| 1,100 | - | 4 | - | d |

[a] Predilution of 30:1, discharge rate of 84 bbl/h.

[b] It is unclear whether Co is the concentration before or after predilution.

[c] Dilution due to ambient waters only. Background levels of approximately 20 mg/l have been subtracted from the sample concentrations.

[d] Background levels reached.

TABLE C-5. MAXIMUM DYE AND SUSPENDED SOLIDS CONCENTRATIONS FOR TEST 2[a], TERN ISLAND

| Downstream Distance (m) | Maximum Concentration: Dye $(C/Co)^b$ | Maximum Concentration: Suspended Solids (mg/l) | Minimum Dilution: Dye | Minimum Dilution: Suspended Solids[c] |
|---|---|---|---|---|
| 160 | $1.99 \times 10^{-5}$ | 10.4 | 50,251 | 320 |
| 210 | $1.81 \times 10^{-5}$ | 9.3 | 55,249 | 358 |
| 250 | $7.53 \times 10^{-6}$ | 5.6 | 132,802 | 595[d] |
| 305 | $6.21 \times 10^{-6}$ | 5.6 | 161,031 | 595[d] |
| 350 | $7.79 \times 10^{-6}$ | 6.8 | 128,370 | 490[d] |
| 400 | $7.89 \times 10^{-6}$ | 5.6 | 126,743 | 595[d] |
| 600 | $2.09 \times 10^{-6}$ | 4.4 | 478,469 | 757[d] |
| 640 | $5.16 \times 10^{-6}$ | 3.2 | 193,798 | 1,042[d] |

[a] Predilution of 75:1, discharge rate of 34 bbl/h.

[b] It is unclear whether Co is the concentration before or after predilution.

[c] Dilution due to ambient waters only. Background levels are typically less than 20 mg/l but exact levels are unknown. Dilutions are calculated without consideration of background concentrations. Actual dilutions should be higher.

[d] Background levels probably reached.

below the surface. Calculated densities showed little variation from bottom to surface or from station to station, indicating well mixed conditions (Ecomar 1983, pp. 15, 30, 31, 33, 40). Table C-6 gives the maximum suspended solids concentrations measured during the test.

Results indicate that measurements made at distances of 100 to 170 m (328 to 558 ft) did not sample the maximum concentrations in the plume since measurements at 650 m (2,113 ft) from the discharge record higher concentrations. Minimum dilution of suspended solids at 100 m (328 ft) was approximately 10,116:1, however, solids dilution did not consistently increase with distance from the discharge and a minimum solids dilution of 2,252:1 was calculated at 650 m (2,133 ft) from the discharge.

A drilling fluid dispersion study was conducted in the Gulf of Mexico in 23 m (75 ft) of water during the summer of 1978 (Ayers et al. 1980a, pp. 351-381). Two discharge rates and volumes were considered: 250 barrels of mud discharged at a rate of 275 bbl/h and 398 barrels of mud were discharged at a rate of 1,000 bbl/h (Ayers et al. 1980a, p. 352). Currents during the low rate discharge ranged from a minimum of 1 cm/sec (0.033 ft/sec) near the bottom to 22 cm/sec (0.72 ft/sec) at 14 m (46 ft) depth. For the high rate discharge test, currents ranged from 0 cm/sec near the bottom to 15.8 cm/sec (0.52 ft/sec) at 7 and 14 m (23 and 46 ft) depth. The drilling mud used in the study was a chrome lignosulfonate-clay mud with density of 2.09 g/cm$^3$ (17.4 lb/gal). Sampling was conducted at the top, bottom, and most dense part of the plume using a rosette sampling array deployed from a helicopter. Ambient water conditions during the 275 bbl/h discharge included water temperatures from 22$^{o}$ C near the bottom to 30.1$^{o}$ near the surface and salinities of 34 ppt near bottom to 24.8 ppt near surface. For the high rate discharge (1,000 bbl/h), temperatures ranged from 34.0 to 24.8 ppt bottom to surface (Ayers et al. 1980a, pp. 363-366).

During both tests, the effluent formed two plumes: a lower plume which contained a majority of the solids and an upper plume several meters thick which remained in the water column much longer than the lower plume. Measurements for these studies were directed toward describing the effect of the upper plume on water quality.

TABLE C-6. MAXIMUM SUSPENDED SOLIDS CONCENTRATIONS[a] FOR NORTON SOUND STUDY

| Distance Down Stream (m) | Depth Noted (m) | Maximum Suspended Solids (mg/l) | Minimum[b] Dilution |
|---|---|---|---|
| 3 | 2 | 2,640 | 117 |
| 6 | 4 | 1,210 | 262 |
| 45 | 4 | 116 | 5,388 |
| 70 | 1 | 201 | 2,140 |
| 100 | 10 | 75 | 10,116 |
| 105 | 11 | 68 | 37,718 |
| 110 | 12 | 92 | 9,429 |
| 150 | 6 | 67 | 43,106 |
| 170 | 1 | 88 | 10,776 |
| 650 | 13 | 194 | 2,252 |
| 690 | 2 | 90 | 10,058 |

[a] Ambient suspended solids concentrations average 60 mg/l.

[b] Assuming a whole mud concentration of 301,740 mg/l. Background levels have been subtracted from sample concentrations before calculating minimum dilution.

Table C-7 shows the maximum measured suspended solids concentrations for both discharge rates. Results indicate that greater dilutions were achieved for the low discharge rate although currents during the high discharge rate test were slightly less than those during the low rate case. No measurements at 100 m (328 ft) were available for these tests. Dilutions at 100 m (328 ft) should be greater than those measured at 45 m (148 ft) and 51 m (167 ft), however.

## DEEP WATER STUDIES

Houghton et al. (1980, pp. 285-308) conducted three tests in Lower Cook Inlet to evaluate the dispersion of drilling effluents in the receiving water. All tests were conducted in 62 m (203 ft) of water with current velocities ranging from 31 to 144 cm/sec (1.0 to 4.7 ft/sec) and discharge rates from 20 to 1,200 bbl/h. Total volumes of mud discharged were very small ranging from 15 to 47 bbl and duration of discharge ranged from a few minutes to 2.5 hours. Salinity and temperature profiles taken at the site indicated little stratification (Houghton et al. 1980, pp. 294-298).

Results from the three tests are shown in Tables C-8 through C-10. All of these tests measured dilution of the dissolved fraction (dye). Although the dissolved fractions are related, the dilution of the dye will not accurately represent the solids dilution if separation of the two plumes occur. Generally, the minimum dilution increased with distance from the discharge in all three tests. There was fluctuation in the magnitude of dilution beginning at approximately 2,600 m (8,530 ft) for test 2 and 2,100 m (6,890 ft) for test 3, however, all dilutions were on the order of 100,000:1 at these distances. High dilutions were obtained at 1,000 m (3,281 ft) (on the order of 40,000 to 100,000:1). Only test 1 measured dilutions at 100 m (328 ft) with a minimum dilution of 38,000:1.

Ayers et al. (1980b, pp. 382-418) conducted drilling mud dispersion tests in the mid-Atlantic at a site 156 km east of Atlantic City, New Jersey, in 120 m (394 ft) of water. Two tests were conducted: approximately 500 bbl of mud were discharged at 500 bbl/h and 220 bbl of mud were released at

TABLE C-7. MAXIMUM SUSPENDED SOLIDS CONCENTRATIONS AND MINIMUM DILUTIONS FOR DRILLING MUDS DISCHARGED TO THE GULF OF MEXICO[a]

| Distance from Discharge (m) | Depth Noted (m) | Solids Concentration (mg/l) | Minimum Dilution |
|---|---|---|---|
| | Low Rate Discharge - 275 bbl/h | | |
| 6 | 8 | 14,800 | 97 |
| 45 | 11 | 34 | 42,060 |
| 138 | 9 | 8.5 | 168,235 |
| 250 | 9 | 7.0 | 242,373 |
| 364 | 9 | 1.2 | c |
| 625 | 9 | 0.9 | c |

| Distance from Discharge (m) | Depth Noted (m) | Solids Concentration (mg/l) | Minimum Dilution |
|---|---|---|---|
| | High Rate Discharge - 1,000 bbl/h | | |
| 45 | 11 | 855 | 1,673 |
| 51 | 12 | 727 | 1,967 |
| 152 | 11 | 50.5 | 28,890 |
| 375 | 16 | 24.1 | 61,905 |
| 498 | 14 | 8.6 | 188,158 |
| 777 | 13 | 4.1 | 461,290 |
| 858 | 2 | 1.2 | c |
| 957 | 12 | 0.83 | c |
| 1,470 | 11 | 2.2 | c |
| 1,550 | 9 | 1.1 | c |

[a] Suspended solids concentration of whole mud is 1,430,000 mg/l.

[b] Ambient suspended solids levels are 0.3 to 1.9 mg/l for the low discharge rate and 0.4 to 1.1 mg/l for the high rate.

[c] Background levels are reached.

TABLE C-8. SUMMARY OF RESULTS FROM TEST 1, LOWER COOK INLET[a]

| Distance from Discharge (m) | Depth (m) | Current Velocity (knots) | Maximum Dye Concentration (ppb) | Minumum Dilution |
|---|---|---|---|---|
| 100 | 1 | 2.40 | 3.0 | 38,000 |
| 200 | 1-7 | 2.65-2.72 | 1.1 | 104,000 |
| 400 | 1-15 | 2.38-2.63 | 0.8 | 143,000 |

[a] Test Conditions: Total Volume Discharged = 47 bbl
Initial Dye Concentration = 114,000 ppb
Initial Suspended Solids Concentration = 20,000 mg/l
Duration of Discharge = 140 min.

TABLE C-9. SUMMARY OF RESULTS FROM TEST 2, LOWER COOK INLET[a]

| Distance from Discharge (m) | Depth (m) | Current Velocity (knots) | Maximum Dye Concentration (ppb) | Minumum Dilution |
|---|---|---|---|---|
| 940 | 1 | 1.89 | 3.6 | 46,000 |
| 1,370 | 1 | 1.89 | 3.3 | 53,000 |
| 1,670 | 1 | 1.90 | 2.1 | 79,000 |
| 1,980 | 7 | 1.91 | 1.4 | 119,000 |
| 2,670 | 15 | 1.92 | 1.3 | 128,000 |
| 4,000 | 30 | 1.44 | 0.1 | 1,660,000 |
| 4,830 | 15 | 1.14 | 0.8 | 208,000 |
| 5,700 | 7 | 0.80 | 0.6 | 277,000 |
| 6,280 | 7 | 0.60 | 0.3 | 553,000 |
| 6,370 | 15 | 0.76 | 0.7 | 237,000 |

[a] Test Conditions: Total Volume Discharged = 15 bbl
Initial Dye Concentration = 166,000 ppb
Initial Suspended Solids Concentration = 103,000 mg/l
Duration of Discharge = 5 min.

TABLE C-10. SUMMARY OF RESULTS FROM TEST 3, LOWER COOK INLET[a]

| Distance from Discharge (m) | Depth (m) | Current Velocity (knots) | Maximum Dye Concentration (ppb) | Minumum Dilution |
|---|---|---|---|---|
| 830 | 1 | 2.05 | 9.1 | 22,000 |
| 1,760 | 1 | 2.10 | 1.9 | 107,000 |
| 2,190 | 7 | 2.23 | 2.7 | 752,000 |
| 5,740 | 15 | 2.35 | 0.3 | 677,000 |
| 6,480 | 7 | 2.35 | 1.5 | 135,000 |
| 7,500 | 1 | 2.07 | 0.5 | 406,000 |
| 9,630 | 30 | 1.92 | 0.0 | - |
| 10,930 | 15 | 1.93 | 0.4 | 508,000 |
| 11,670 | 7 | 1.57 | 0.3 | 677,000 |
| 13,150 | 1 | 1.52 | 0.1 | 203,000 |

[a] Test Conditions: Total Volume Discharged = 40 bbl
Initial Dye Concentration = 203,000 ppb
Initial Suspended Solids Concentration = 700,000 mg/l
Duration of Discharge = 2 min.

275 bbl/h. The mud was discharged at at constant rate and shunted to 12 m (39 ft) below the water surface. Oceanographic conditions during the tests included a predominant current to the south and southwest at speeds of 26.9 cm/sec and 21.5 cm/sec [at 10 m (33 ft) depth] for the low rate and high rate discharge tests, respectively (Ayers et al. 1980b, pp. 383, 385, 387). During both tests two plumes formed; a lower plume containing the bulk of the solids and an upper plume. The upper plume was sampled in the tests.

Results of the two tests are shown on Tables C-11 and C-12. Generally, the dilution increases with distance from the discharge. It appears that the plume may not have been sampled at 15 m (49 ft) from the source. Minimum dilutions at 100 m (328 ft) varied from approximately 61,000 to 86,000:1 for the high and low rate discharge tests, respectively.

Ray and Meek (1980, pp. 223-258) conducted drill muds and cuttings discharge monitoring from a semisubmersible drilling platform on Tanner Bank (off southern California) in 63 m (207 ft) of water. Mud discharge rates varied from 10 to 754 bbl/h. Currents showed a predominant southeasterly flow averaging 21 cm/sec (0.7 ft/sec) (Ray and Meek 1980, p. 223).

Results of these tests are shown in Table C-13. All tests showed a very high dilution within 100 m (328 ft) of the discharge (on the order of 100,000:1) and that background suspended solids concentrations were approached at 200 m (656 ft). One reason for the large dilutions observed is a phenomenon called "standpipe pumping" (Ray and Meek 1980, p. 226). As waves pass the rig, they create a large surge of water in and out of the pipe resulting in increased initial dilutions.

TABLE C-11. SUMMARY OF MINIMUM DILUTIONS FOR DRILLING MUDS DISCHARGED TO THE MID-ATLANTIC - LOW RATE DISCHARGE (275 bbl/h)[a]

| Distance from Source (m) | Depth (m) | Suspended Solids Concentration (mg/l) | Minumum Dilution[b] |
|---|---|---|---|
| 0 | 12 | 1,398 | 199 |
| 5 | 12 | 56 | 5,044 |
| 15 | 14 | 122 | 2,293 |
| 73 | 14 | 12.5 | 24,122 |
| 89 | 14 | 9.7 | 31,885 |
| 93 | 10 | 5.2 | 66,048 |
| 97 | 23 | 4.2 | 86,687 |
| 192 | 16 | 3.5 | 110,960 |
| 590 | 7 | 0.4 | c |
| 701 | 7 | 1.3 | 924,667 |

[a] Test Conditions: Total Volume Discharged = 220 bbl
Initial Dye Concentration = 277,400 ppb
Background Suspended Solids = 0.1-1.6 mg/l
Bulk Density = 1.21 g/cm$^3$

[b] Dilutions are calculated using a modified solids concentration obtained by subtracting the ambient suspended solids concentration (assume an average of 1.0 mg/l) from the measured concentration.

[c] Background levels reached.

TABLE C-12. SUMMARY OF MINIMUM DILUTIONS FOR DRILLING MUDS DISCHARGED TO THE MID-ATLANTIC - HIGH RATE DISCHARGE (500 bbl/h)[a]

| Distance from Source (m) | Depth (m) | Suspended Solids Concentration (mg/l) | Minumum Dilution[b] |
|---|---|---|---|
| 0 | 14 | 100,400 | 2 |
| 5 | 12 | 82 | 3,091 |
| 15 | 24 | 1,195 | 210 |
| 119 | 10 | 5.1 | 61,073 |
| 149 | 1 | 4.9 | 64,205 |
| 193 | 3 | 4.6 | 69,556 |
| 332 | 1 | 1.8 | 313,000 |
| 352 | 1 | 1.0 | c |

[a] Test Conditions: Total Volume Discharged = 5000 bbl
Initial Dye Concentration = 250,400 ppb
Background Suspended Solids = 0.1-2.4 mg/l
Bulk Density = 1.19 g/cm$^3$

[b] Dilutions are calculated using a modified solids concentration obtained by subtracting the ambient suspended solids concentration (assume an average of 1.0 mg/l) from the measured concentration.

[c] Background levels reached.

TABLE C-13. SUMMARY OF MINIMUM DILUTIONS FOR DRILLING MUD DISCHARGES TO TANNER BANK[a]

| Discharge Rate (bbl/h) | Distance (m) | Depth (m) | Current (cm/sec) | Transmittance (Percent) | Suspended Solids (mg/l) | Minimum Dilution[b] |
|---|---|---|---|---|---|---|
| 10 | 0 | 12 | 11.8 | - | 499 | 502 |
| | 105 | 12 | | 49.1 | 5.2 | 59,524 |
| | 155 | 8 | | 62.8 | 2.03 | 242,718 |
| | 450 | 23 | | 77.1 | 1.79 | 316,456 |
| 10 | 0 | 12 | 45.2 | - | 252 | 996 |
| | 76 | 15 | | 66.6 | 1.95 | 263,158 |
| | 145 | 15 | | 65.7 | 1.17 | c |
| | 440 | 5 | | 48.4 | 1.01 | c |
| 12 | 80 | 15 | 14.9 | 57.6 | 1.06 | c |
| | 160 | 5 | | 74.7 | 0.978 | c |
| | 225 | 15 | | 75.7 | 0.614 | c |
| | 290 | 10 | | 74.0 | 1.44 | c |
| | 450 | 10 | | 84.8 | 0.724 | c |
| 12 | 0 | 12 | 29.8 | - | 43.04 | 5,947 |
| | 90 | 10 | | 46.4 | 1.59 | 423,729 |
| | 130 | 15 | | 51.6 | 2.20 | 208,333 |
| | 175 | 15 | | 74.6 | 2.11 | 225,225 |
| | 250 | 20 | | 77.5 | 1.33 | c |
| | | 10 | | 83.3 | 1.51 | c |
| 20 | 0 | 12 | 2.2 | - | 279.2 | 899 |
| | 55 | 10 | | 28.4 | 2.74 | 143,678 |
| | 140 | 5 | | 41.3 | 1.81 | 308,642 |
| | 200 | 10 | | 40.5 | 2.18 | 211,864 |
| | 275 | 15 | | 63.4 | 1.01 | c |
| | | 5 | | 55.6 | 1.56 | c |
| 754 | 0 | 12 | 15.9 | - | 328 | 765 |
| | 74 | 10 | | 0.0 | 25.2 | 10,331 |
| | 500 | 5 | | 19.3 | 4.04 | 82,237 |
| | 625 | 20 | | 80.8 | 1.10 | c |
| | 800 | 20 | | 23.7 | 4.73 | 67,024 |
| | 1,000 | 25 | | 10.9 | 0.563 | c |

[a] Test Conditions: Initial Solids Concentration = 250,000 mg/l
Background Solid Concentration = 0.81-1.5 mg/l.

[b] Dilutions are calculated using a modified suspended solids concentration obtained by subtracting the background concentration (1.0 mg/l) from the measured concentration.

[c] Background levels reached.

# APPENDIX D

# FIELD OBSERVATIONS OF SOLIDS DEPOSITION

## FIELD OBSERVATIONS OF SOLIDS DEPOSITION

Northern Technical Services (1981, pp. 87-91) conducted a study (Table C-1) to measure bottom deposition in the Beaufort Sea (Reindeer Island). Settling pans were deployed at various locations in the vicinity of the discharge. In the deep water test [8.4 m (28 ft)], larger particles were deposited near the discharge while finer materials and drilling mud were deposited further away. The maximum deposition of drilling muds was 173 $mg/cm^2$ at 6 m (20 ft) from the discharge. Little deposition of drilling muds and cuttings occurred at distances greater than 30 m (98 ft) from the discharge. Drilling muds were quickly resuspended and carried away after initial deposition (Northern Technical Services 1981, pp. 87-88).

Northern Technical Services (1983, pp. 40-51) also conducted deposition studies at Tern Island [6.7 m (22 ft)] in the Beaufort Sea. Predischarge and postdischarge sediment samples were collected to determine if drilling effluents (mud discharges only) accumulated on the seafloor. Grain size and trace metal sediment analyses showed no indication of drilling effluent accumulation.

Ecomar (1983, pp. 25-26, 49-60, 75-77) deployed 22 sediment traps [1 m (3.3 ft) above the seafloor] at various distances up to 967 m (31,725 ft) downcurrent from the drilling platform in 12 to 13 m (39 to 43 ft) of water in Norton Sound (COST well no. 2). The majority of solids settling occurred within 100 to 125 m (328 to 410 ft) of the discharge. Highest accumulations occurred in the sediment traps placed within 50 m (164 ft) of the discharge. Solids accumulations ranged from 2 to 1,740 $g/m^2$. The maximum deposition (1,740 $g/m^2$) occurred at 12 m (39 ft) from the source (Ecomar 1983, p. 49). Nearfield sedimentation could not be completely described by the selected placement of the sediment traps near the source. At distances greater than 300 m (984 ft) from the discharge, solids accumulations in the traps were near the measured background level (Ecomar 1983, p. 55). Trace metal analysis of sediment samples did not show significant accumulation of barite or chromium. However, background sedimentation rates (3 $g/m^2/h$ due to a storm) were relatively high during the test, so the results may reflect the contribution of background sedimentation rather than accumulation of drilling materials.

Sedimentation studies were performed by Ecomar (1978, pp. 238-291) at Tanner Bank to trace the settling and bottom transport of drilling discharges. Nineteen sediment traps were deployed 10 m (33 ft) above the bottom at various distances from the platform. Grab samples of bottom surface sediments were collected prior to, during, and after drilling operations. Cuttings and drilling mud solids were deposited in sediment traps up to 125 m from the source, but were not detectable at 915 m (3,002 ft). Maximum induced sedimentation (67 $g/m^2/day$ estimated) occurred approximately 64 m (210 ft) downcurrent. Measurable induced sedimentation was absent at the control trap [915 m (3,002 ft) downcurrent]. Detectable but insignificant accumulations of discharged materials were present at some downcurrent stations within 125 m (410 ft) of the source.

Deposition studies (bottom sampling, television monitoring, and sediment traps) in 62 m (203 ft) of water in Lower Cook Inlet showed little accumulation of cuttings on the bottom (Houghton et al. 1980, p. 285). The cuttings deposition rate varied from $5.24 \times 10^3$ $g/m^2/h$ [at 85 m (279 ft)] to 1.25 $g/m^2/h$ within 100 m (328 ft) of the discharge. No cuttings were identified in the control trap located 2.9 km (9,514 ft) from the source.

Deposition studies of drilling fluids were conducted by Gettleson (1978) in East Flower Garden Bank, Gulf of Mexico. Test conditions included 129 m (423 ft) of water and bottom currents toward the west-southwest. Results showed that drilling fluids and cuttings were distributed to 1,000 m (3,281 ft) from the discharge.

An offshore drilling site approximately 50 km northwest of Palawan Island, Philippines was examined 15 months after well completion to determine impact of drilling operations on coral growth (Hudson et al., 1982, pp. 890-

908). Drilling took place in 26 m (85 ft) on the reef with 3 cm/sec (0.10 ft/sec) currents to the north. Data was gathered using divers, coral cores, and photomosaics. No trace of a cuttings pile was found, but some cuttings were present in sediment-filled depressions within 20 m (66 ft) of the wellheads (Hudson et al. 1982, p. 907).

Fate of drilling discharges (cuttings and drilling muds) in the mid-Atlantic (off the New Jersey coast) was studied by EG&G Environmental Consultants (1982, p. 3-1 through 5-2) using side-scan sonar mosaics, sediment samples, underwater television monitoring, and bottom photographs. Drilling took place in 120 m (394 ft) of water with bottom currents typically less than 10 cm/sec (0.33 ft/sec). Physical effects of the discharge were observed 1 year after drilling. Visual observations indicated that within 100 m (328 ft) of the discharge, accumulations consisted of numerous small piles of drilling materials (mostly cuttings). Elevated barium levels in sediments occurred out to 1.6 km (5,249 ft) from the discharge (EG&G Environmental Consultants 1982, pp. 4-7, 4-9). Results of these studies showed that physical alterations of the sediments near the well sites are long-lasting due to the low energy nature of the mid-Atlantic site.

Deposition studies on Georges Bank 2 years after drilling had ceased (Bothner et al., 1983, pp. 12-30) showed similar results. Studies were conducted in 80 m (262 ft) and 140 m (459 ft) of water with residual bottom currents of 3.5 cm/sec (0.11 ft/sec). Results of sediment core analyses showed evidence of cuttings accumulation within 500 m (1,640 ft) of the source (Block 410) (Bothner et al. 1983, p. 13). Elevated barium levels (two times the background level) in sediments occurred at stations approximately 2 km (6,562 ft) from the source.

Crippen et al. (1980, pp. 636-669) conducted studies in the Canadian Beaufort Sea to determine the concentrations of metals in sediments and benthic fauna following drilling. Drilling took place from an artificial island that was in an advanced state of erosion at the time of the survey. Elevated levels of mercury, lead, zinc, cadmium, arsenic, and chromium were found in sediment samples collected within 45 m (148 ft) with elevated mercury levels out to 1,800 m (5,905 ft). Mercury contamination of sediments was obvious within 100 m (328 ft) of the discharge (Crippen et al. 1980, p. 641). However, coarse grained material from the island was observed out to a distance of 300 m (984 ft) (Crippen et al. 1980, pp. 640, 645).

Tillery and Thomas (1980, pp. 562-581) conducted studies in the Gulf of Mexico to determine the distribution of metals in sediments. Twenty study sites (platforms) were located in less than 18 m (59 ft) to 92 m (302 ft) of water. Sediment samples were collected at distances of 100 m (328 ft), 500 m (1,640 ft), 1,000 m (3,281 ft), and 2,000 m (6,562 ft). These data show decreasing surficial sediment concentrations with distance from the source for barium, cadmium, chromium, copper, lead, and zinc (Tillery and Thomas 1980, p. 565). However, concentrations of cadmium, chromium, and copper measured at primary stations were similar to those measured at control stations.