

CHAPTER TWO HUNDRED FIVE

SEWAGE DISPOSAL IN SHALLOW COASTAL WATERS

by

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Abstract

The disposal of sewage effluent into coastal waters for dilution and final disposal requires an effective mixing of sewage with the seawater in order to achieve the necessary or demanded reduction of bacterial population. Most of the design parameters originate from work done on ocean outfalls. RAWN et al. (1960) developed curves from field data for the determination of initial dilution in a waste issuing from a horizontal port. ABRAHAM (1963) extended these curves to show that the dilution is a function of the depth of discharge port, the diameter of the discharge orifice D and the FROUDE number F .

The question, to which extent this calculation method is also valid for outfalls in shallow water regions, is still open. In connection with the actual design of a diffuser in shallow coastal water the method of ABRAHAM was applied together with a new method derived by BERGEN (1980) which is based upon experiments which were carried out in the Leichtweiss-Institute at semi-technical scale. After the diffuser had been taken into operation by means of in-situ measurements the demanded dilution could be checked and herewith also the reliability of the applied design method for practical use.

Experimental investigations on concentration ratio

For a comprehensive application, especially in case of discharges at low jet velocities (FROUDE number $F < 1$), the calculation method of ABRAHAM (1963) is insufficient. Therefore investigations were carried out in order to extend ABRAHAM'S work into a wider range of validity (Table 1).

The experiments were carried out in a water tank with a depth of 3.5 m. For the measurement of instantaneous concentrations along the axis of freshwater upwelling in seawater the conductivity method was selected. For this purpose a grid of horizontal and vertical tungsten wires was installed in the tank so that disturbances on the dispersion in the tank were reduced to a minimum (Fig. 1).

It was the aim of the investigation to describe approximately by means of a 1st order theory diffusion processes. All derivations are related to an axially symmetrical and vertical buoyant jet originating from the discharge of a lighter fluid into a heavier one at still water.

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Table 1: Parameter variations in the experiments of the Leichtweiss-Institute and of ABRAHAM

Parameter	Range of variations			
	LEICHTWEISS-INSTITUTE		ABRAHAM	
	from	to	from	to
FROUDE number	0.0001	11.7	1	95
REYNOLDS' number	$0.15 \cdot 10^3$	$45 \cdot 10^3$	$1.8 \cdot 10^3$	$8.7 \cdot 10^3$
outlet velocity	0.0014 m/s	0.45 m/s	0.1 m/s	0.68 m/s
concentration ratio c_m/c_o	0.76	0.001	0.67	0.085
dilution	1 : 1.3	1 : 1000	1 : 1.5	1 : 12

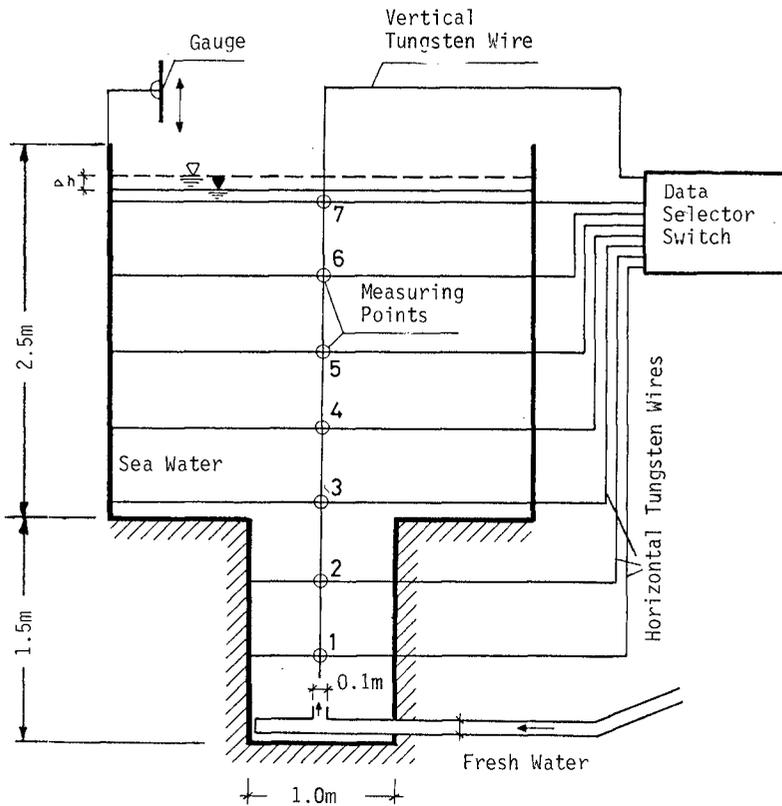


Fig. 1: View of the test facility for measuring concentrations along the axis of jet

In case of low outlet velocities the distribution profile of concentration is not so distinct as in case of high velocities; besides the mean upwelling velocity in the axis of jet is much higher than in cross direction. As for design purpose mostly maximal data are needed an uniform distribution of concentration c and velocity v is assumed in the cross-section of the jet. It follows that the concentration at any point of the cross-section is equal that along the axis.

Table 2 shows as example the results of one test series. For different outlet velocities ranging from very low ($v = 0.0014$ m/s) up to velocities of 0.45 m/s the connected FROUDE and REYNOLDS' numbers are listed together with the measured concentration ratios at different levels $\frac{x}{D}$.

Table 2: Test results of concentration ratio measurements (BERGEN, 1980)

TEST SERIES II $\Delta\rho_o / \rho_o = 0.02192$						
No.	TEST	$\frac{x}{D}$	v_o [m/s]	Fr	Re	$\frac{c_m}{c_o}$
31	1	3,5	0.0015	0.0001	148	0.0080
32		8,5				0.0040
33		18,5				0.0040
34		23,5				0.0001
35		28,5				0.0015
36		33,5				0.0015
37	2	3,5	0.0020	0.0002	197	0.0121
38		8,5				0.0078
39		18,5				0.0043
40		23,5				0.0042
41		28,5				0.0019
42		33,5				0.0024
43	3	3,5	0.0048	0.0011	483	0.0406
44		8,5				0.0188
45		18,5				0.0185
46		23,5				0.0068
47		28,5				0.0046
48		4				3,5
49	8,5		0.0366			
50	18,5		0.0081			
51	23,5		0.0359			
52	28,5		0.0109			
53	33,5		0.0083			
54	5	3,5	0.2315	2.4920	23150	0.7715
55		8,5				0.1736
56		18,5				0.0616
57		23,5				0.0321
58		28,5				0.0046
59		33,5				0.0173

In Fig. 2 these data are plotted through which for each test linear curves were drawn for further use.

A qualitative analysis of the test results revealed that at low jet velocities (e.g. $v_o = 0.0015$ m/s. Curve A in Fig. 3 a relatively high initial dilution v_o is obtained in the direct vicinity of the outlet,

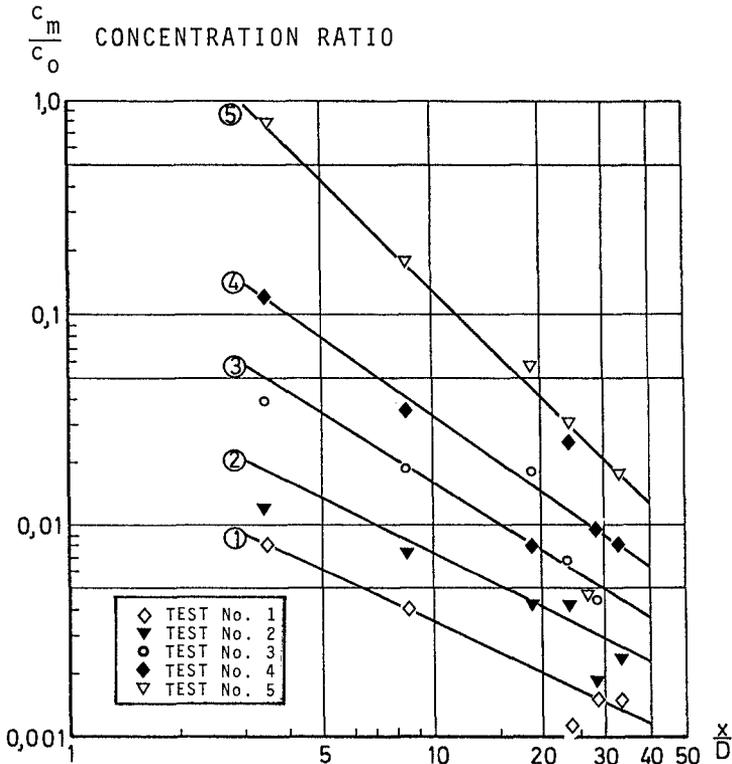


Fig. 2: Correction curves for measured concentration ratios (BERGEN, 1980)

here demonstrated by the lowest point of curve A (at $x/D = 3.5$, with x = vertical distance from outlet and D = diameter of outlet pipe = 0.10 m in the tests). In the course of further upwelling the dilution further increases by a factor between 4 to 6 (at $x/D = 35$).

At higher jet velocities (e.g. $v_0 = 0.2315$ m/s, which is more than two orders of magnitude higher than the previous example, curve B (in Fig. 3) the initial dilution is considerably lower but increases by a factor between 20 and 50 (at $x/D = 35$). These results are in agreement with the statement of ABRAHAM (1959) that for Froude numbers $\rightarrow 0$ (low velocity) the mean concentration c_m decreases faster than for Froude numbers $\rightarrow \infty$.

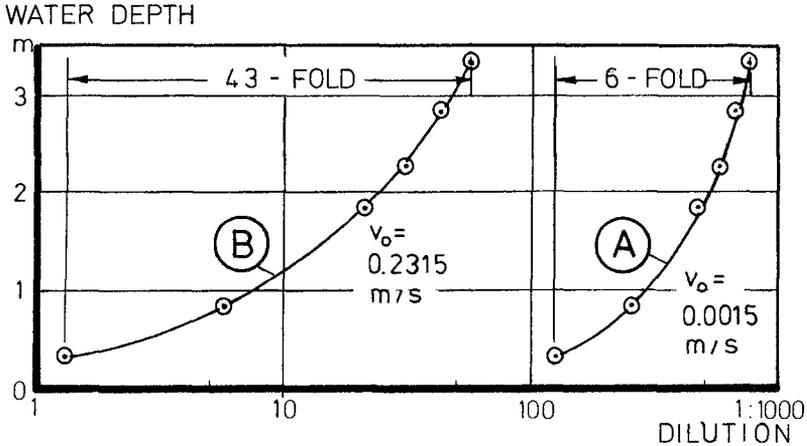


Fig. 3: Test results of dilution distribution at low (curve A) and at higher (curve B) jet velocities

Computation method for the determination of the concentration ratio

Based upon the already mentioned assumptions and approximations BERGEN (1980) derived an equation for the computation of concentration ratio by means of experimental data.

The following linear approach

$$\frac{c_m}{c_o} = \left[\frac{x}{D} \right]^{-1} \left[B_1 \cdot \left[\frac{x}{D} \right]^2 + B_2 \right]^{-1/2}$$

was abandoned in favour of a nonlinear approach in which a hyperbolic cross-sectional shape of the jet is assumed (Fig. 4)

After certain transformations BERGEN (1980) obtained the following equation:

$$\frac{c_m}{c_o} = 2 \left[\frac{b-3}{2} \right] \sqrt{\frac{Fr}{b}} \cdot D \left[\frac{5-b}{2} - \frac{2}{5} \right] \cdot \left[\frac{x}{D} \right]^{-\frac{2}{5}}$$

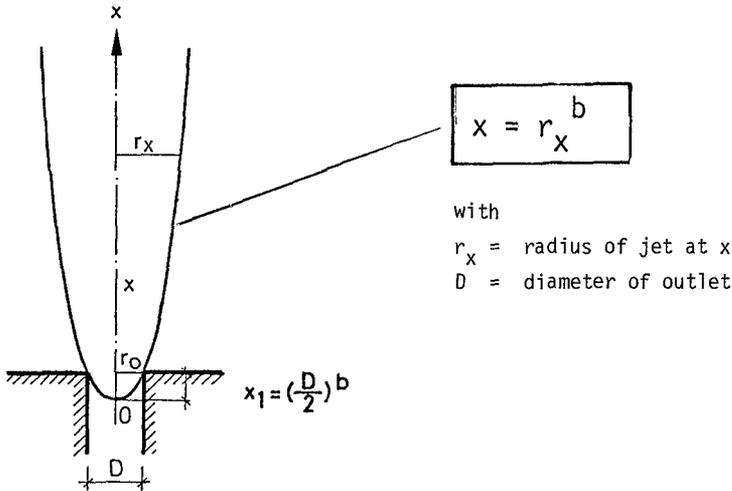


Fig. 4: Hyperbolic cross-sectional shape of jet (schematic)

By introducing three coefficients which are functions of two known parameters (Froude number F and outlet diameter D) and only one unknown (parameter b)

$$B_3 = 2 \left[\frac{b-3}{2} \right] \cdot \sqrt{\frac{Fr}{b}} \quad (B_3 = f(b, Fr))$$

$$B_4 = D \left[\frac{5-b}{2} - \frac{2}{b} \right] \quad (B_4 = f(b, D))$$

$$B_5 = \frac{2}{b} \quad (B_5 = f(b))$$

the above equation can be written

$$\frac{c_m}{c_0} = B_3 \cdot B_4 \cdot \left[\frac{x}{D} \right]^{-B_5}$$

For the determinations of the three coefficients the iteration method was applied so far until the computed concentration ratio was equal the measured one

$$\frac{c_m}{c_0} (\text{theory}) \cong \frac{c_m}{c_0} (\text{experiment})$$

Table 3 shows as example the computed coefficients obtained by iteration for the measured concentration ratio c_m/c_o (experiment). The scattering of the value b can be explained by the fact that in the equation no distinction is made between the direct vicinity of jet release and the further distant where upwelling is more defined.

Table 3: Computation of coefficients B_3 , B_4 and B_5 and parameter b by iteration for measured concentration ratio (BERGEN, 1980)

TEST SERIES II $\Delta\rho_o / \rho_o = 0,02192$								
No.	TEST	$\frac{x}{D}$	v_o [m/s]	$\frac{c_m}{c_o}$ experim.	B_3	B_4	B_5	b
31	1	3,5	0,0015	0,0080	0,0081	1,701	0,436	4,59
32		8,5		0,0039	0,0077	1,364	0,460	4,35
33		18,5		0,0021	0,0073	1,160	0,480	4,17
34		23,5		0,0018	0,0073	1,110	0,485	4,12
35		28,5		0,0015	0,0072	1,072	0,490	4,08
36		33,5		0,0013	0,0071	1,035	0,495	4,04
37	2	3,5	0,0020	0,0175	0,0119	2,417	0,403	4,96
38		8,5		0,0083	0,0111	1,851	0,427	4,68
39		18,5		0,0043	0,0110	1,508	0,448	4,46
40		23,5		0,0036	0,0104	1,441	0,454	4,41
41		28,5		0,0030	0,0103	1,364	0,460	4,35
42		33,5		0,0026	0,0102	1,304	0,465	4,30
43	3	3,5	0,0048	0,0500	0,023	2,715	0,394	5,08
44		8,5		0,0195	0,027	1,800	0,430	4,65
45		18,5		0,0085	0,025	1,315	0,464	4,31
46		23,5		0,0065	0,024	1,202	0,475	4,21
47		28,5		0,0055	0,024	1,140	0,482	4,15
48	4	3,5	0,0190	0,1170	0,107	1,851	0,427	4,68
49		8,5		0,0410	0,096	1,192	0,476	4,20
50		18,5		0,0160	0,088	0,844	0,526	3,80
51		23,5		0,0120	0,086	0,771	0,542	3,69
52		28,5		0,0095	0,084	0,723	0,554	3,61
53		33,5		0,0080	0,083	0,689	0,563	3,55
54	5	3,5	0,2315	0,7600	1,165	1,181	0,477	4,19
55		8,5		0,1720	0,983	0,614	0,588	3,40
56		18,5		0,0460	0,882	0,414	0,712	2,81
57		23,5		0,0320	0,864	0,388	0,743	2,69
58		28,5		0,0230	0,848	0,366	0,778	2,57
59		33,5		0,0175	0,837	0,352	0,806	2,48

With respect to a parameter b which is independent of the distance x from outlet a parameter B_e is introduced as follows:

$$B_e = \frac{\sum_{i=1}^n b_i}{n}$$

with n = number of data from one test

By assuming $b \equiv B_e$ then only the parameter b has to be replaced in the derived equation.

If a satisfactory relation between parameter B_e and a given experimental or design parameter can be found the derived equation can be applied for actual design.

Fig. 5 shows for the parameter Be related to the REYNOLDS' number Re a relative good agreement so that this graph can be used as key curve for design purpose.

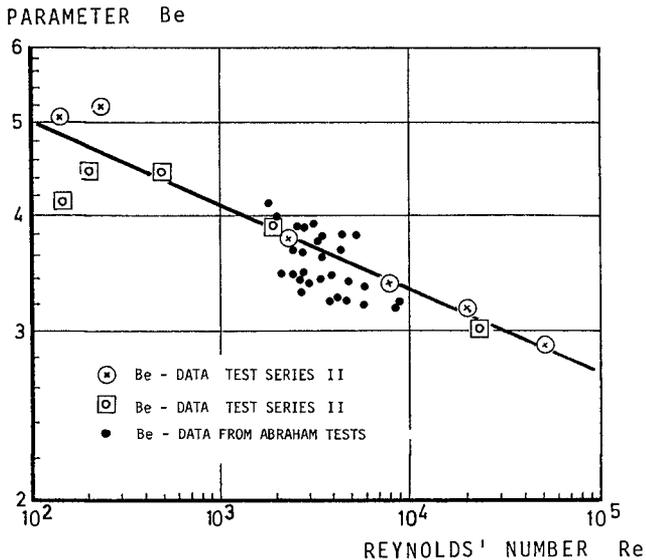


Fig. 5: Key curve for the calculation of concentration ratio (BERGEN, 1980)
Application of the computation method for design

As could be shown in the preceding chapter the single design parameters on concentration ratio depend from each other so that the optimal values have to be found by iteration. In order to facilitate the computation of the concentration ratio number according to BERGEN'S equation for engineering purpose three diagrams (II, III, IV) in relation to diagram I as the key curve (Fig. 5) were developed (Fig. 6).

Actual design of a multiport diffuser in shallow coastal water

The sewage of the city of Kiel for many years was released through a single point outlet into the Baltic Sea. The distance from the shoreline was 250 m (Fig. 7).

Due to bacterial population above the allowed boundary values and odour nuisance the recreational beaches adjacent to the point of release had to be restricted for public use. In order to re-establish bathing water quality it was demanded to extend the outlet up to 1.500 m distant from the shoreline in order to prevent further shore pollution. By extensive field measurements (DETTE, 1984) it was concluded that a multiport

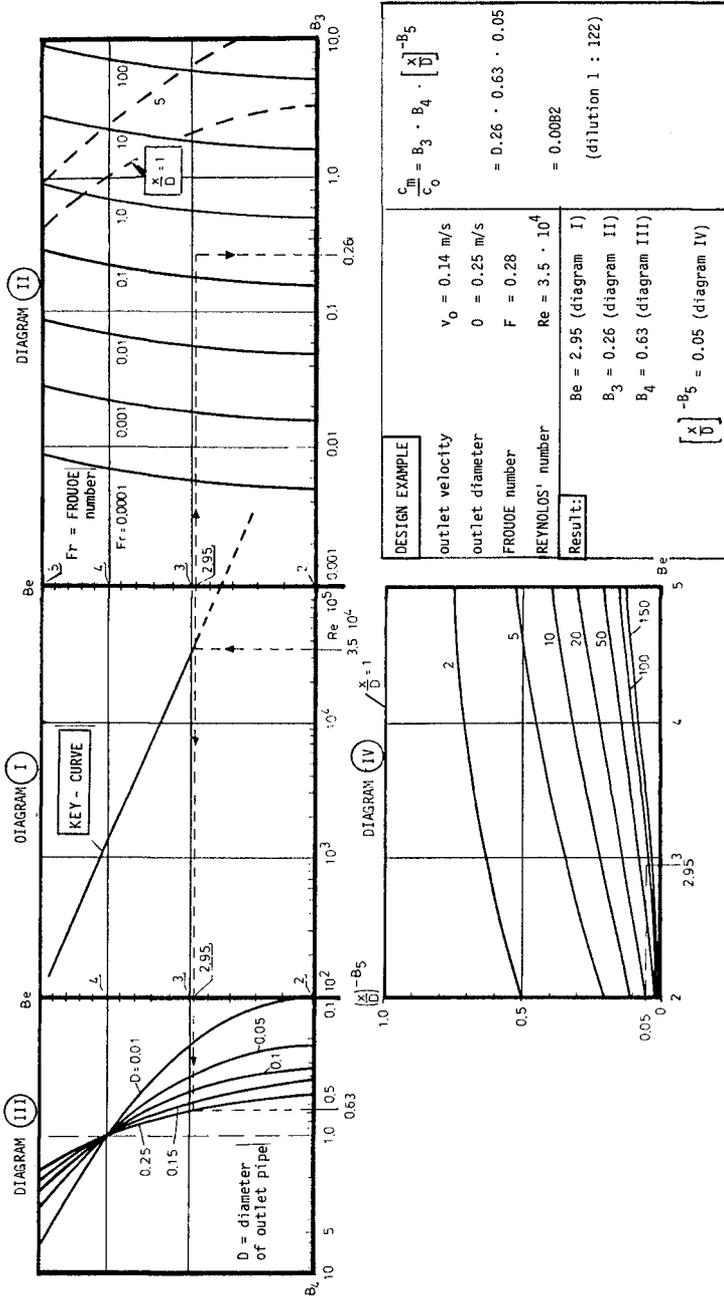


Fig. 6: Application diagrams for the computation of the concentration ratio c_m/c_o (BERGEN, 1980)

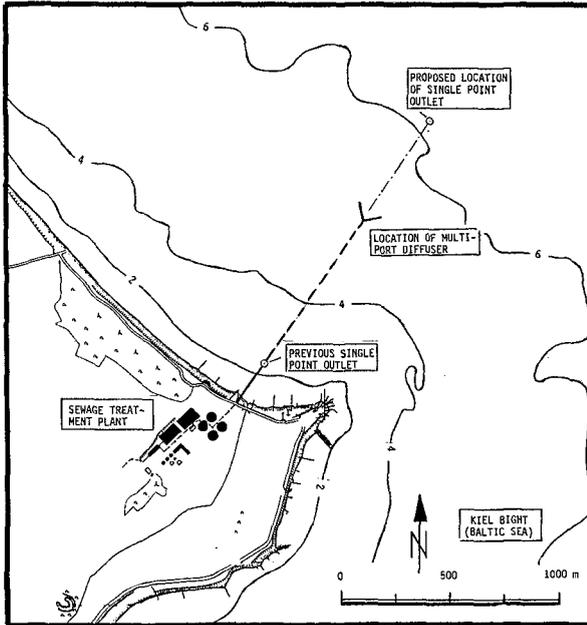


Fig. 7: Sewage release in shallow coastal water

y-shaped diffuser should be built at a distance of 1.000 m from the shoreline (Fig. 7).

As design criteria for the diffuser it was demanded that a dilution of 1 to 10 should be obtained at the water surface above the diffusers. With respect to the optimization of porthole diameter and number of portholes for a given sewage discharge of $Q = 0.7 \text{ m}^3/\text{s}$ in one arm of the y-shaped diffuser the calculation methods of ABRAHAM (1959) and that of BERGEN (1980) were applied.

The results are plotted in Fig. 8.

In order to obtain an uniform outflow from all portholes variable distances between the single portholes were calculated and suggested for execution (Fig. 9). Details of the diffuser system are shown in Fig. 10. For the 1000 m long submarine pipeline of DN 1500 mm (diameter) tubes of 6 m length were welded together on land to lengths of 50 m which were afterwards brought into the water and transported as floating elements to their final position. For the underwater connection of the sections special couplings (type: Straub Flex) were used.

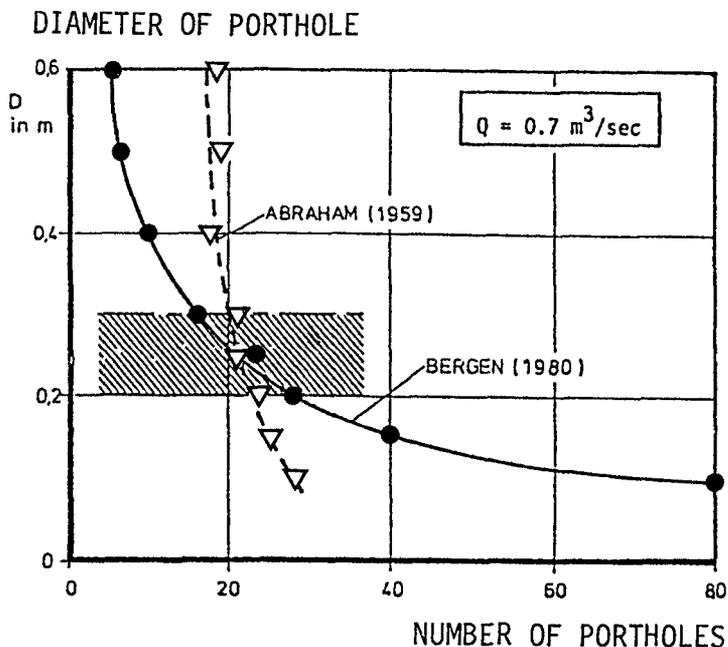


Fig. 8: Computation of porthole numbers in relation to outlet diameter according to ABRAHAM (1959) and BERGEN (1980)

Control measurements on initial dilution

After the new diffuser had been taken into operation control measurements were carried out in the direct vicinity of the diffuser in order to know to which extent the number of coliforms has been reduced in comparison to those values sampled at the plant itself. The reduction in the number of coliforms can be regarded in shallow water as direct indicator of the obtained dilution. Fig. 11 shows the locations where samples have been taken from the water surface. In Table 4 the results are listed. With respect to the number of total coliforms a mean reduction to approx. 3 percent is obtained directly above the diffuser in comparison to a demanded reduction to 10 percent. At a distance of 10 m from the diffuser already a further reduction of one order of magnitude is reached (0.3 percent).

It is therefore concluded that the applied calculation method on concentration ratio and the layout of the diffuser fulfilled the targets so that a general application for sewage release in shallow water can be recommended.

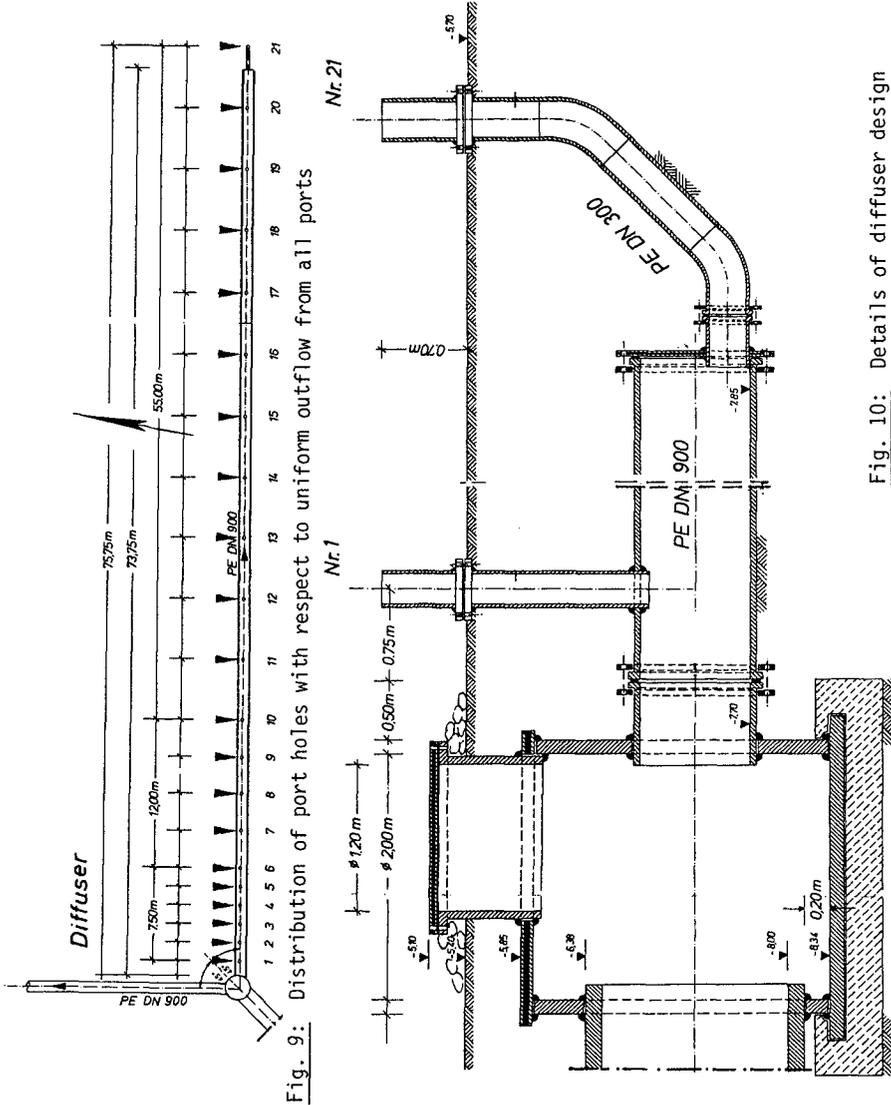


Fig. 10: Details of diffuser design

Table 4: In-Situ measurements of coliforms in the vicinity of the diffuser carried out by Institute of Marine Microbiology at University of Kiel

Sample	Temperature	Salinity	Coliforms		Remark
			Total (37°C)	Fecal (44°C)	
-	°C	%	10 ³ mg/l	10 ³ mg/l	-
Sewage plant	-	-	254	13	-
1	10.8	12.5	5	0.8	<u>A B O V E</u> the diffusers
2	10.8	12.5	6	0.7	
3	10.8	12.5	8	1.1	
4	10.5	12.5	8	1.5	
5	10.8	12.5	8	1.0	
6	10.8	12.5	5	1.6	
7	10.5	12.5	4	1.0	
8	10.8	12.5	10	1.4	
Mean value	10.8	12.5	7	1.1	
Percent of plant value	-	-	2.8 %	8.5 %	
9	10.8	12.8	0.2	0.08	<u>10 m</u> <u>distance</u> from diffusers
10	10.8	12.8	0.6	0.15	
11	10.5	12.8	0.6	0.13	
12	10.8	12.8	0.8	0.26	
13	10.8	12.8	1.1	0.26	
14	10.8	12.8	1.0	0.17	
Mean value	10.8	12.8	0.7	0.18	
Percent of plant value	-	-	0.3 %	1.4 %	

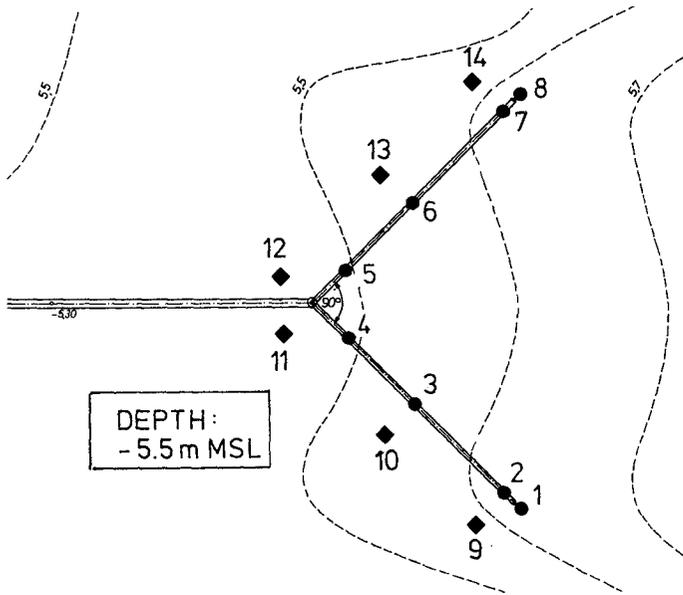


Fig. 11: Location of control measurements on coliforms

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