FEASIBILITY STUDY OF AN OCEAN DISCHARGE OF MINE WASTES FROM GAG ISLAND, INDONESIA

Prepared by

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INTRODUCTION

Gag Island (Fig. 1) is a small island in the Halmahera Sea at the west end of the Dampier Straits off the west coast of West Irian, Indonesia. The island has a lateritic nickel deposit and it has been proposed to dispose of the mine tailings and effluent from the metals recovery plant through a submerged ocean outfall system. This preliminary study concerns chiefly the marine geologic criteria which must be considered in the location and design of such a disposal system in order to (1) maximize the efficiency of the disposal system while (2) minimizing its potential deleterious impact on the environment in the vicinity of the disposal site.

The major topics discussed here are:

I. Criteria for an efficient submerged discharge.

II Critical environmental conditions in offshore area near potential disposal site and the characteristics of the wastes.

III Physical and chemical interaction between the environment and the effluent.

IV Conclusions and recommendations

CRITERIA FOR EFFICIENT MARINE OUTFALL DESIGN

Pearson (1961) has listed in Table 1, factors which should be considered for the general design of a marine waste disposal system. In this study Category 1-7 is assumed;or that waste disposal is a beneficial use of the ocean. Topics underlined in Table 1 are discussed in this report whereas topics underlined with a dotted line have been treated by Wyrtki (1972). Other topics where applicable to the Gag Island situation will be studied by other consultants.

PHYSICAL ENVIRONMENT AND CHARACTERISTICS OF THE EFFLUENT

In short what will be discussed here are the knowns or data which will be used to satisfy the criteria underlined in Table 1 and thus to investigate the possible disposal schemes.

Wrytki (1972) has provided the physical details of the environment which is summarized below. Gag Island is an ovoid island (11 x 9 kilometers) located at 0° 27's and 129° 52'E with a maximum height of 332 meters (Teledyne survey-Bechtel Job 9264). The topography of the island is rugged. The only level area is a valley extending northwestward from an embayment just north of the east-west centerline of the island. There are two clusters of buildings

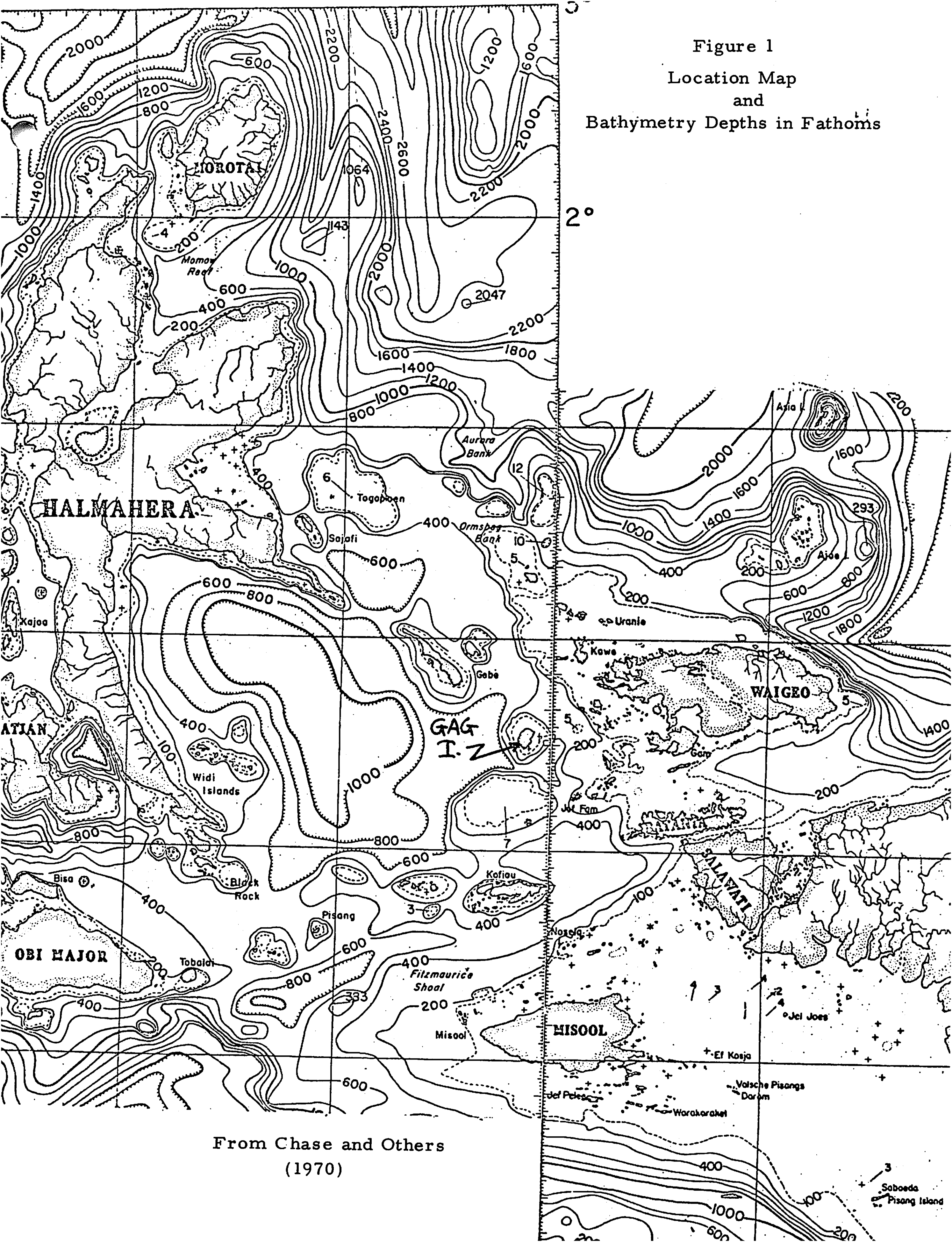


Figure 1

Location Map and Bathymetry Depths in Fathoms

From Chase and Others (1970)

TABLE I

Table 17.3. FACTORS TO BE CONSIDERED IN THE DESIGN OF MARINE WASTE DISPOSAL SYSTEMS (from Pearson, 1961)

I. *Beneficial uses*

1. Water contact sports
2. Marine recreation, boating
3. Marine working environment
4. Fishery, propagation, migration, etc.
5. Economic fishery, propagation, harvesting
6. Industrial commercial use, coding, etc.
7. Waste disposal
8. Other

II. *Water quality criteria to protect beneficial uses*

1. Public health
    - (a) Coliform
    - (b) Other
2. Fishery
    - (a) Toxic substances
    - (b) Antagonistic substances
    - (c) Oxygen depressants
    - (d) Stimulants, fertilizers
    - (e) Transparency, turbidity
    - (f) Suspended and settleable debris
3. Nuisance
    - (a) Grease and oil films
    - (b) Floating debris
    - (c) Settleable debris
    - (d) Odors
4. Aesthetic
    - (a) Sleek areas
    - (b) Colors
    - (c) Turbidity—transparency
    - (d) Floating debris
    - (e) Plankton bloom
    - (f) Other
5. Economic and other

III. *Oceanographic characteristics of outfall sites*

1. General water circulation system
2. Current
    - (a) Surface and subsurface
    - (b) Strength and direction as a function of time
    - (c) Effect of wind, wave, tide, littoral drift
3. Eddy diffusivity or dispersion characteristics
4. Density structure, salinity-temperature-depth relationship
5. Wave and swell effects
6. Submarine topography
7. Submarine geology

IV. *Waste dispersion considerations*

1. Initial mixing—diffuser
    - (a) Jet mixing
    - (b) Buoyancy—gravitational mixing
    - (c) Density gradients—thermoclines
    - (d) Diffuser orientation
    - (e) Waste dilution—flow continuity
    - (f) Port selection, area—spacing
2. Waste transport—dispersion
    - (a) Current regiment
    - (b) Eddy diffusion
    - (c) Mixing depth, effective
    - (d) Rational dispersion equations
        - (1) Concentration dilution only—conservative waste
        - (2) Concentration including decay—nonconservative waste, i.e., bacteria, radioisotopes, BOD, etc.

V. *Economic analyses*

1. Various types of treatment and effluent characteristics.
2. Length, depth, and cost of outfall systems for each type of effluent to meet water quality criteria requirements.
3. Selection of optimum and least-cost combination of treatment and outfall system to protect beneficial uses.

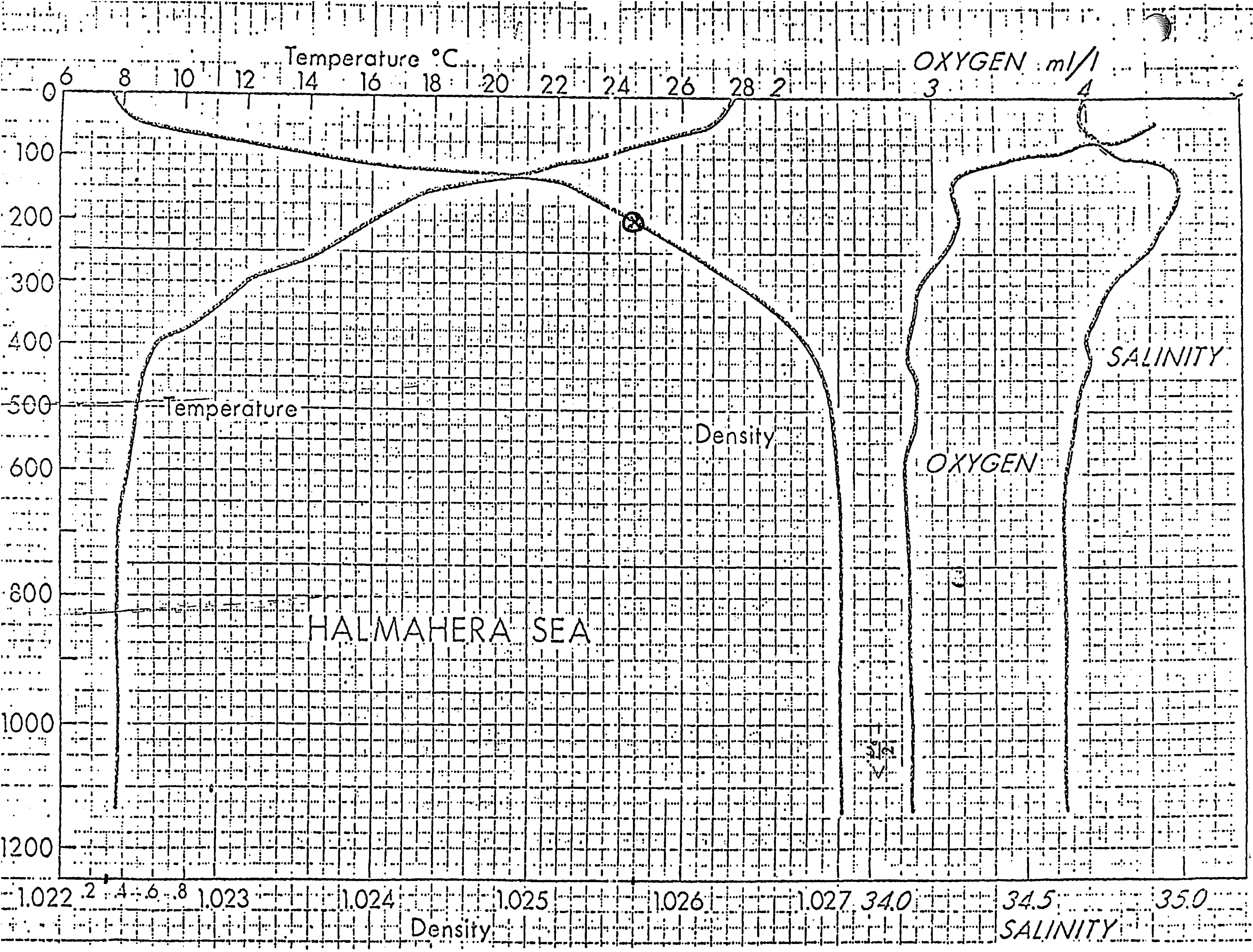
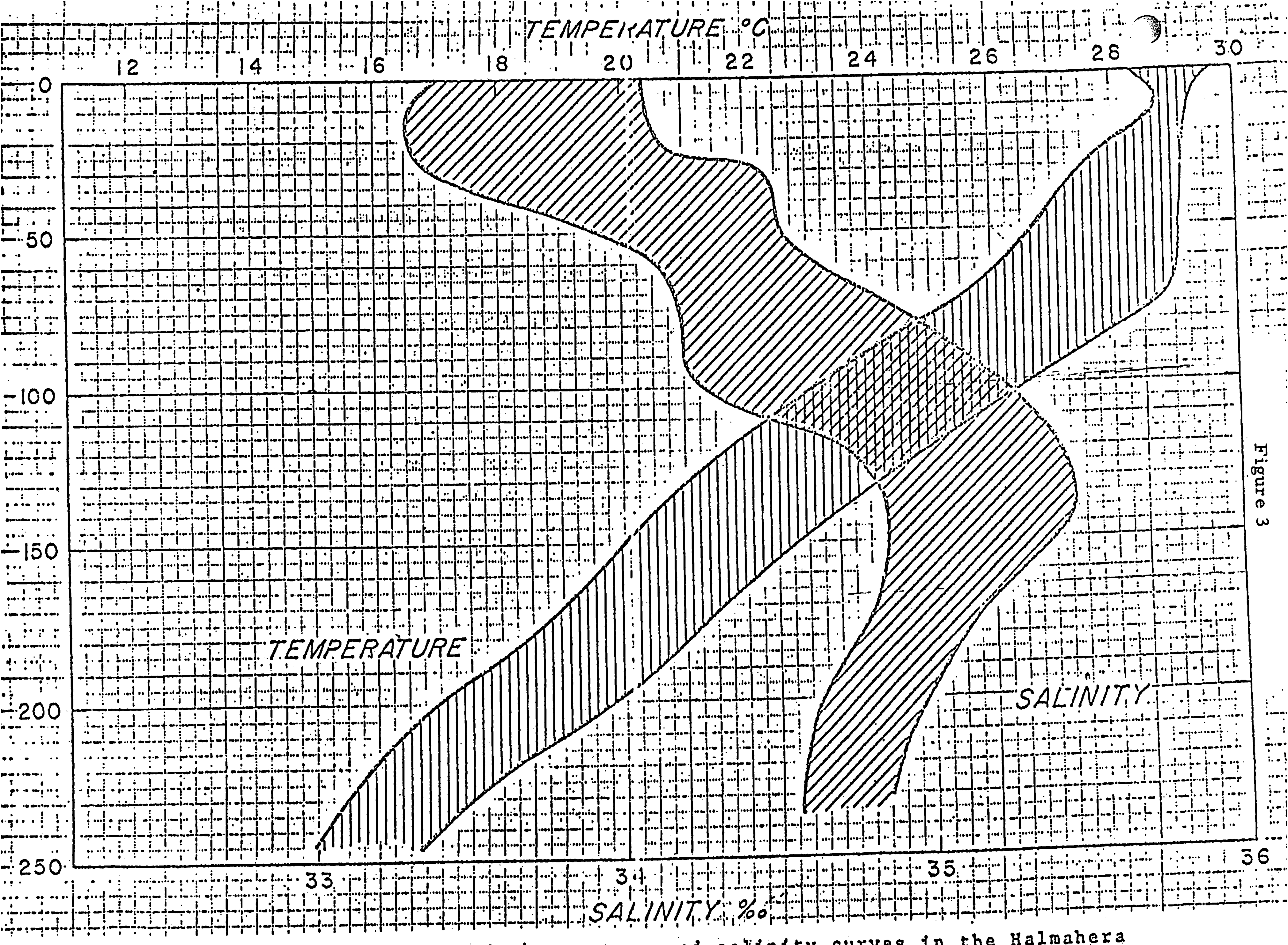


Figure 2

From Wyrtki 1972

Figure 5. Vertical distribution of temperature, density, oxygen content and salinity at SNELLIUS Station #353 in the Halmahera Sea.



~~Figure 3.~~ Envelopes of vertical temperature and salinity curves in the Halmahera Sea according to observations of the SIBOELA.

on the edge of the embayment: Gambier on the north shore and Camp 1 on the south-west shore. The preferred site for the head of the outfall is in the vicinity of Gambier (Morehouse, 1972).

Detailed offshore surveys for the area off the northeast coast of Gag have been run by Smith, More, and Keown (1972, Plan S835-11, 12, 13) showing relatively flat bottom to about 20M and a break in slope from 20 to about 200 meters (presumably the edge of the coral reef) and a ramp with slopes decreasing seaward in water deeper than 200 meters.

The embayment appears also in the bathymetry as a submarine valley with its head at 200 meters at the base of reef, (although in this area the reef front is not as steep as shown to the north), with various feeder channels converging to the apparent main channel at 300 meters near the current meter station (Plan No. 5835-13).

Wyrtki (1972) notes in deeper water beyond the detailed survey (1) north west of Gag is a deep channel (500M) about 12 nautical miles separating Gag from Waigeo Island, (2) south and southwest is a ten nautical mile wide channel separating Gag from a shoal area to the south increasing in depth from 850M to more than 1000M going southeast to southwest.

A more general survey (Chase and others, 1970) Fig. 1, suggests that the embayment east of Gag Island swings to the south and joins the southern channel which leads into a large Halmahera closed basin with depths exceeding 1800M (1000 fathoms) bounded by Halmahera on the north and west and Gebe on the northeast.

Physical oceanographic data reported by Wyrtki (1972) from the SNELLIUS Expedition is for the Halmahera basin and is shown as Fig. 2 and 3. The density structure is stable with (1) surface density rather low at 1.0224, (2) a well defined two part pycnocline (a) from 10 to 120 meters, ρ from 1.0224 to 1.025, (b) from 120 to 600 meters, ρ from 1.025 to 1.027 and (3) a deep isopycnal layer to the bottom. The oxygen profile shows the basin waters are well oxygenated with no oxygen minimum with the lowest oxygen values of about 3 ml/l beginning at the top of the second pycnocline.

Marine geologic data for the area is extremely sparse. A generalized bottom sedimentalogical map from Van Bemmelen (1949), Fig. 4, shows globigerina ooze (calcium carbonate) in the general vicinity of Gag with terrigenious muds (slightly reduced) in the Halmahera basin to the west of Gag and shelf sediments to the east around West Irian. However, investigation of the original data from the SNELLIUS (Neeb, 1943) and SIBOGA Expeditions (Boggild, 1916) shows actually very few samples were used to construct the map (Fig. 5). Sample S156 taken east of the island is coral sand whereas S151, S159, S-47, S148 and 353 taken respectively north, south and west of Gag are for foraminifera ooze, and calcium carbonate. Table II lists the pertinent facts on these samples.

TABLE II

Sample SIBOGA	Depth M	% C_aC03	Position		% < 0.05mm	
S147	2039	32.7	0°22'42"S	128°52'42"E	Sand	Glob. Ooze
S148	1855	36.9	0°17'42"S	129°14'30"E	97.3	Glob. Ooze
S151	845	69.2	0°12'42"S	129°48'E	82.7	Glob. Ooze
S156	469	88.0	0°29'12"S	130°5'18"E	3.7	Coral Sand
S159	411	64.8	0°59'6"S	129°48'48"E	14.8	Glob. Ooze
SNELLIUS						
353	1900	42.6			-	Glob. Ooze

From Neeb (1943)

These samples indicate a high calcium carbonate productivity in these waters from (1) coral reefs as shown by coral sands and from (2) planktonic foraminifera by the globigerina ooze samples which consist of tests or shells of floating single cell organisms.

The coral sand sample S156 at the depth of 469M suggest some type of bottom current transporting coarser sediment from the reefs in the area. The last lowering of sea level was only 200M so the sand could not be related to Pleistocene coral reefs or to subaerial stream transport at lower stands of sea level. In any case, much more sampling is needed around Gag Island to determine the lithology of the bottom sediments.

CHARACTERISTICS OF THE WASTE

Three distinct types of material are to be disposed (a) tailings solids (b) tailings solution and (c) BNC liquor from the processing plant. Their basic properties are given in Table III. Practically , the tailings solids plus solution are combined as the tailings slurry. A specific analyses of one slurry sample is found in Table IV. Accordingly there are three possible combinations of discharged material.

Case I	Discharge of BNC Liquor only thru separate outfall.
Case II	Discharge of the tailings slurry only through separate outfall
Case III	Discharge of both the BNC Liquor and the tailings slurry through one outfall

Figure 4

From Van Bemmelen (1949, p. 13)

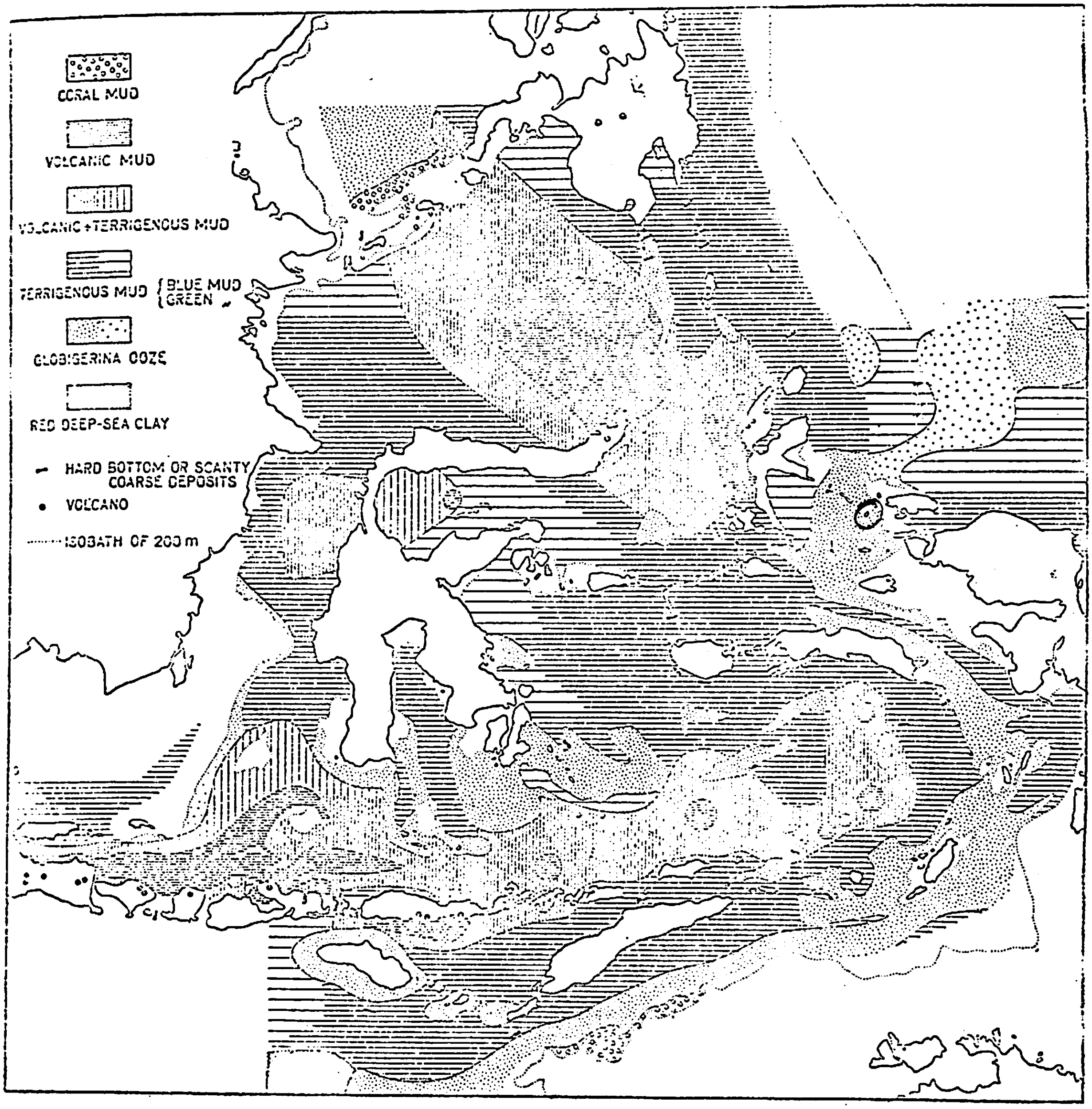
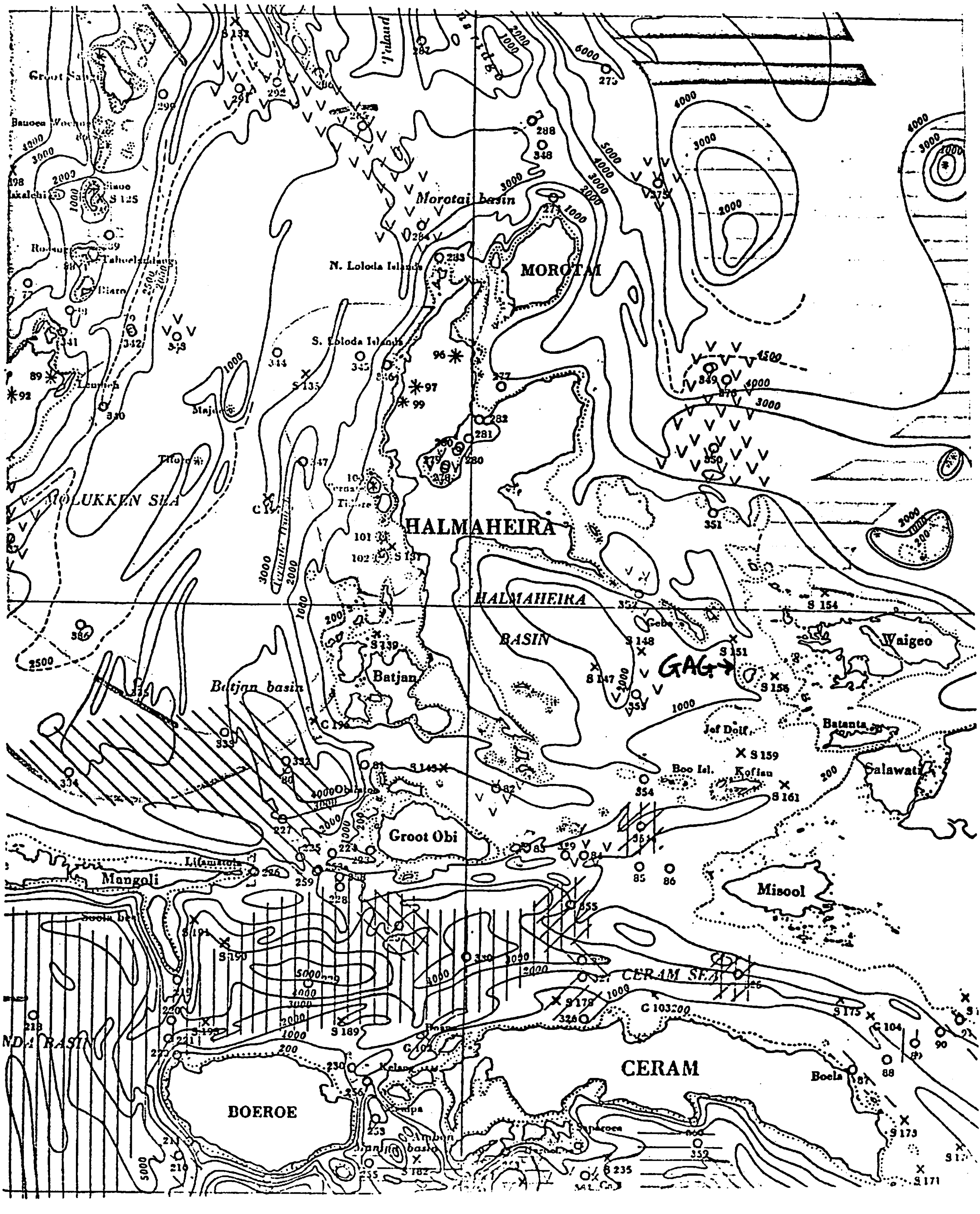


FIG. 10. *Chart of the deep sea deposits in the eastern part of the East Indies,* composed by NEEB, (1943) (somewhat simplified).

Figure 5



From Neeb (1943)

TABLE III

Projected Effluents

Component	Tailings Solids (percent)	Tailings Solution (grams per liter)	BNC Barren Liquor (grams per liter)
Fe	35 - 45	<0.1	<0.01
Ni	0.2-0.4	<0.1	<0.1
Co	<0.1	<0.1	<0.01
Mg	4 - 8	<0.5	<0.1
SiO_2	10 - 20	---	---
Cr	1 - 3	---	---
Al	4 - 8	---	---
Mn	1 - 2	---	---
CO_2	<0.5	<1.0	<2.0
S_T	<0.2	<0.5	3 - 5
Na	---	<0.1	1 - 2
NH_3	<0.2	<1.0	0.5-2
$S(SO_4)$	---	<0.5	0.5-1.5
$S(S_2O_3)$	---	<0.5	2.5-3.5
FLOW	12,000 tons/day 140 Kilograms / second	12,000 m^3/day 140 liters/sec	12,000 m^3/day 140 liters/sec

Approximate Particle Size of Tails (percent)

+250u	<2
+125-250u	<5
+ 63-125u	5-10
+ 44--63u	5-10
+ 30--44u	5-10
+ 20--30u	5-20
+ 10--20u	10-30
+ 5--10u	30-60
-5u	

The summary of the important characteristics for each case is given in Table V.

INTERACTION OF EFFLUENT WITH ENVIRONMENT

Given the three types of discharge materials the question now is what happens when they are introduced into the marine environment. The results of the interaction for each case will be divided into two categories (A) physical effects including mixing, changes of density, etc., and (B) chemical effects including possible chemical reactions with sea water on sediments. The physical and chemical oceanographic background environment is assumed to be that shown in Fig. 2. The composition of the bottom sediments is assumed to be carbonate sand or ooze in the area of interest. The conditions for the end of the discharge pipe are:

Depth	200M
Water Temp.	25°C
Density	1.0257 gm/cm^3
Oxygen	3.2 ml/1
pH	8.0

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TABLE IV

LABORATORY ANALYSIS REPORT

JOB NO. 9264-002

DATE 7/31/72

TITLE P T Pac. Nikkel - Mine Tailings

SHEET NO. 1 OF 3

SAMPLE NO.	DATE TAKEN	DATE REC'D	COLLECTOR	SAMPLE DESCRIPTION
2742		7/18/72		Mine Tailing Slurry Aliquot 1
2742'		7/18/72		Mine Tailing Slurry Aliquot 2
2742 A		7/18/72		Mine Tailing Filtrate Aliquot 1
2742 A'		7/18/72		Mine Tailing ~~Slurry~~ FILTRATE Aliquot 2

ITEM NO.	TYPE OF ANALYSIS	SAMPLE NO.					
		2742	2742'	Ave.	2742 A	2742 A'	Ave.
1	pH	9.50	9.50	9.50	9.50	9.50	9.50
2	Conductivity, umho/cm	11,000	11,300	11,150	11,500	11,700	11,600
3	Dissolved Solids g/liter	6.60	6.60	6.60	6.60	6.60	6.60
4	Total Solids g/liter	200	202	201	6.60	6.60	6.60
5	Suspended Solids g/liter	193	195	194	0.00	0.00	0.00
6	Hydroxide Alk. (OH) g/liter	1.2	1.2	1.2	1.3	1.3	1.3
7	Carbonate Alk (CO_3) g/liter	2.0	1.9	2.0	2.4	2.3	2.4
8	*Iodine Demand as (O_2) g/liter	0.48	0.44	0.46	0.48	0.48	0.48
9	** Chem. Ox. Dem. (O_2) g/liter	7.0	6.9	7.0	0.07	0.07	0.07
10	Total Org. Carb. (C) g/liter	.01	.01	.01	.01	.01	.01
11	Total Kjeldahl (N) g/liter	3.9	4.1	4.0	3.4	3.5	3.5
12	Ammonia (N) g/liter	3.0	3.1	3.1	3.0	3.1	3.1
13	Nitrate (N) g/liter	.001	.001	.001	.001	.001	.001
14	Ferrous Iron (Fe^{++}) g/liter	38.8	38.3	38.6	.01	.01	.01
15	Ferric Iron (Fe^{+++}) g/liter	50.9	51.4	51.1	.01	.01	.01

REMARKS: *Iodine demand due mainly to dissolved ferrous iron.

**Chem. Ox. Demand (COD) due mainly to ferrous iron.

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TABLE IV (cont)

LABORATORY ANALYSIS REPORT

JOB NO. 9264-002 DATE 7/31/72

TITLE P T Pac. Nikkel - Mine Tailings SHEET NO. 2 OF 3

SAMPLE NO.	DATE TAKEN	DATE REC'D	COLLECTOR	SAMPLE DESCRIPTION
2742		7/18/72		Mine Tailing Slurry Aliquot 1
2742'		"		" " " " 2
2742 A		"		" " Filtrate " 1
2742 A'		"		" " Slurry " 2

ITEM NO.	TYPE OF ANALYSIS	SAMPLE NO.					
		2742	2742'	Ave	2742 A	2742A'	Ave.
16	Chloride as (Cl) g/liter	---	---	---	0.03	0.03	0.03
17	Sulfate as (SO_4) g/liter	---	---	---	4.20	4.20	4.20
18	*Reducing Sulfur as (SO_4) g/liter	---	---	---	0	0	0
19	Iron as Fe_2O_3 % of Solids	---	---	80			.03
20	Si as SiO_2 T of Solids			12			1.0
21	Mg as MgO % of Solids			3			25
22	Al as Al_2O_3 % of Solids			2.5			.03
23	Cr as Cr_2O_3 % of Solids			1.3			.01
24	Mn as MnO_2 % of Solids			0.4			.03
25	Ni as NiO % of Solids			0.4			.6
26	Ca as CaO % of Solids			0.25			.3
27	Co as Co_2O_3 % of Solids			0.12			.01
28	Ti as TiO_2 % of Solids			0.10			ND
29	V as V_2O_3 % of Solids			0.05			ND
30	Cu as CuO % of Solids			0.04			.01

REMARKS: *Difference between SO_4 concentration and SO_4 concentration after oxidation of sample with iodine.

ND - not detected

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TABLE IV (cont)

LABORATORY ANALYSIS REPORT

JOB NO. 9264-002

DATE 7/31/72

TITLE P T Pac. Nikkel - Mine Tailings

SHEET NO. 3 OF 3

SAMPLE NO.	DATE TAKEN	DATE REC'D	COLLECTOR	SAMPLE DESCRIPTION
2742		7/18/72		Mine Tailing Slurry Aliquot 1
2742'		"		" " " " 2
2742 A		"		" " Filtrate " 1
2742 A'		"		" " " ~~Slurry~~ " 2

ITEM NO.	TYPE OF ANALYSIS	SAMPLE NO.					
		2742	2742'	Ave	2742A	2742A'	Ave
31	Ba as BaO % of Solids			0.002			.02
32	Sr as SrO % of Solids			0.01			ND
33	Zn as ZnO			0.01			.001

REMARKS: Items 19 - 32 by spectrographic analysis and Atomic Absorption spectrophotometry.

CHECKED BY:

TABLE V

	Case I BNC	Case II Slurry	Case III BNC & Slurry
pH	9.5?	9.5	9.5?
Temperature	160°F	220°F	190°F*
Discharge			
Weight/Sec	140 Kgm	280 Kgm	420 Kgm
Volume/Sec	140 Liters	175 Liters	315 Liters
Density#	1.00 g/cm^3	1.60 g/cm^3	1.33 g/cm^3

Discharge (Q) = Velocity (v) x Cross-sectional Area (a)

For A 12 inch pipe (30 cm) A = 707 cm^3
For A 20 inch pipe (50 cm) A = 1963 cm^3 = 2 cu ft

	12 Inch Pipe	12 Inch Pipe	20 Inch Pipe
Velocity	198 cm/sec 6.2 ft/sec	248 cm/sec 8 ft/sec	160.5 cm/sec 5.1 ft/sec
Discharge	4.6 cu ft/sec	5.6 cu ft/sec	11.2 cu ft/sec

? Estimate Because of High Ammonia Content
* A 1:1 Mix by Volume in Absence of Enthalpy Data
\# Assuming ϱ = 1.00 for Fluids and 4.00 g/cm^3 for Solids
Or 140 Kilograms Solids/4.00 g/cm^3 = 35 Liters solids/sec

Case I - DISCHARGE OF BNC LIQUOR ONLY

Physical Interactions

The differences between the environment and the discharge at the end of the outfall are:

	Environment	Effluent	Δ
Water Temp.	25°C	72°C	+47°C
Density	1.0257/cm^3	1.00	0.0257
Oxygen	3.2 ml/l	Reduced	-(oxygen demand)
pH	9.5	8.0	+1.5
Velocity	0,33 ft/sec	6.28 ft/sec	+5.9 ft/sec
Froude Number		6.2	

As the effluent has (1) a higher temperature, (2) a lower density with respect to the ocean and (3) is being discharged at some positive velocity out the end of a pipe in (4) a deep water, the situation is similar to that of marine sanitary outfalls as shown in Table VI; although for the Gag Island situation the temperature is hotter, the depth greater and the Froude number lower. Current practise in the design of marine sanitary outfalls use equations developed by Brooks (1960) (see Norris and Kensnar (1971, p. 18-19) on the proposed design of San Francisco's deep marine outfall) where initial dilutions of 100 parts sea water to one part effluent are accomplished by use of diffusers. Unfortunately at this stage of the analyses insufficient time or date is available to use the computer solutions developed by Ditmars (1969). However, estimates of the performance of the discharge jet can be made using work done by Pearson (1961), Rawn and others (1960) Hart (1961); summarized by Wiegel (1964, Chap. 16 Mixing Processes). Although no decision has been made on the orientation of the discharge pipe as the water is so deep (660 feet) and the discharge velocity so low, the jet may be considered vertical so that Table VII may be used. The Froude number is less than ten so the jet must be considered by buoyancy Case II of Table VII and depicted in Fig. 6b.

Solutions of concentration and velocity ratios as a function of Froude numbers and depth-diameter of discharger ratios are given in Fig. 7. The limiting velocity ratio Um/ Uo is 0.05 or 0.33/6.3 where the velocity at the jet axis equals the ambient environmental velocity which is off scale of Fig. 7 at Z/Do =150 or the plume will rise at least to 150 feet above the discharge. However, such results are not strictly true,as in this case the discharge is not into water of uniform density but into the pycnocline of varing density so the mixing water is somewhat heavier reducing the buoyancy.

Figure 6

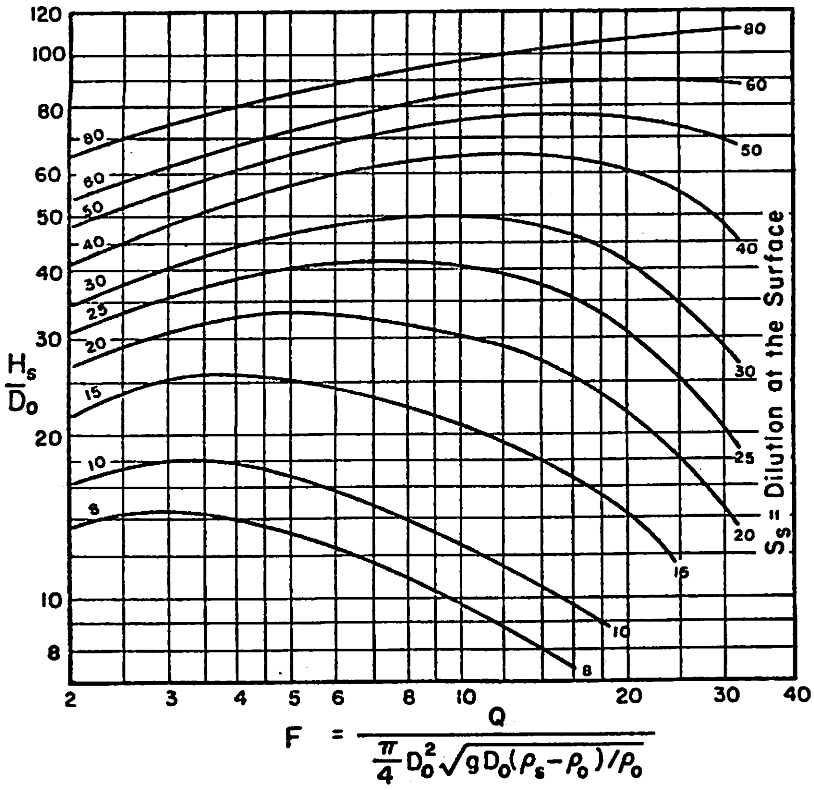


Fig. 16.13. Dilution at the surface, S_s, as a function of H_s/D_o and N_F for horizontal discharge (after Rawn, *et al.*, 1960)

$$N_F = \frac{Q}{\pi/4} D_o^2 \sqrt{gD_o(\rho_s - \rho_o)/\rho_o} = \frac{u_o}{\sqrt{gD_o(\rho_s - \rho_o)/\rho_o}},$$

where ρ_s is the density of the receiving water and ρ_o is the density of the effluent.

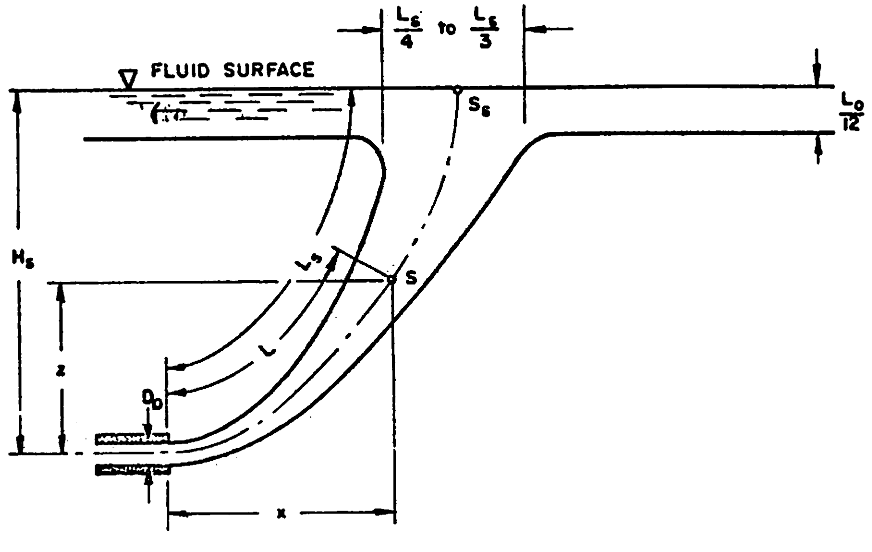


Fig. 16.12. Sketch of single rising column (after Rawn, *et al.*, 1960)

Table VI

TABLE 1.—TYPICAL DIMENSIONS OF CALIFORNIA OCEAN OUTFALLS[a] AND CONDITIONS OF SOUTHERN CALIFORNIA OFF-SHORE WATERS[5]

Item	Range of Value		Diffuser	Source[b]
	High	Low		
Depth of outlet below air-water surface, H, in feet	210 54	6 0	yes no	3 3
Diameter of discharge opening, D, in feet	0.83 2.5	0.33 0.33	yes no	3 3
Velocity of discharge, V, in feet per second	19.55 5.92	4.01 0.44	yes no	3 3
Ratio of depth to diameter, H/D	343 21	7.2 0	yes no	3 3
Froude number, $\mathbf{F}$	21.35 5.28	5.67 0.33	yes no	3 3
Temperature of effluent, in °F	83	63		2
Salinity of receiving waters, in gm per liter	34.3	33.5		4,2,1
Temperature of receiving waters, in °F	76	49		4,2,1
Density of receiving waters, ρ_s, in gm per cc 10^{-3}	25.9	22.5		4,2,1
Density difference, surface, and bottoms, in gm per cc	0.0018			4,2,1

[a] Extreme ranges are not always given, but the majority of outfalls occur within the values quoted.

[b] The sources are (1) Allan Hancock Foundation, (2) Caldwell, Hyde and Rawn, (3) Pearson, and (4) Stevenson, Tibby, and Gorsline.

Table VII

TABLE 1.—FORMULAS DESCRIBING DISTRIBUTION OF CONCENTRATIONS AND VELOCITIES IN A TURBULENT WATER JET DISCHARGED VERTICALLY UPWARD INTO WATER OF HIGHER DENSITY

I. Non-buoyancy Case, $F = \infty$

- A. Zone of Flow Establishment: $z/D < 6.4$ for velocities, $z/D < 5.2$ for concentrations.
  1. For $y < D/2 - 0.078z$: $u/u_o = 1$
     For $y > D/2 - 0.078z$: $8/u_o = \exp(-77(y + 0.078z - D/2)^2/z^2)$
  2. For $y < D/2 - 0.096z$: $c/c_\rho = 1$
     For $y > D/2 - 0.096z$: $c/c_o = \exp(-62(y + 0.96z - D/2)^2/z^2)$
- B. Zone of Established Flow: $z/D > 6.4$ for velocities, $z/D > 5.2$ for concentrations.
  1. $u/u_m = \exp(-77(y/z)^2)$, $u_m/u_o = 6.4D/z$
  2. $c/c_m = \exp(-62(y/z)^2)$, $c_m/c_o = 5.2D/z$

II. Buoyancy Case, $F \rightarrow 0$

- A. $u/u_m = \exp(-80(y/z)^2)$, $u_m/u_o = 3.65\ F^{-2/3}(z/D + 2)^{-1/3}$
- B. $c/c_m = \exp(-80(y/z)^2)$, $c_m/c_o = 9.7\ F^{-2/3}(z/D + 2)^{-5/3}$

III. Intermediate Case, moderate values of F

$$\frac{g\int_o^{z_t} dz \int_o^\infty 2\pi y\,(\rho_n - \rho)\,dy}{u_o^2\,(D^2/4)}$$

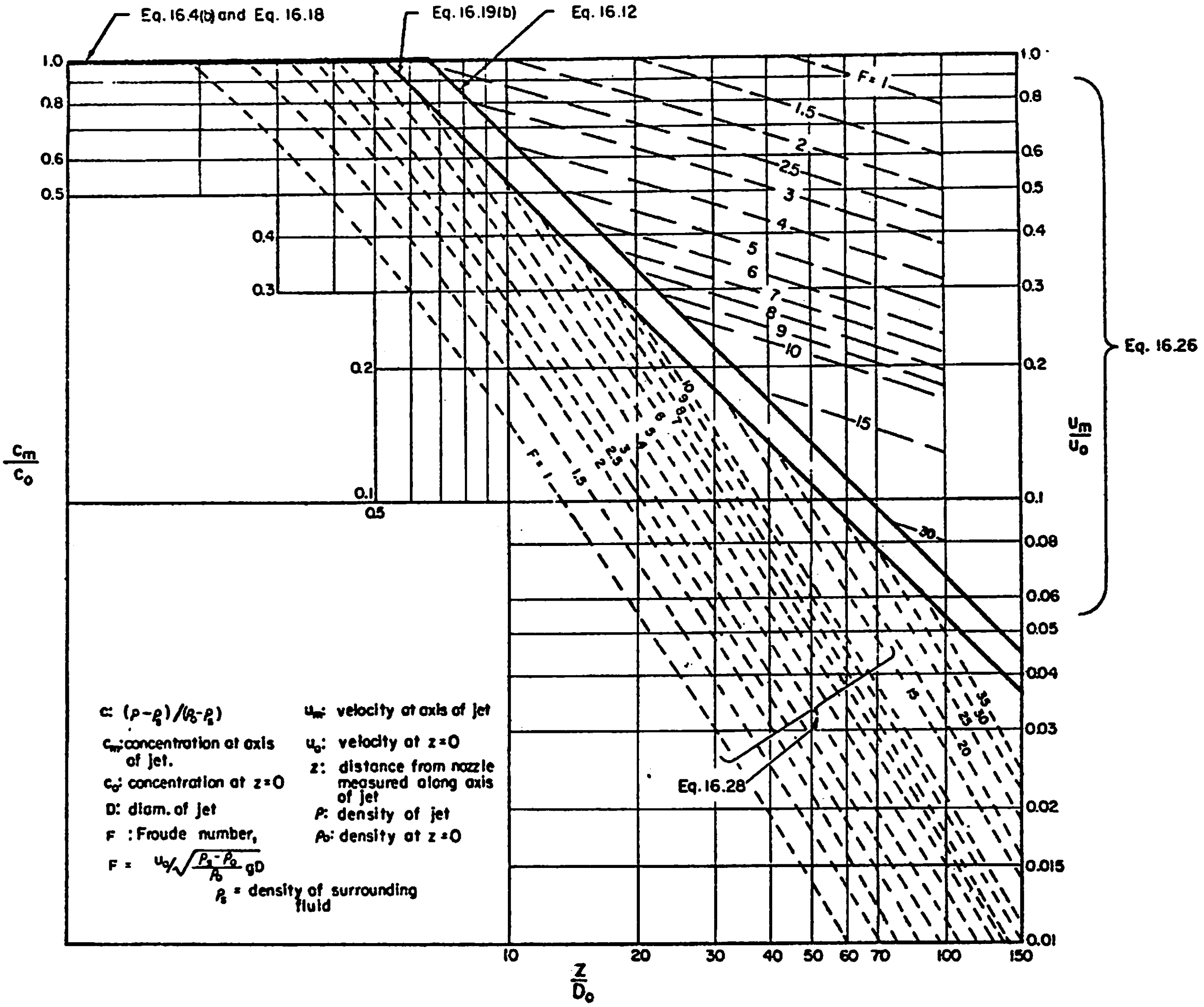
- A. For velocities: $(z_t/D)^2 \approx 5.94\ F^2$
- B. For concentrations: $(z_t/D)^2 \approx 5.94\ F^2$

(1) The concentration, c, is defined as $(\rho - \rho_n)/(\rho_o - \rho_n)$.

(2) z_t is the value of z for which the equations of the non-buoyancy and buoyancy cases coincide. F must be greater than about 10.

From Hart (1961, p. 175)

Figure 7



From Wiegel (1969)

Fig. 16.9. Concentration and velocity along jet axis (adapted from Abraham, 1960)

$$\frac{u}{u_o} = 1, \quad \text{for } y < \frac{D_o}{2} - C_2 x \qquad (16.4b)$$

$$\frac{c}{c_o} = 1, \quad \text{for } r < \frac{D_o}{2} - C_3 x. \qquad (16.18)$$

$$\frac{c_m}{c_o} = \frac{1}{2C_3}\frac{D_o}{x}. \qquad (16.19b)$$

for $(x/D_o > 6 \text{ or } 7)$,

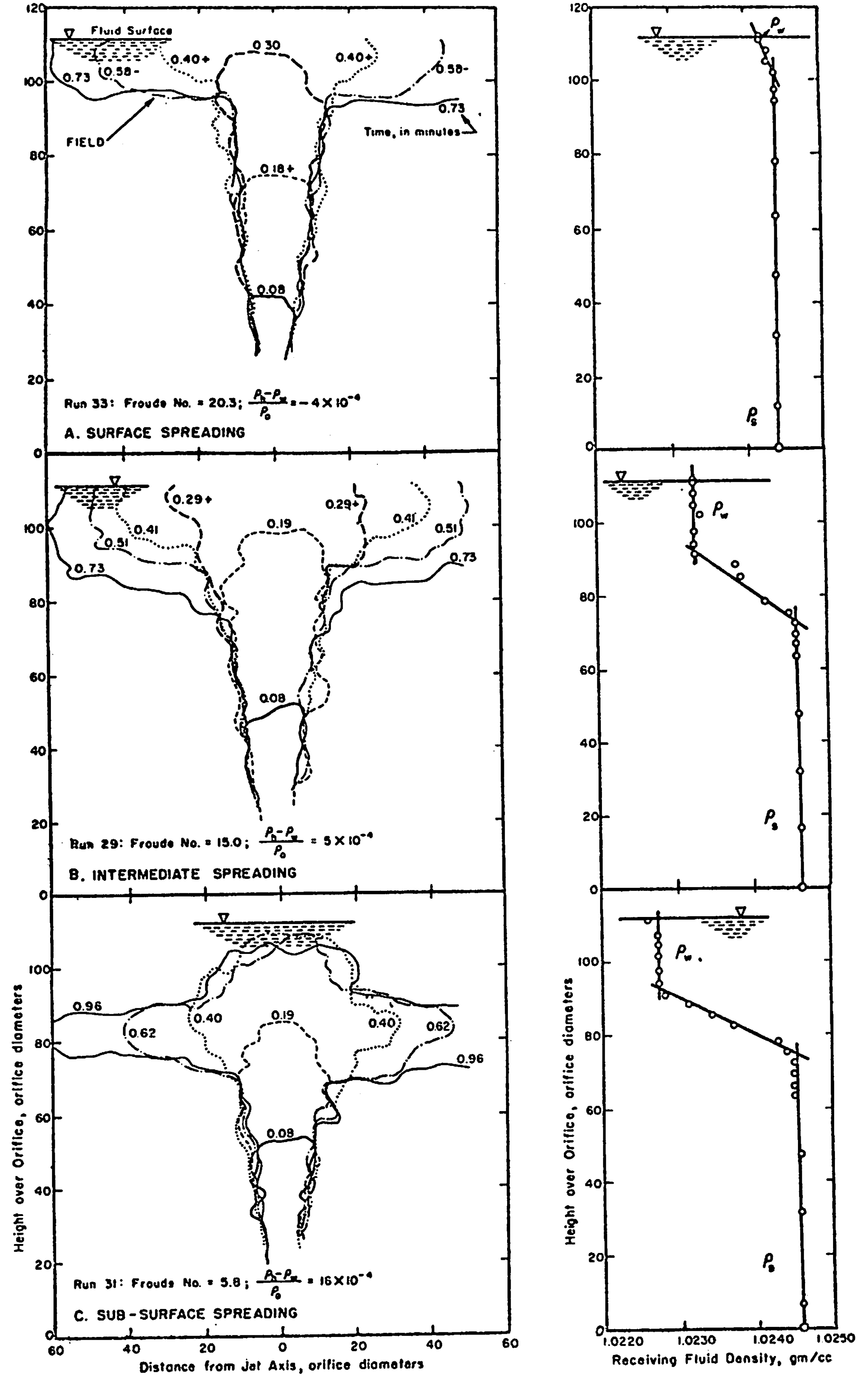
$$\frac{u_m}{u_o}\frac{x}{D_o} = 6.2 \qquad (16.12)$$

for the circular orifice.

$$\frac{u_m}{u_o} = 3.65 N_F^{-2/3}\left(\frac{x}{D_o} + 2\right)^{-1/3}, \qquad (16.26)$$

$$\frac{c_m}{c_o} = 9.7 N_F^{2/3}\left(\frac{x}{D_o} + 2\right)^{-5/3}, \qquad (16.28)$$

Figure 8



JET AND FIELD PROFILES AT TIMES (IN MINUTES) AFTER START OF TEST

DENSITY-HEIGHT CURVE FOR RECEIVING FLUID AT START OF TEST

Fig. 16.15. Jet and field profiles and density-height curve (adapted from Hart, 1961)

Various test models of discharge plumes are shown in Feg. 9. All unfortunately being discharged into the deep isopycnal layer. Rawn and others (1961) showed to produce a completely submerged field below a thermocline.

$$\frac{(Sp-1)\rho d-\rho o}{Sp} > \rho s$$

Where:

Sp = Volumetric Dilution Factor
= $1/p$; p = Fraction of Discharged Material
ρd = Density at Depth
ρo = Initial Density of Effluent
ρs = Density of Surface Isopycnal Layer

For $\rho d = 1.0257$
$\rho o = 1.00$
$\rho s = 1.0223$

The field will stay submerged for dilutions greater than $Sp = 7.55$

Rawn and others (1960) have plotted for a homogeneous ocean the dilution factor as a function of depth in discharger diameters, and Froude number Figs. 9 and 10. The critical value of Sp as of 7.5 occurs at H/D of 12 or 12 feet above the discharger. At H/D of 100 or 100 feet Sp = 100 for Froude number of about 6. Fig. 11 shows various schemes for increasing dilution. Another way to increase dilution is to discharge at some depth below the thermocline (actually the pycnocline in the real ocean) where dilution is caused by spreading of the jet under the pycnocline if the critical value of Sp is exceeded. Hart (1961, p/ 190) developed the relationship:

$$Sp = 1 + 1.18\,(10^{-2})\,(H + 3)^{3.25}$$

which is computed for various depths and H/D in Table VIII.

In summary for Case I discharge of BNC liquor as the density and the Froude number are low the discharge is buoyant and will rise as a jet probably to the base of the surface mixed layer. The dilution factor at 100 feet above the pipe is about 100 although in reality it must be somewhat less as the mixing is in the pycnocline and not in the isopycnal layer as is assumed in both the Rawn and other (1960) and the Hart (1961) experiments.

CHEMICAL INTERACTIONS

The BNC liquor is a fluid and as the discharge is positively buoyant, all mixing and reactions will be (1) with the overlying sea water for a submerged field or (2) with sea water and the atmosphere for a surface field. In the BNC

Figure 9

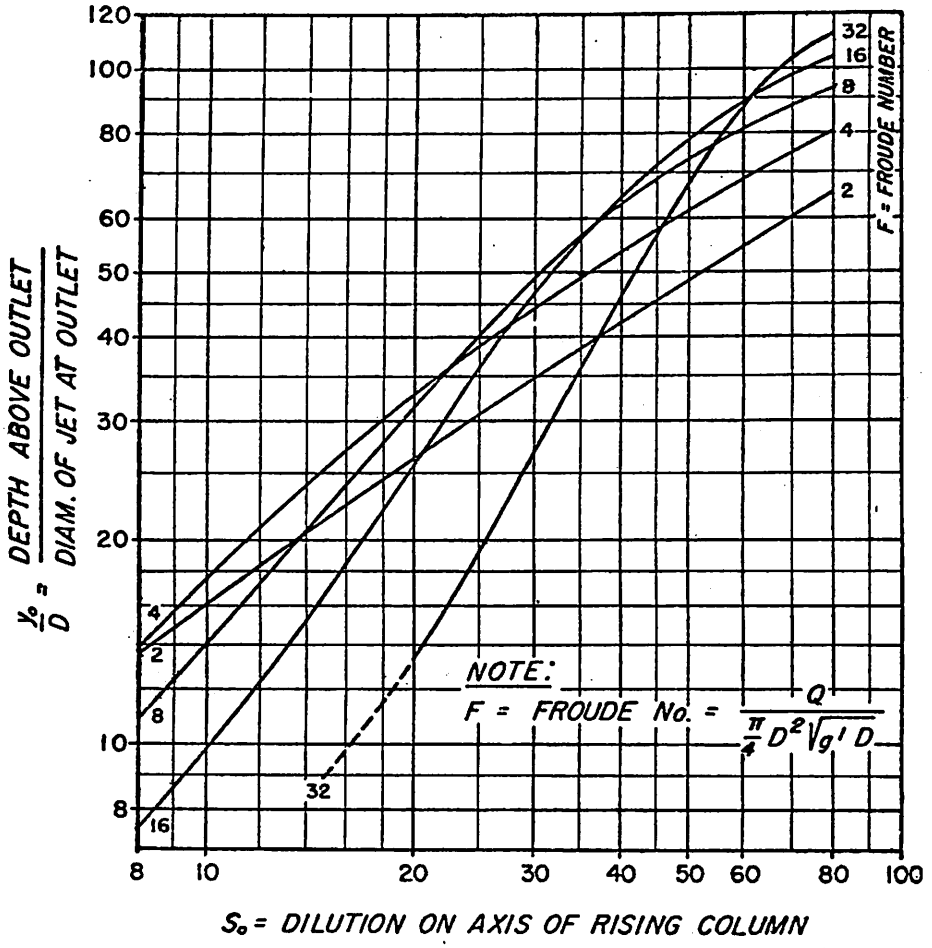


FIG. 8.—DILUTION AS A FUNCTION OF y_o/D FOR CONSTANT F FOR HORIZONTAL DISCHARGE

From Rawn and Others
(1960, p. 84)

Figure 10

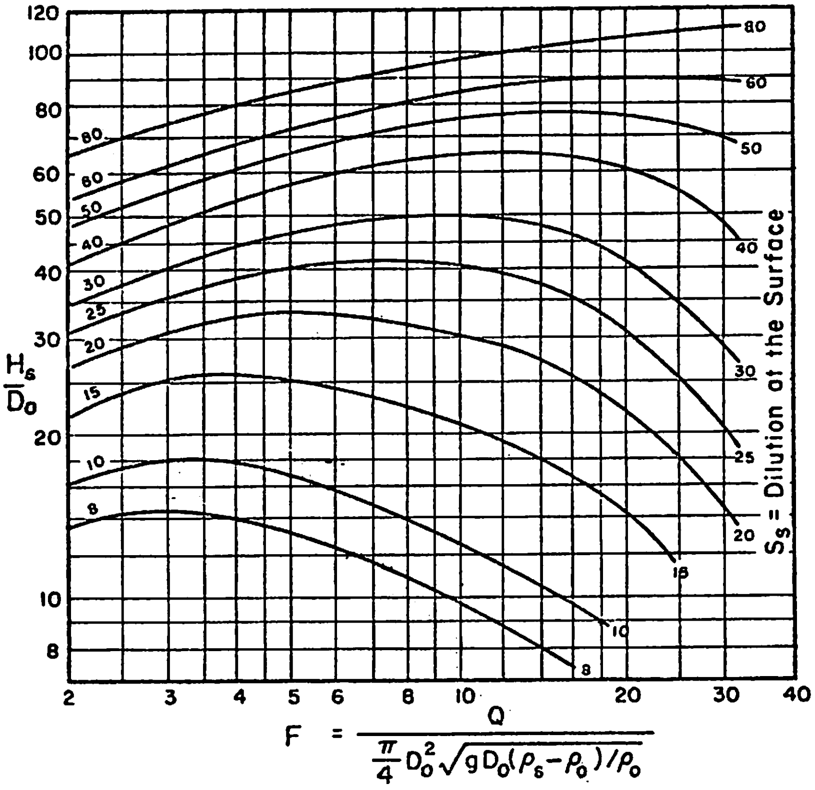


Fig. 16.13. Dilution at the surface, S_s, a a function of H_s/D_o and N_F fo horizontal discharge (after Rawn *et al.*, 1960)

TABLE VIII

Dilution as function of height above discharger with developed pycnocline

For $Q^{0.61}$ - 2.5 See Hart (1961, p. 190)

Height* in feet	Sp#
660	6.9×10^{6}
600	5.1×10^{6}
500	2.8×10^{6}
400	1.38×10^{6}
300	5.5×10^{5}
200	1.48×10^{5}
100	1.64×10^{4}
50	1.9×10^{3}
40	9.6×10^{2}
30	4×10^{2}
20	1.25×10^{2}
10	2×10^{1}
5	1×10^{0}

* Height measured along centerline of jet to center of thermocline (pycnocline). Essentially = H/D for a one foot diameter pipe.

\# Assumes mixing with water of constant density. Mixing with water of decreasing density would reduce the value of Sp.

Figure 11

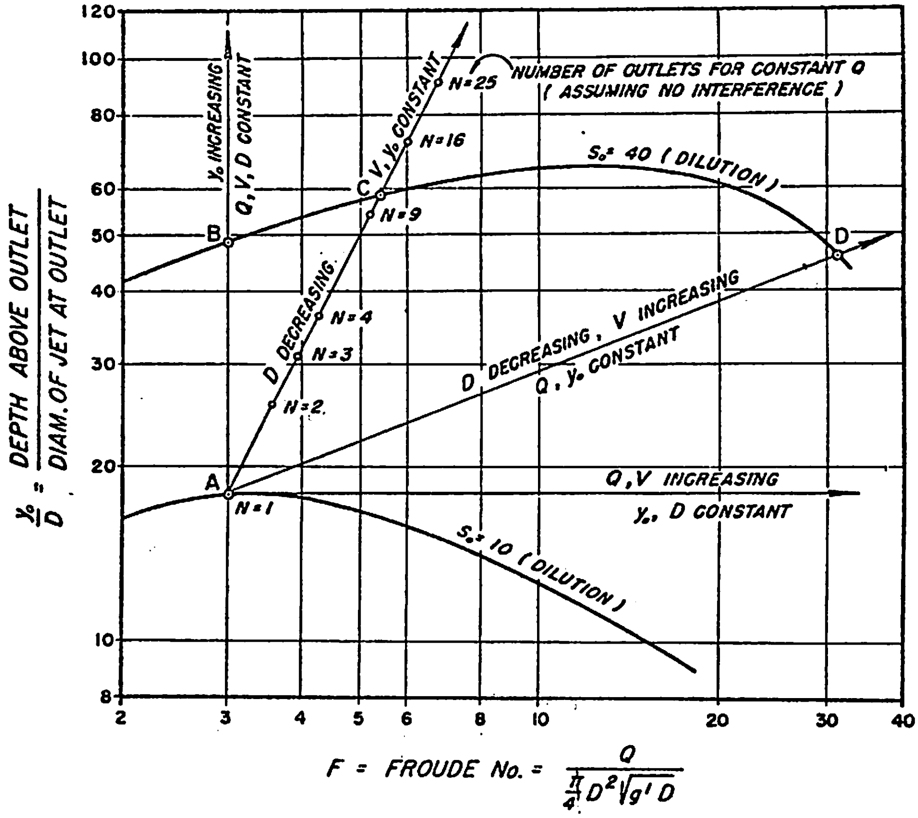


FIG. 9.—DIFFERENT METHODS FOR INCREASING DILUTION

From Rawn and Others
(1960, p. 85)

liquor the compounds with potentially deleterious environmental effects are ammonia with initial concentrations up to 2.0 g/l and thiosulfate up to 3.5 g/l. As shown by equilibrium calculations by Wyrtki (1972) both compounds have potential oxygen demands. However, the rate of oxidation is very slow as work on (a) ammonia by Downing and Knowles (1920) Fig. 12) indicated a half-life of ammonia by oxidation to nitrate is about 3 to 4 days in the presence of oxygen and nitrogen bacteria and (b) thiosulfate by Chen and Morris (1970) Fig. 13) shows thiosulfate is stable in alkaline pH for at least 3 days and is the dominant species during the oxidation of reduced sulfur as sulfide.

Fig. 14 indicated if the ammonia level can be reduced to 0.7 mg/l or by 10^{-3} there is essentially no effect on ambient oxygen levels in the environment due to ammonia. Thus, both ammonia and thiosulfate have no effective oxygen demand if diluted sufficiently and are added to oxygen rich waters.

However, the major environmental impact of unoxidized ammonia is its toxicity at alkaline pH to both fish and plant life (McKee and Wolf, 1963, p. 139), (Table IX). Thus the dilution of ammonia because of toxicity should be from 1.5 g/l to below .15 mg/l or by an additional order of magnitude to $(10)^{-4}$

The initial calculations of the behavior of the discharge jet indicates the plume will rise at least to the base of the surface mixed layer at a depth of only 10 meters then spread laterally. The bottom sediments near by are chiefly carbonate sands and oozes which have a significant content of foraminifera shells indicating a reasonably high productivity rate of planktonic organisms in the area. In general the plankton move up and down near the surface as a function of light. Thus the 10 meter depth is shallow enough for large numbers of plankton besides fish to traverse daily.

It seems unlikely that dilutions as great as 10^{-4} can be obtained before the plume reaches 10 meters. Thus there would be a patch of highly toxic water over the outfall near the surface with toxicity decreasing roughly concentrically from the center of the plume until the effluent is diluted to safe levels by lateral mixing. If the plume surfaces the area of the toxic zone will decrease as surface wave action will increase the rate of dilution.

Figure 12

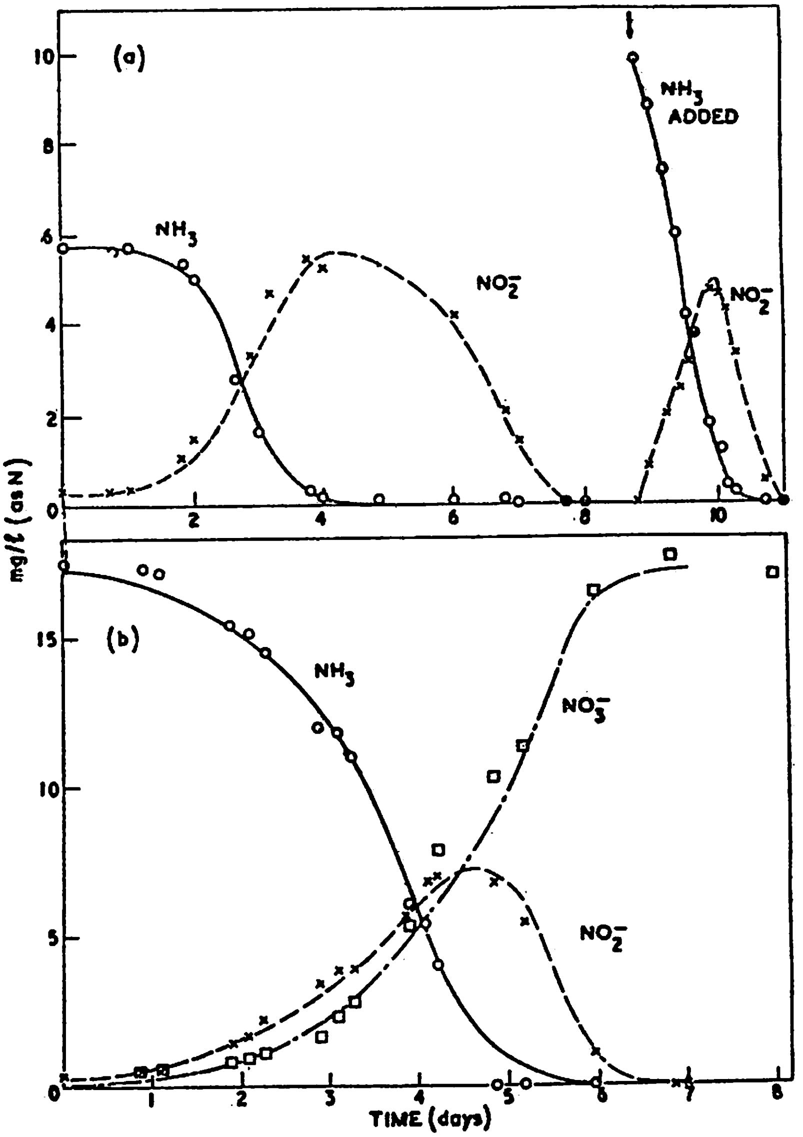


Fig.1. Actual course of nitrification in incubated samples of estuary water (points) and curves calculated assuming that the system obeys bacterial-growth kinetics according to equations 5 to 8 in the text.

(a) Extra ammonia was added on the ninth day–nitrate was not measured. Temperature 29.3–30.8; k_M 1.95/day; k_B 2.0/day

(b) Temperature 18.8°C; k_M 0.6/day; k_B 2.0/day

From Downing and Knowles
(1970)

Figure 13

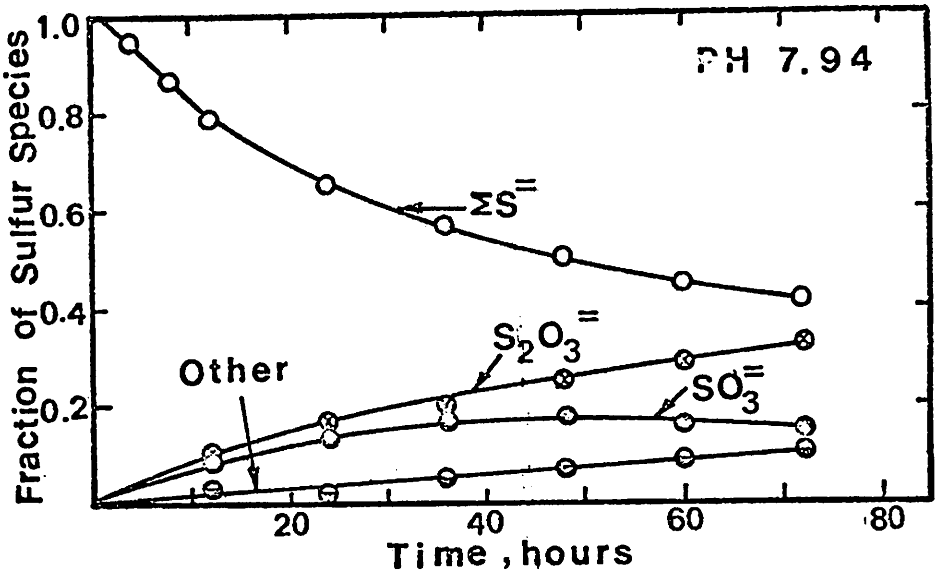


Fig. 1. Kinetics of Sulfide Oxidation by O_2, pH 7.94.
$\Sigma S^= = 1 \times 10^{-4}$ M, $[O_2] = 8 \times 10^{-4}$ M

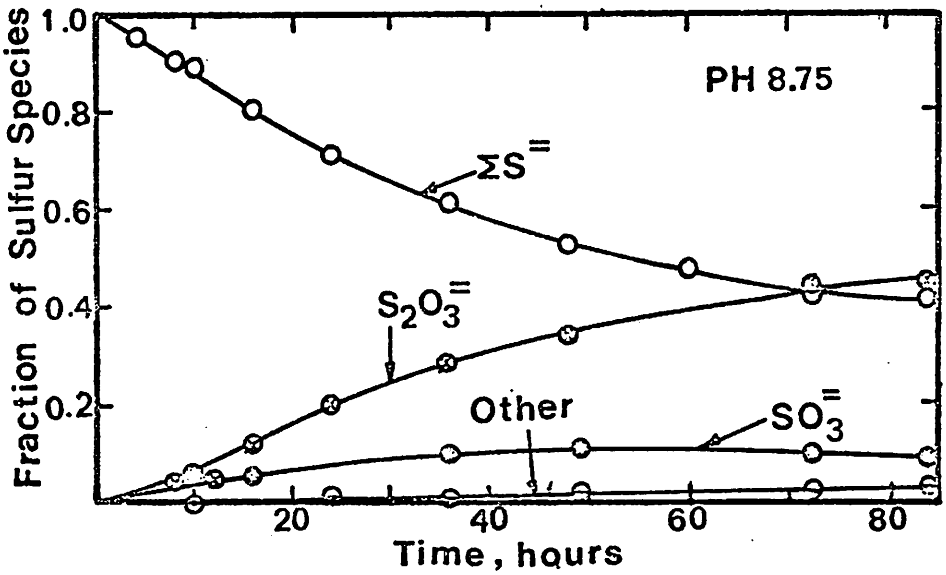


Fig. 2. Kinetics of Sulfide Oxidation by O_2, pH 8.75.
$\Sigma S^= = 1 \times 10^{-4}$ M, $[O_2] = 8 \times 10^{-4}$ M

From Chen and Morris
(1950)

Figure 14

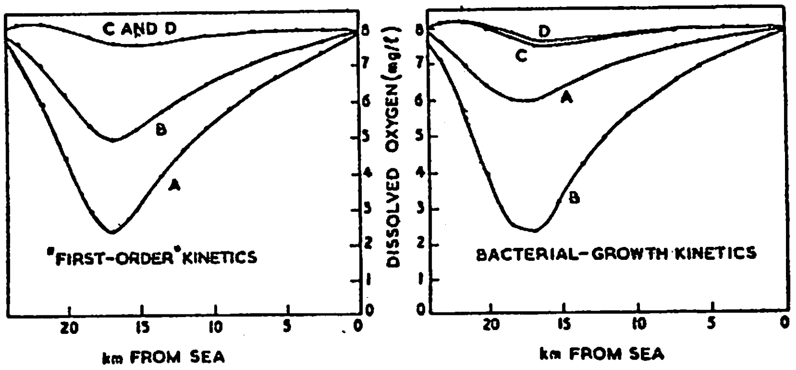


Fig.4. Predicted effects of nitrification on dissolved oxygen distribution in a hypothetical estuary receiving an effluent from an activated-sludge plant in its central reaches assuming (a) first-order kinetics, (b) bacterial-growth kinetics. Freshwater flow from river 25 m.g.d. (113,650 m^3/day). Point of entry of effluent 14.8 km from sea. A, effluent not nitrified; B, effluent half nitrified; C, effluent fully nitrified but with 0.7 mg N/l ammonia leak; D, no load, i.e. air-saturation values for dissolved oxygen, except for a slight influence of the 8 mg/l boundary value at landward and seaward boundaries.

From Downing and Knowles
(1970)

TABLE IX

The following concentrations of ammonia have been reported to be toxic or lethal to fish in the time specified:

Concentration NH_3 in mg/l	*Time of Exposure*	*Type of Fish*	*Reference*
0.3-0.4	--	trout fry	1465
0.3-1.0	--	fish	1044
0.6*	100-200 minutes	rainbow trout	88
0.7	390 minutes	rainbow trout	2970
1.0-2.0	--	fish	1465
1.2	193 minutes	*Squalius cephalus*	2970
2.0	--	fish	1045
2.0-2.5	1-4 days	goldfish	313
2.5	1-4 days	goldfish	1466
2.0-7	--	fish	1460, 1466
2.9	13 hours	*Cichla ocellaris*	145
3.1 (soft water, 30°C)	96-hour TL_m	bluegill sunfish	2936
3.4 (soft water, 20°C)	96-hour TL_m	bluegill sunfish	2936
5.0		rainbow trout	2977
5-7 (distilled water, 20°C)	6 hours	minnows	2942
6-7 (hard water, 20°C)	6 hours	minnows	2942
7-8	1 hour	sunfish	363
13	--	fish	346
17.1	1 hour	minnows	362
17-136	15-16 minutes	eel, roach, trout	1467
23.7 (hard water, 30°C)	96-hour TL_m	bluegill sunfish	2936
24.4 (hard water, 20°C)	96-hour TL_m	bluegill sunfish	2936
75.7	less than 4 minutes	trout	146

*un-ionized ammonia

Brockway (1044) states that an ammonia concentration of 1.0 mg/l decreases the ability of the hemoglobin to combine with oxygen and hence the fish may suffocate. A concentration as low as 0.3 mg/l causes a noticeable drop in the oxygen content of the blood of fishes. In the foregoing table, the work of Ellis (313) is most widely quoted and concentrations of 2.5 mg/l have been considered harmful in the pH range from 7.4 to 8.5. Ellis reports, however, that concentrations of 1.5 mg/l are not harmful to most varieties of fish and Schaut (362) claims that minnows were not harmed by a one-hour exposure to 4.3 mg/l. Solutions containing mixtures of ammonium and cyanide ions are more toxic to fish than solutions containing either ion alone (1468).

With respect to other aquatic life, the following results were reported by the Academy of Natural Sciences of Philadelphia (2936):

Organism	*Time of Exposure*	*Type of Water*	*Temperature °C*	*Concentration of NH_3 as N in mg/l producing noted effect*
Physa heterostropha (snail)	96-hour	soft	20	90 (a)
		hard	20	133.9 (a)
		soft	30	94.5 (a)
		hard	30	133.9 (a)
Navicula seminulum (diatom)	5-day	soft	22	420 (b)
		hard	22	420 (b)
		soft	28	320 (b)
		hard	28	420 (b)
		soft	30	410 (b)
		hard	30	350 (b)

(a) 96-hour TL_m
(b) 50-percent reduction in division (growth)

Algae, which thrive on high nitrate concentrations, appear to be harmed or inhibited when the nitrogen is in the form of ammonia. Gusseva (584) reported that 0.4 to 0.5 mg/l of ammonia nitrogen caused a complete disappearance of *Aphanizomenon*. The lethal concentration of ammonia for *Daphnia* has been reported at 8 mg/l (2977). Stammer (147) reports the following toxicity threshold values for indicator organisms of a saprophytic system, in terms of free ammonia:—Organisms of the oligosaprobic and β-mesasaprobic zones, 0.08 to 0.4 mg/l; those of the α-mesasaprobic zones 0.3 to 4.3 mg/l; and those of the polysaprobic zone 3.2 to 220 mg/l.

From McKee and Wolfe
(1963, p. 134)

CASE I
CONCLUSIONS

The positive buoyancy of the jet will produce a discharge plume which will rise to near the surface or actually to the surface into zones of high planktonic productivity. Because of the potential undiluted toxicity due to ammonia in the BNC liquor, a single discharge for this effluent is not recommended with its present chemical composition.

Possible ways to reduce the ammonia concentrations to levels where its potential toxicity can be diluted at depth to harmless surface concentrations are:

(1) Recycle the ammonia for reuse in the process plant.

(2) Removal of ammonia by shore side denitrification using standard sanitary engineering techniques of (1) air stripping or (2) ion exchange (Adams and others, 1970).

For examples (1) and (2) the ammonia should be reduced to a concentration at a single outfall of 15 mg/c which assumes a practical dilution of 10^{-2} before leaving the jet zone. This would be an S value of 100 which should be reached in the vicinity of 100 feet above the outfall.

CASE II
DISCHARGE OF TAILINGS SLURRY

CASE III
DISCHARGE OF BNC LIQUOR AND TAILINGS SLURRY

Physical interactions:

	Environment	Case II Effluent	Case II	Case III Effluent	Case III
Water temp.	25°C	104°C	+79°C	84°C	+65°C
Density	1.0257	1.60	+0.574	1.33	+0.3
Oxygen	3.2	Reduced		Reduced	
pH	8.0	9.5	+1.5	9.5	+1.5
Velocity	0.33 ft/sec	8 ft/sec	+7.67 ft/sec	5.1 ft/sec	4.77 ft/sec
	10 cm/sec	248 cm/sec		160.5 cm/sec	

The two possibilities can be considered together as both have bulk densities greater than the environment. Much of the experience with effluents of greater density than ambient is with fluids with a high dissolved solids content, such as brines from desalination plants rather than with mixtures of particulate solids and fluids such as the mine slurry. Studies on the properties of brine discharges also are designed to mix or dilute the brine rapidly thus the effluent is ejected upward against the density contrast. Work by Turner (1966) and Abraham (1967) show for such brines the jet (1) rises to some level above the discharger until the initial inertia of the upward moving jet is overcome by the negative buoyancy of the brine then (2) collapses back down and spreads laterally around the discharge. A good analogy is the behavior of an upward water jet in a fountain. Design criteria for brine disposal by dilution by fountaining is given in Zeitoun and others (1970).

However, with such high density contrast and the discrete particle load of the effluent, use of such a technique here may clog the exit ports with particles if the lateral velocities away from the port are not competent enough to transport the particles. Thus the settling velocities of the mine slurry particles must be known. The solids have a density of 4.00 and a grain size distribution as follows:

Classification	Size Fraction Millimeters	Microns	Percent
Medium Sand	.250	250	2
Fine Sand	.125-.250	125-250	5
Very Fine Sand	.063-.125	63-125	5-10
Silt	.044-.063	44-63	5-10
Silt	.030-.044	30-44	5-10
Silt	.020-.030	20-30	5-20
Silt	.010-.020	10-20	10-30
Silt	.005-.010	5-10	30-60
Clay	.005	5	

Accordingly most of the particles have settling velocities governed by Stokes Law:

$$V_s = 2/9 \; \frac{\rho_s - \rho_f)\, G\, r^2\, (.64)}{\mu}$$

Where: ρ_s = Density of Particle
ρ_f = Density of Media
G = Acceleration Due to Gravity
μ = Viscosity

As Stokes Law is for spheres a correction of 64% is needed to correct for the settling tendency of non-spherical particles (Krumbein and Pettijohn, 1938, p. 107).

The variables for our examples are (1) the density of the settling media which would range from the bulk density of 1.60 (Case II) or 1.33 (Case III) to 1.025 that of the environment, and (2) the viscosity which is a function of temperature from a minimum of 0.002838 poise (104°C) (Case II) or 0.0033 (84°C) to .016 that of the environment. Settling velocity curves for these range of valves are shown in Fig. 15 along with curves in seawater for normal silicate sediment with a ρ of 2.65. The graphs indicate that with decreasing fluid density and viscosity the denser particles behave as coarser particles with a lower density. This property is called hydraulic equivalence. Thus a 10 micron particle with a density of 4.0 in a flow of bulk density 1.6 at a temperature of 220°F has the same settling velocity as a 40 micron particle of density 2.65 settling in a similar bulk density flow (shape factors are assumed equal). Knowledge of the hydraulic equivalence is important because most data on flows and settling in the ocean are for natural materials with a density of 2.65. For example, the erosion-transportation-deposition graph (Fig. 16) as a function of grain size and current velocity is for sediments with a density of 2.65. For use in Fig. 13 the grain size of the high density particles has been converted to that of 2.65 by hydraulic equivalence, for the various possible conditions and for converted grain size of .030 millimeters of 30 microns which is the upper limit of the most abundant grain size population.

HYDRAULIC EQUIVALENT

Equivalent = 4°C
Equivalent = 2.65
Equivalent = 1.64

Temp. Eff.	25°C.			84°C			104°C		
eff.	1.60	1.33	1.025	1.60	1.33	1.025	1.60	1.33	1.02
Tailings Particle Size									
.030mm	.054	.060	.062	.096	.11	.12	.12	.125	.13
30 Microns	54	60	62	96	110	120	120	125	130
	Equivalent = 1.04								
.030mm	.042	.046	.048	.074	.081	.085	.085	.089	.097
30 microns	42	46	48	74	81	85	85	89	97

Now using Figure 16 we see that for oceanic velocities of 10 cm/sec caused by tides etc. (Wyrtki, 1972) All material finer than .6mm in suspension would be carried by such a current and material coarser than .6mm would settle out. As shown above even in the worst case the hydraulic equivalent is not as course as .6mm. However as 10 cm/sec is below the erosion curve, once the current ceases and the particles settle out they would not be resuspended by a 10 cm/sec current. Notice (1) that .2 mm is the most easily eroded material with particles both coarser and finer requiring higher velocities and (2) the minimum velocity for erosion is about 15 cm/sec.

Thus if the outfall was designed to operate by the fountaining principle the ambient velocities must be above 15 cm/sec periodically to insure that at slack tide the particles do not settle out and build up around the outlet eventually covering and clogging the orifice.

Thus disposals schemes should try to take advantage of the negative buoyancy of the effluent and not try to dilute the effluent in the vicinity of the discharge. This would mean maintenance of a density flow along the

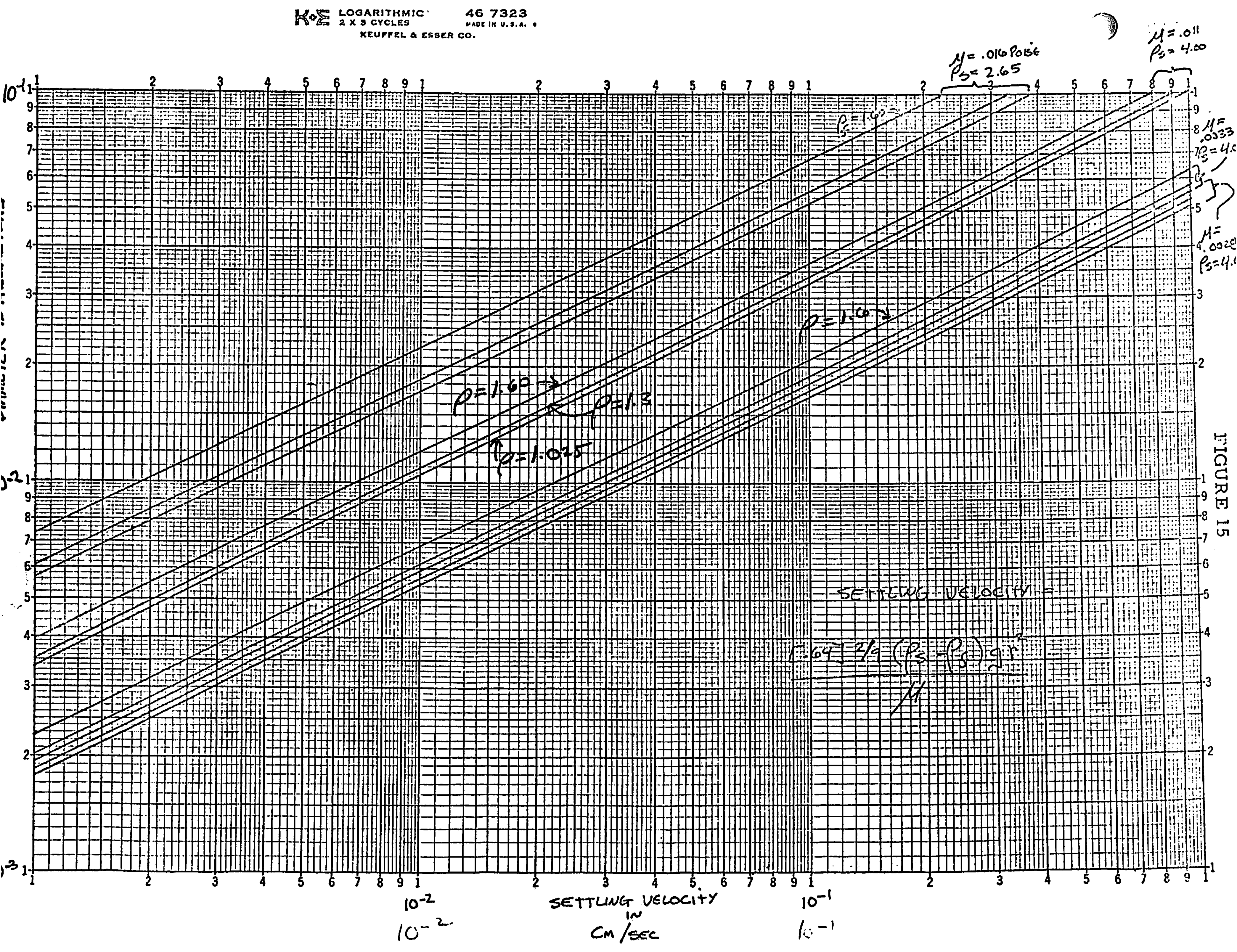
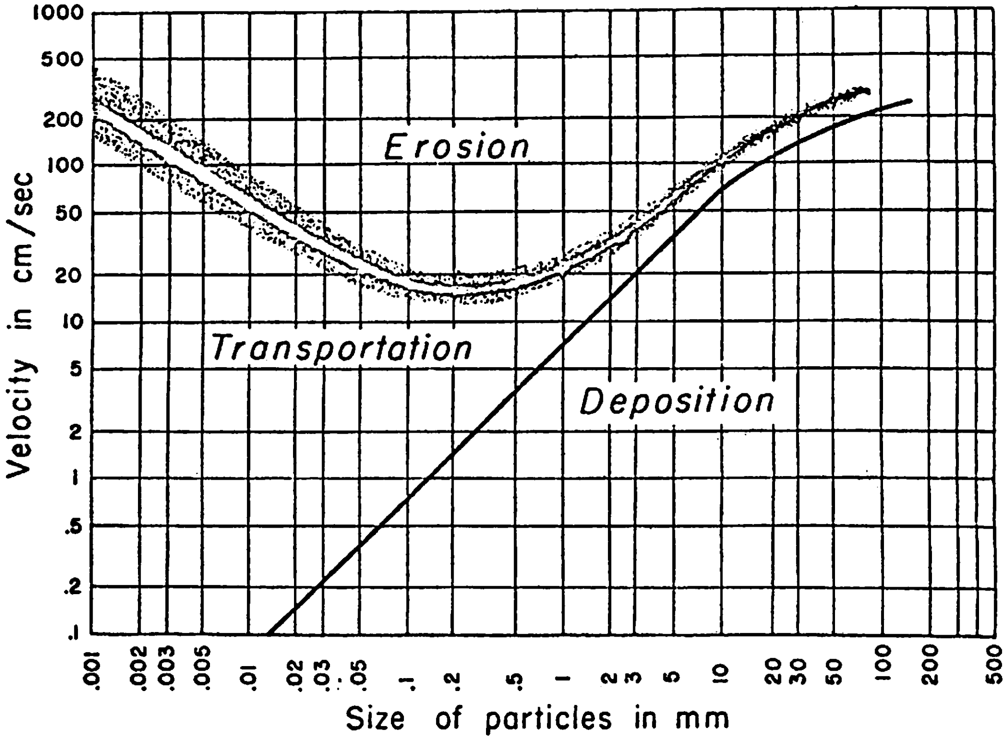

K+E LOGARITHMIC 2 X 3 CYCLES KEUFFEL & ESSER CO.
46 7323 MADE IN U.S.A.
μ = .016 Poise
ρ_s = 2.65
μ = .011
ρ_s = 4.00
μ = .0333
ρ_s = 4.0
μ = .0026
ρ_s = 4.0
ρ_s = 1.6
ρ = 1.60 →
ρ = 1.3
ρ = 1.025
ρ = 1.60 →
SETTLING VELOCITY =
$\frac{[.64]\, 2/9\, (\rho_s - \rho_f)\, g r^2}{\mu}$
10^{-1}
10^{-2}
10^{-3}
1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1
10^{-2}
10^{-1}
SETTLING VELOCITY IN CM/SEC

FIGURE 15

Figure 16

~~FIG. 2~~



Graph showing velocities at which different size grades of sediment will be eroded, transported, or deposited; plotted on double logarithmic scale. After Hjulstom (1939, p.10).

bottom a sufficient distance away from the discharger. Natural density flows or turbidity currents are common in nature and in many cases are difficult to prevent. Flows have been examined experimentally by Kuenen (1952) and Bell (1942). The classic example is the density current which occurs in Lake Mead during flood season when muddy cold waters dive under the surface of Lake Mead travelling along the drowned Colorado River Channel until blocked by Hoover Dam (Figures 17 and 18). The Lake Mead flows are characterized by (1) low velocities averaging about 0.5 ft./sec from 1. ft/sec at the head of Lake Mead and (2) density contrasts of up to 0.2 gm/cm^3 (Gould, 1952, p.45) Kuenen (1952) investigated high density contrast flows with $\Delta \rho = 0.6$. He found that a modified Chazy-Manning equation describes the velocity of his experimental flows or

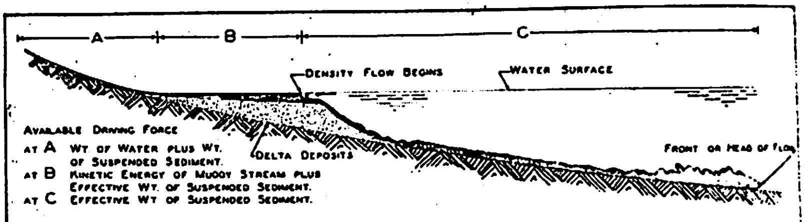
$V = C(m \times s \times d)^{1/2}$
where C = Chazy constant
M = Hydraulic radius = cross section area/wetted pair
S = Sine of slope
d = effective density = $\frac{\rho_f - \rho_m}{\rho_f}$

The results of Kuenen's (1952) experiments are shown in Figures 19 and 20. The initial conditions are very similar to the effluent of Case II initial density 1.60 and velocity of 90 cm/sec and allowing for the hydraulic equivalence, except in Kuenen's experiments the volume of the flow was finite not a continuous discharge. These experiments show that a high density flow will persist after some initial dilution even on a horizontal surface if given sufficient initial velocity.

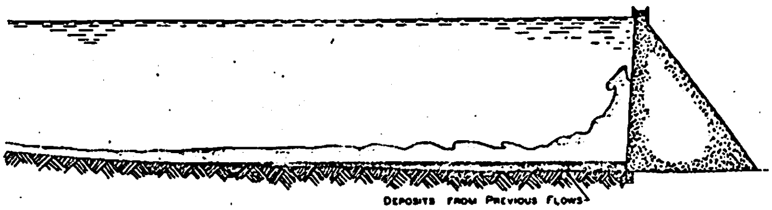
In actual discharges of high density material into the Mediterranean and iron mine tailing into a Norwegian Fjord (Carstens and Tesaker, 1972) (Figure 21) density flows were generated. In fact in the Norwegian example at Rana Fjord in which 10 million tons of solids was discharged over a period from 1964 - 1971, density current actually eroded a channel and incorporated part of the bottom into the flow. They also found their results could be described by the Chazy-Manning equation and found C' essentially independent of slope but a function of excess density (Figure 21). The velocity profiles indicate that the Rana Fjord turbidity current actually entrained water up to 7 meters above the bottom which a maximum velocity of 26 cm/sec in the turbid nose and a bottom velocity of 20 cm/sec well above the value needed for minimum erosion. Carsten and Tesaker (1972, p. 196) estimated that 18% of the material from the plant was carried in suspension and the rest as bed load of which only 10% of the capacity is needed to transport the mine solids which explained the erosion of the submarine canyon.

The use of the Chazy equation to describe the density flow requires open channel flow or the material flow in a confined channel which in the case of (1) the laboratory experiments was the walls of the plume and (2) Rana

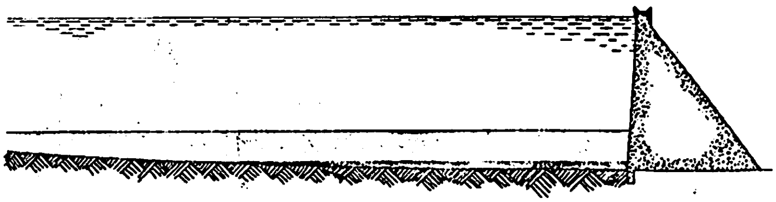
Figure 17



1. A TURBID DENSITY FLOW RESULTS AS MUDDY STREAM ENTERS THE RESERVOIR



2. HEAD OF FLOW BREAKS ON DAM



3. FLOW COMES TO REST AS SUBMERGED MUDDY LAKE

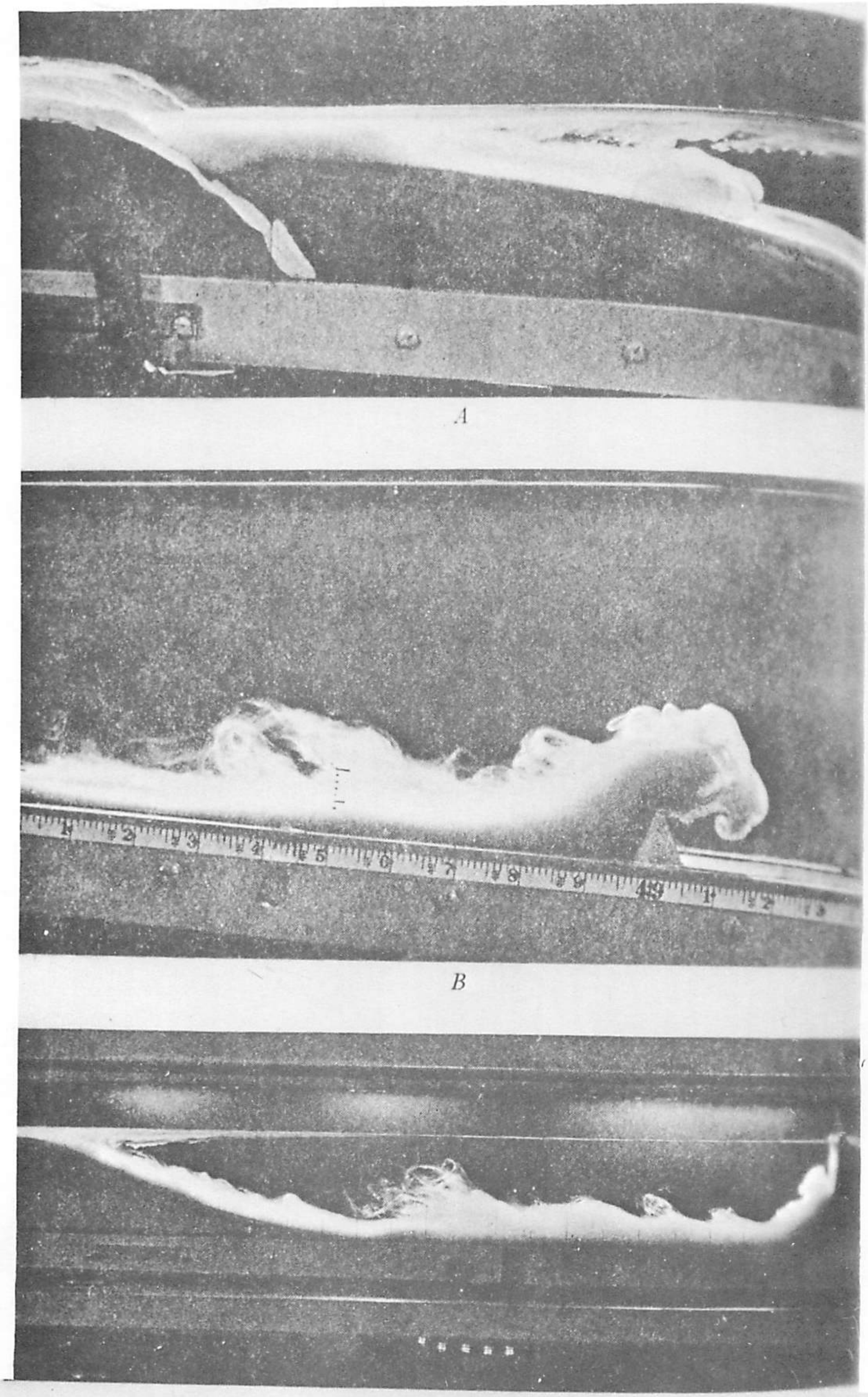


FIG. 8.—(*A*) A muddy stream enters the reservoir and is changed to a density flow which moves along the delta. (*B*) The underflow leaps a channel obstruction. (*C*) The turbid water climbs toward the surface as it strikes the dam.

Fjord was the sides of the created canyon. The Chezy Constant C can be determined as by Carsten and Tesaker (1972) or computed as:

$$C = \frac{1.49\, m^{1/6}}{M} = \sqrt{\frac{8G}{f}}$$

m = Manning Roughness
f = Darcy-Weisbach Coefficient or a combined Chezy-Manning equation:

$$V = \left(\frac{1.49}{M}\right) \frac{(\rho_s - \rho_m)^{1/2}}{\rho_s} (s)^{1/2} (m)^{2/3}$$

Where:
ρ_f = Density of flow
ρ_m = Density of surrounding media
s = Slope

For triangular shaped channels $m = \frac{\text{Depth max.}}{4}$

For channels where the depth is much less than the width
$m = \frac{\text{Depth max.}}{2}$

The importance of the Manning m is shown below

Velocity variations
as a function of $\Delta\rho = \rho_f - \rho_m$
and roughness

$\Delta\rho$	n = .01	.02	.035
.2	18.6 36.6 62	15.6 30.4 51.5	9.0 17.5 29.7
.02	10.7 20.9 35.5	5.3 10.4 17.3	3.4 5.9 10.0
.002	3.5 6.7 11.3	1.7 3.3 5.6	0.9 1.9 3.2

From Hurley
1962

M/Sec
KTS FT/sec

Thus it is possible to calculate the velocity of the current as a function of $\Delta\rho$, n, slope, and shape of channel. If these were known, when the settling velocity exceeded the product of the current velocity times the slope or the verticle downward vector exceeded the horizontal vector particles would settle out and the current would be destroyed (Johnson 1962). The other boundary condition at the current-water interface the upper limit of velocity is when the boundary wave breaks or that the ratio of the Richardson number to the Reynolds number is less than a constant or

$$\frac{Ri}{Re} = \frac{Vg^*}{v^3} < \theta_c^{\,3}$$

Where Ri = Richardson number
Re = Reynolds number
V_3 = Velocity of current
θ_c = .00257 (Keulegan 1949)

which is satisfied for high Reynolds number

Where $Re = \frac{hv}{\nu}$
h = height of flow
v = velocity of flow
ν = knuematic viscosity = 0.0136 stoke

Initial for	CASE II	CASE III
	$Re = 3 \times 10^5$	6×10^5

Thus the current would expand in height due to entrapment of water at its upper interface and by the high turbulence reduce the density of the flow. This of course was born out by Kuenen's experiments as the initial density was quickly reduced. More detailed discussions of the hydraulic behavior of turbidity currents are found in Johnson 1962.

Another possible regime of flow for density currents is sheet flow or simple bottom traction flow. In areas where either (1) the turbidity flow collapses but there is still a gradient (2) the material is swept by bottom currents. Natural examples of sheet flow are found on the Monterey Fan (Wilde, 1964) where the discharge overtops the sides of the channels and the flow continues along a broad front. Table shows sheet flow velocities up to 1m/sec carrying particles up to .1mm on very low slopes.

For either sheet flow or channelized flow, natural turbidity currents travel long distances: for example as sheet flows at least 100 miles on the Monterey Deep-sea Fan (Wilde, 1964), as channelized flows 90 miles in fresh water Lake Mead until the underflows are blocked by Hoover Dam (Gould, 1952), and over 1250 miles in the Cascadia Channel on the Cascadia Deep-sea Fan (Hurley, 1964).

TABLE 10

Table 1

CORE	SLOPE	Geometric Mean Modal Size mm.	Current Velocity w/α cm/sec. ρFluid=1.64	ρFluid=1.09	ρFluid=1.04
HMS 6	.0068	.097	29	42	46
HMS 7	.0068	.068	15	21	24
HMS 8	.0154	.068	7	9	10
HMS 9	.0108	.068	9	14	14
HMS 10	.0031	.097	63	91	100
HMS 11	.0042	.068	24	35	37
BG 12	.0060	.068	17	25	26
BG 15	.0060	.097	33	47	52
MEN 4	.0023	.068*	44	64	67
MARE 1	.0038	.097	51	74	82
MARE 6	.0197	.177	29	43	46
LFGS 3	.0068	.097	29	42	46
LFGS 62	.0108	.068	9	13	14
LFGS 68	.0050^{E}	.097	39	56	62
LFGS 70	.0063	.097	31	45	49
LFGS 72	.0108	.097	18	26	29
LFGS 74	.0090	.097	22	31	34

^{E} Slope estimated

* Sample contains over 90 percent mica flakes, so values too high

Thus bottom currents properly triggered at the end of an outfall are a convenient mechanism to (1) initially dilute the effluent to a density of 1.1 (Kuenen's (1952) Experiments) which maintains itself with a proper gradient so that the flow may (2) transport both fluids and particulate matter down slope into deep water at great distances from the disposal site.

Chemical Interactions For either Case II or Case III the effluent will sink to the bottom eventually so that the chemical interactions will be between the effluent and (1) bottom waters and (2) bottom sediments. The exact properties of the mixing bottom waters will be a function of how far the density flow carries before it breaks up. However, as experimental evidence and the few actual cases show, there is initial mixing at least in the upper portions of the flow so that (1) the temperature of the flow should drop to nearly that of ambient seawater and (2) the fluid phase of the effluent will react with water at the discharge site. Because of the relatively high velocities of the flow the fluids and solids should reach deep water before any significant amount of chemical reactions could occur. For example, at a slow speed of only 30 cm/sec the flow would take only about four days to travel 110 kilometers to a deposition site at 2000 meters water depth in the Halmahera Sea. (See Figures 12 and 13 for reaction rates.)

The solids in the effluent are essentially iron oxides (80%) and clays (magnesium-alumino-silicates (17.5%). Iron oxides are not commonly found in marine sediments in such concentrations except in the hot brine pools of the Red Sea (Bischoff, 1969). The oxygen demand required by oxidation of Fe^{++} to Fe^{+++} is limited by the kinetics of the reaction. The reaction will not occur in the flow which is reduced and the reaction $Fe^{+++} \longrightarrow Fe^{++}$ is more likely to occur. The solids as Fe_2O_3 likely will mix with the bottom sediment as $CaCO_3$ so any reaction should be between these two phases as the clay minerals in the effluent are essentially inert and quite common in the marine environment. Once the material has settled out after the turbid flow has broken up, reduced conditions will probably persist as Baas-Becking and others (1960) have found in near shore environments. Sulfate reducing bacteria naturally produce anarobic conditions in marine sediments by reducing the sulfate in sea water to sulfide in the presence of organic matter. Equilibrium diagrams for the iron system are shown in Figures 22 and 23 and for the seawater system at reducing or oxidizing conditions at pH. 9.5 hematite Fe_2O_3 is stable. In several reducing conditions FeS_2 will be formed. The siderite field $FeCO_3$ is so restricted that it is unlikely that it will be formed from the reaction of Fe_2O_3 and $CaCO_3$ thus the carbonate sediments will remain as calcium carbonate.

In summary, the chemical reactions for Case II and Case III will be to maintain reducing conditions in the flow and in the area of deposition with essentially no change in the mineralogy of the solids in the effluent or in the bottom sediments. The thickness of potential deoxygenated water above the site of deposition will be an inverse function of the surface area of the site of deposition so the widest possible area is recommended.

Figure 22

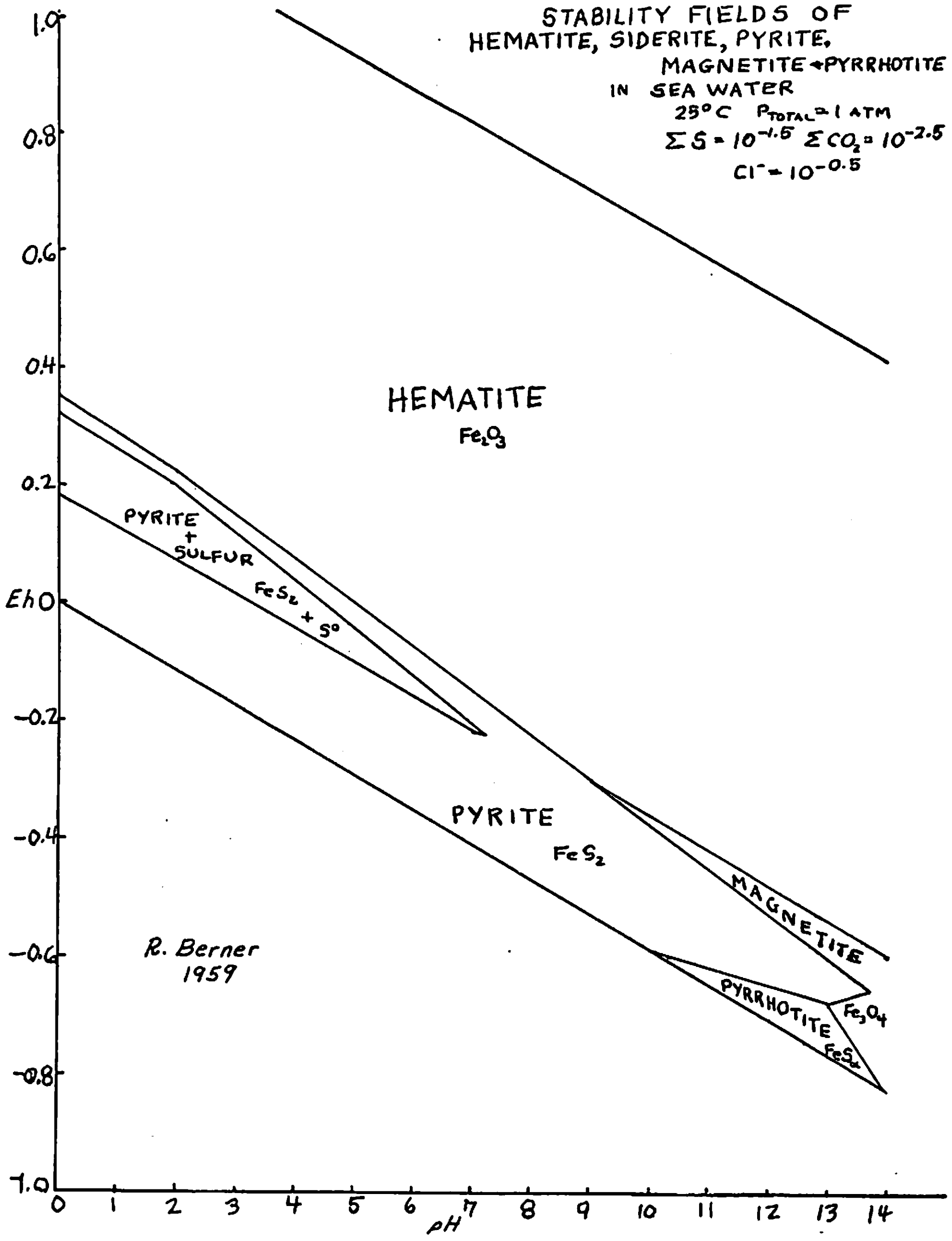
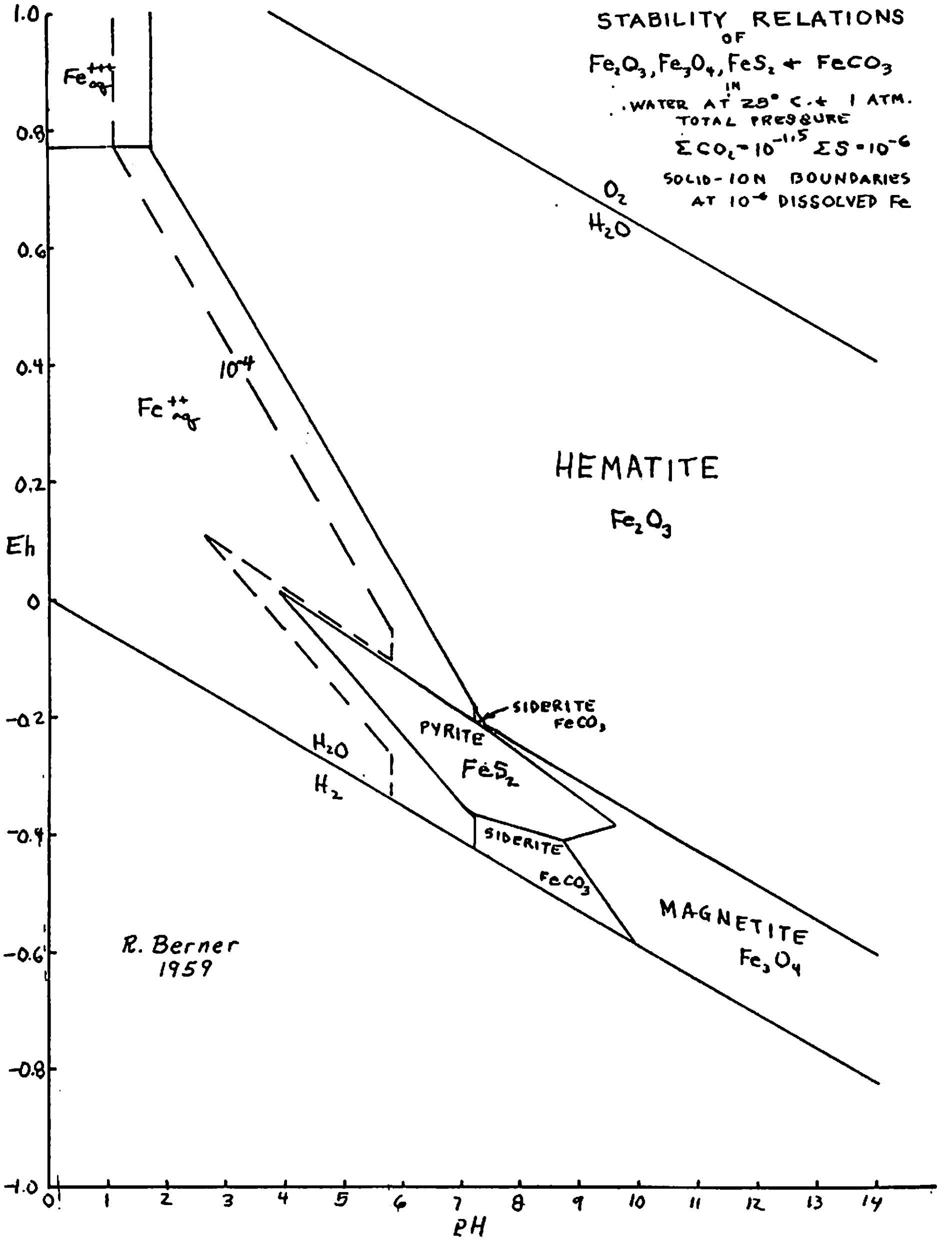

STABILITY FIELDS OF
HEMATITE, SIDERITE, PYRITE,
MAGNETITE + PYRRHOTITE
IN SEA WATER
25°C $P_{TOTAL} = 1$ ATM
$\Sigma S = 10^{-1.5}$ $\Sigma CO_2 = 10^{-2.5}$
$Cl^- = 10^{-0.5}$
HEMATITE
Fe_2O_3
PYRITE + SULFUR
$FeS_2 + S^0$
PYRITE
FeS_2
MAGNETITE
Fe_3O_4
PYRRHOTITE
FeS_x
R. Berner
1959
Eh
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
pH
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Figure 23


STABILITY RELATIONS OF Fe_2O_3, Fe_3O_4, FeS_2 + $FeCO_3$ IN WATER AT 25° C. + 1 ATM. TOTAL PRESSURE
$\Sigma CO_2 = 10^{-1.5}$ $\Sigma S = 10^{-6}$
SOLID-ION BOUNDARIES AT 10^{-6} DISSOLVED Fe
Fe^{+++}_{aq}
Fe^{++}_{aq}
10^{-4}
O_2
H_2O
HEMATITE
Fe_2O_3
SIDERITE
$FeCO_3$
PYRITE
FeS_2
SIDERITE
$FeCO_3$
MAGNETITE
Fe_3O_4
H_2O
H_2
R. Berner
1959
Eh
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
pH
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

The oxygen demand is due almost entirely to ammonia in the BNC liquor which because of its rate of oxidation will be a factor at the site of deposition and would not deplete the oxygen in the waters above the flow during the passage of the turbid flow. However, as the environment in the bottom, except for a surface ring of a few centimeters, is reduced naturally the eventual oxygen demand of the ammonia is just a small fraction of the total amount of ammonia introduced into the environment.

CONCLUSIONS: CASE II AND CASE III

Effluents with a higher density than the surrounding sea water ejected with sufficient turbulence and velocity will form a density flow which will flow downslope until it either (1) mixes at the surface of the flow destroying the density gradient which will produce sedimentation or (2) loses forward velocity so that the settling velocity of the particles exceeds the horizontal velocity which also produces sedimentation.

Design values needed to determine the eventual resting place of the effluent are:

(1) Detailed bathymetry seaward of disposal sites (that is smooth slopes or channels).

(2) Roughness factors of bottom sediments along the proposed paths of the flow.

Conversion of the size distribution of the effluent solids by hydraulic equivalents show present bottom currents are unlikely to resuspend the sediments once it has been deposited.

Because of the toxicity of the BNC liquor, it is recommended that ammonia be removed or converted to nitrate or the BNC liquor be combined with the tailings to produce a larger discharge at a higher velocity to move the effluent site into deeper water.

Thus, Case III is recommended as the fundamental effluent arrangement.

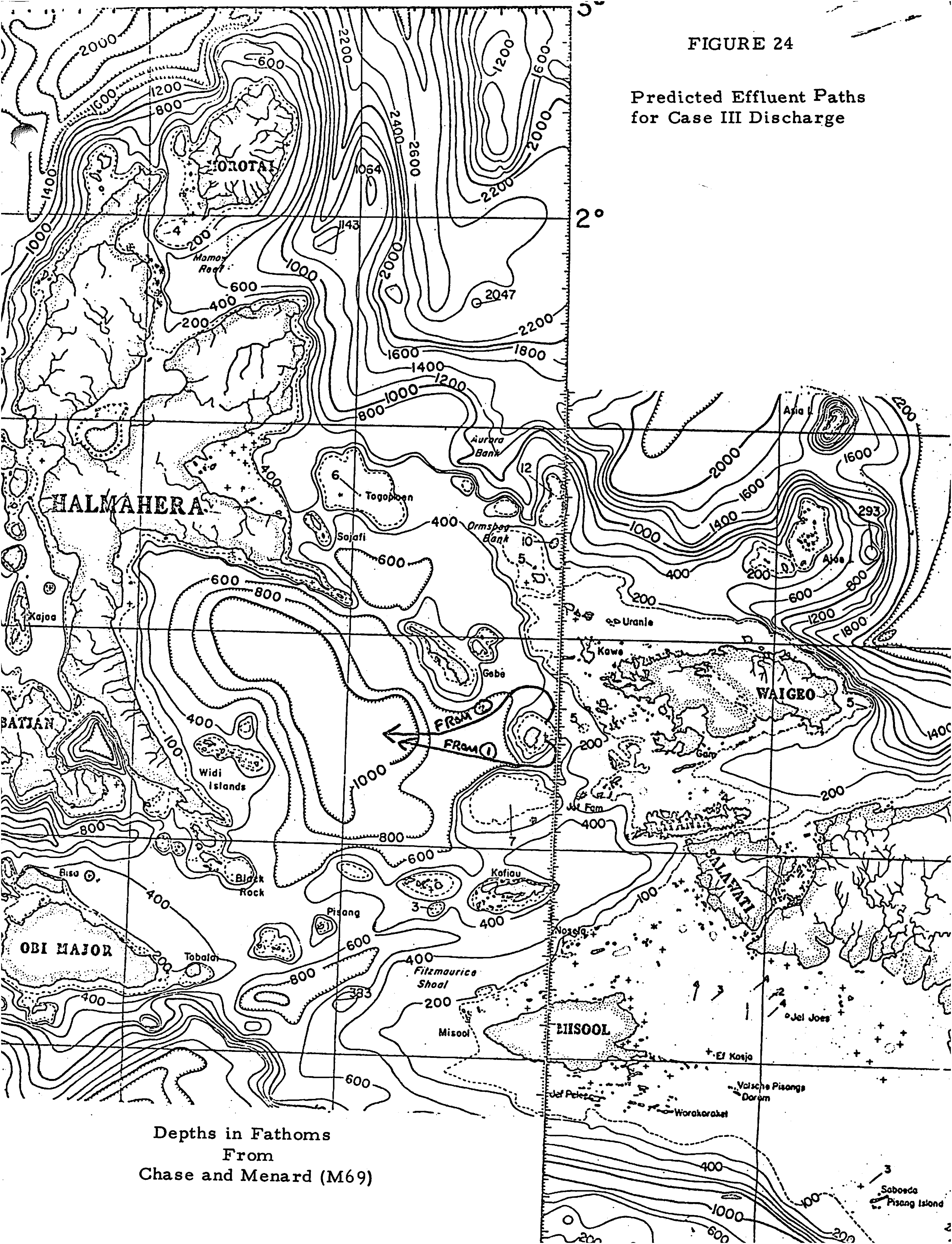
CONCLUSIONS AND RECOMMENDATIONS

(1) The composition of the discharge should be a combination of the mine slurry and the BNC liquor which will produce an effluent of greater density than the ambient sea water environment. This discharge will flow as a density current downslope from the discharge site at a distance which is a function of the bottom topography, bottom sediment hydraulic characteristics, and turbulence and volume of discharge of the effluent.

(2) The advantages of such a discharge primarily are (1) there will be no surface toxicity which would be the case if only the buoyant BNC liquor is discharged (2) it provides a mechanism for transportating the material great distances from land and into deep water (3) chemical reactions in the bottom sediments in deep water could proceed at environmentally acceptable slow rates because of the low bottom temperatures and naturally reducing conditions.

FIGURE 24

Predicted Effluent Paths for Case III Discharge



Depths in Fathoms
From
Chase and Menard (M69)

SITE RECOMMENDATIONS

Two possible locations for the discharger are considered at this time (1) due east of Gambier at the current meter site in 200 meters of water and (2) north of the island at the closest approach to shore of the 200 meter contour. In the absence of detail bathymetry seaward of these sites it would seem each would be equally good from an oceanographic viewpoint. From preliminary and scanty bathymetric data both sites eventually draw into the large Halmahera basin (Fig. 24). The probable path of effluent from site (1) is first east to about 400 meters then south then west about 30 nautical miles to the 2000 meter closed contour of the Halmahera basin below which the current should break up and deposit its load. The path from site (2) is northeast to the mid point of the channel then northwest to the axis of the channel between Gag and Geve then southwest to the 2000 meter contour of the Halmahera basin.

With the present scanty bathymetry data site (1) is preferred because (1) there is bathymetric evidence of a channel-canyon system aligned with the embayment into Gag island which means initially the discharge will be confined in a channel which is more conducive to long range continuance of the flow as a discrete density flow and (2) the gradient from site (1) to the closed 600 fathom contour (1080 meters) is steeper than from site (2) again conducive to long range flow. In fact, the detailed bathymetric survey north of the island shows no evidence of channelling thus there would be a good chance that no discrete flow could be formed and the material would be deposited by sheet flow action at the axis of the channel between Gag and the Waigeo island shelf and not continue into the Halmahera basin.

RECOMMENDATIONS FOR GATHERING ADDITIONAL DATA

Because of the lack of detailed environmental information recommendations must be qualified; thus a program is proposed below to gain additional information.

I. Bathymetry - Near shore survey adequate, however detailed surveys needed downslope of any proposed outfall site. These should be conducted chiefly parallel to the slope to identify channels. Sub bottom profiles not necessary unless the characteristics of the discharge flow will produce headward erosion as in the case of Rana Fjord which threatened undermining of the outfall structure.

II. Bottom Samples - At present only three samples have been described near Gag island. A line of cores or grabs should be taken seaward of any disposal site. This sampling could be designed to include sampling for the biologists to determine not only the characteristics of the sediments but also the benthic fauna in the area.

III. Water column sampling appears adequate for calculations used there but must be confined for the particular site.

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