CHANGES IN FILTERING EFFICIENCY OF PLANKTON NETS DUE TO CLOGGING UNDER TOW

By

PAUL E. SMITH, ROBERT C. COUNTS, and ROBERT I. CLUTTER

Bureau of Commercial Fisheries
California Current Resources Laboratory
La Jolla, California, USA

The problem of clogging is inherent in sampling plankton and this paper reports a study of clogging rates in tests of design variables of plankton nets, such as mesh size, filtering area, and net form. Telemetering flow meters were used to determine the effects of these variables on the rate of clogging of pairs of plankton nets under tow in waters of different clarity. Metering of flow is necessary for evaluating clogging. A water clarity measurement is not useful for predicting clogging rate and the gross appearance of the net after the tow is not necessarily a reliable indicator of whether clogging has lowered filtration efficiency during the tow. Fine mesh nets with comparable mesh aperture area filter as well initially as do nets with larger apertures but clog much more rapidly. Compared to silk with mesh apertures 0·550 mm wide, nylon with apertures 0·333 mm, 0·201 mm and 0·101 mm wide clog 3, 5 and 35 times as rapidly. In the cylinder-cone nets of 0·333 mm nylon mesh, the volume filtered at more than 85% efficiency was increased six-fold by doubling the filtering area. An equation describing the relation of the ratio of filtering area to mouth area for 0·333 mm nylon is:

$$\log_{10} R = 0{\cdot}38 \log_{10} \frac{V}{A} - 0{\cdot}17$$

where R is the ratio of filtering area to mouth area, V is the volume to be filtered and A is the mouth area of the net. The cylinder and cylinder-cone nets were superior in sustained filtration efficiency to cone-shaped nets. We attribute this advantage to the oscillations of the cylindrically placed mesh which tend to clean the mesh at a higher rate. An example is given of the method by which a new net was designed to lessen the probability of clogging.

INTRODUCTION

"... Four places of decimals in a computed coefficient can hardly offer compensation for an error so fundamental as the variation in the straining capacity of the net".

KOFOID (1897)

Intensive studies of productivity on traditional fishing grounds have elicited continuing interest in the problems of sampling zooplankton since HENSEN

| J. Cons. perm. int. Explor. Mer | 32 | No. 2 | 232–48 | Copenhague, Novembre 1968 |

initiated quantitative plankton sampling in the 1890's. The problem of clogging is inherent in the process of sampling plankton and remains to be fully evaluated. This paper reports a study of clogging rates in tests of design variables of plankton nets, such as mesh size, filtering area, and net form, under differing field conditions.

HENSEN (1895) carried out filtering experiments on silk meshes of several sizes to determine the amount of filtering area required to allow water to pass efficiently into the net. Although he recognized that clogging of the mesh apertures reduced filtration, he reasoned that "... in the worst cases not more than 5% of the net could be affected and usually much less ..." (p. 101). KOFOID (1897) demonstrated the importance of clogging under certain conditions. REIGHARD (1897) suggested that the problem of estimating the volume filtered could be most simply solved by installing a flow meter in the mouth of the net.

LANGFORD (1953) emphasized that even though the total volume filtered could be closely estimated, the tow did not equally represent all parts of the water column through which the net was drawn if clogging occurred during the tow. During calibration trials, YENTSCH and DUXBURY (1956) noted that the flow meter of a CLARKE-BUMPUS sampler filtering lake water stopped after 4 to 8 minutes with mesh aperture widths of 0·07 mm and after 15 minutes with a 0·12 mm aperture net. TRANTER and HERON (1965) found that the filtration efficiency of the Australian modification of the CLARKE-BUMPUS sampler decreased from 75% to 45% in 10 successive tows of 17 m in a hydraulic test channel.

In addition to causing misrepresentation of the water column, progressive clogging has two secondary effects on the accuracy of sampling. First, clogging some mesh apertures increases pressure from the inside to the outside of the net through the remaining open apertures. HENSEN (1895) said that this pressure increased the probability of the extrusion of small or soft-bodied organisms. Second, as clogging proceeds, the impermeability of parts of the net forces water to bypass the net mouth. Partial rejection of water by a net propagates a turbulent front of water ahead of the net which may be detected by zooplankters (FLEMINGER and CLUTTER, 1965). The rate of clogging may be expected to change regionally and seasonally and thus make more variable the errors caused by avoidance, the loss of organisms through the meshes and misrepresentation of the water column.

METHODS

The tests reported here were conducted from the R.V. "Black Douglas" of the California Current Resources Laboratory of the Bureau of Commercial Fisheries, La Jolla, California, at the following sites: just offshore of the breakwater at San Pedro, California (33° 45′ N, 118° 15′ W), 8.–9. October ("San Pedro I") and 13.–14. October ("San Pedro II"); offshore from Santa Catalina Islands (33° 25′ N, 118° 20′ W), 10.–12. October 1965. The San Pedro and Catalina sites were selected for marked differences in water clarity. Secchi disc readings were taken with a newly painted white weight with a diameter of 30 cm. Several clarity estimates were made each day.

DEFINITION OF TERMS

Several terms are used in this report to describe plankton nets, their mesh and their filtration performance as follows:

1. *Mesh size*

The width of the mesh aperture in millimeters. The commonly used standard sieve numbers, manufacturers' grades, and meshes per inch or centimetre do not translate easily to mesh size and it is suggested that their use be discouraged.

2. *Mesh area*

The total area of the completed net, to include the mesh apertures and filaments (expressed in square metres).

3. *Porosity*

That fraction of the mesh area which is open. This can be determined by planimetry of photographs or drawings of mesh or, in the case of monofilament nylon meshes, by the equation:

$$1)\ B = \frac{a^2}{(a+f)^2}$$

B = Porosity
a = Aperture width, and
f = Diameter of the filament

4. *Filtering area*

The product of porosity times mesh area (expressed in square metres).

5. *Filtering area ratio*

The ratio of filtering area to mouth area calculated by the following equation:

$$2)\ R = \frac{\text{filtering area}}{\text{mouth area}}$$

6. *Filtration efficiency*

The percentage of the water encountered which is filtered after passing through the mouth of the net. It is determined by the equation:

$$3)\ F = \frac{\text{Volume of water filtered}}{\text{Volume of water encountered}} \times 100$$

In practice this value is determined indirectly by comparing the velocities inside and outside the mouth of the net. The term is the reciprocal of filtration coefficient (HENSEN, 1895).

In every test, two nets with a mouth diameter of 1 m were mounted, one at each side of a 1 × 3 m rectangular steel frame. Nets 4 and 7 (Table 1) are similar in dimensions to a net described by AHLSTROM (1948, Figure 4). Net 4 had a mesh size of 0·333 mm nylon (NITEX*), and net 7 had a mesh size of 0·550 mm silk mesh (AHLSTROM, 1954). The silk net has been the "standard" net in surveys made by the California Cooperative Oceanic Fisheries Investigations (CalCOF I) since the beginning of the work in 1949 (Marine Research Committee, 1955). The 0·333 mm nylon net was chosen as a reference net for

TABLE 1. Description of plankton nets tested for clogging rate

Net #	Form	Mesh material	Mesh size (mm)	Porosity	Filtering area (m^2)	R^1	Total length (m)
1	Cone	Nylon	0·333	0·46	2·50	3·2	3·1
2	Cone	Nylon	0·333	0·46	3·75	4·8	4·7
3	Cylinder-cone	Nylon	0·333	0·46	2·50	3·2	2·5
4[2]	Cylinder-cone	Nylon	0·333	0·46	3·75	4·8	3·8
5	Cylinder-cone	Nylon	0·333	0·46	5·00	6·4	5·1
6	Cylinder-cone	Nylon	0·571	0·49	3·75	4·8	3·6
7[3]	Cylinder-cone	Silk	0·550	0·36	2·50	3·2	3·3
8	Cylinder-cone	Silk	0·550	0·36	3·75	4·8	4·9
9	Cylinder-cone	Silk	0·450	0·34	3·75	4·8	5·2
10	Cylinder	Nylon	0·333	0·46	1·25	1·6	1·4
11	Cylinder	Nylon	0·333	0·46	2·50	3·2	2·2
12	Cylinder	Nylon	0·333	0·46	3·75	4·8	3·1
13	Cylinder	Nylon	0·333	0·46	5·00	6·4	4·0
14	Cylinder	Nylon	0·201	0·43	5·00	6·4	4·2
15	Cylinder	Nylon	0·101	0·36	5·00	6·4	4·9
16	Cylinder	Silk	0·550	0·36	5·00	6·4	4·9

[1] $R = \frac{\text{Filtering Area}}{\text{Mouth Area}}$

[2] Nylon in CalCOF I net form.

[3] Standard CalCOF I net.

clogging because this mesh size had been recommended as an interim standard net (Biological Methods Panel Committee on Oceanography, 1964). The other 14 nets were designed specifically to test the effects of different mesh sizes, filtering areas and net forms on the rate of clogging and the duration of efficient filtration.

Three net forms were tested: cone, cylinder-cone and cylinder. Each cone net tapered evenly from a mouth of 1 m diameter to its cod end. Each cylinder-cone net had an anterior cylinder with a diameter of 1 m, which contained 40% of the total filtering area, followed by a cone tapering to the cod end. The cylinder nets had all their mesh in the cylinder which was followed by a short nonfiltering cone made of dacron sailcloth tapering to its cod end. All cod ends had a diameter of 0·10 m. All nets had dacron webbing 2·54 cm wide along their lengths to strengthen them. The cone and cylinder-cone nets had 8 longitudinal ribs; the cylinder nets had 9. Three ribs in the longest cylinder nets (13, 14, 15 and 16, Table 1) had a 2·3 mm cable sewn into the seams for additional support.

The filtering area of the standard CalCOF I net (7, Table 1) is about 2·5 m^2 which is 3·2 times the mouth area of 0·7854 m^2 ($R = 3·2$). A nylon net with a mesh size of 0·333 mm (net 4, Table 1) and with the same dimensions has 3·75 m^2 filtering area and an R of 4·8 times the mouth area. This is explained by the difference in porosity which is 0·46 for this nylon mesh size and is 0·36 for the silk mesh after shrinkage and use. In the design of the other 14 nets, the filtering areas were adjusted to 1·25, 2·50, 3·75 and 5·00 m^2 and R thus equalled 1·6, 3·2, 4·8 and 6·4. In addition to the 0·333 nylon and 0·550 mm silk meshes, tests were made with nylon meshes of three additional sizes, 0·101, 0·201, and 0·571 mm, and one silk net with a mesh size of 0·450 mm. The latter silk net was tested for clogging rate but as yet has not been used enough

TABLE 2. Water clarity estimates by Secchi Disc

Sites, Dates and Tows	Number	Secchi depth in metres		
		Maximum	Median	Minimum
San Pedro I 8. and 9. October Tows 1–14	15	6·5	4·5	3·5
Catalina 10., 11. and 12. October Tows 15–31	21	30	24	19
San Pedro II 13. and 14. October Tows 32–38	12	7·0	6·25	4·5

to permit comparison with nylon or shrunken silk. It is predicted that after more use, its mesh apertures will be reduced to a size approximately the same as that of the 0·333 mm nylon mesh. Water flow through each of the paired nets was monitored by a ducted flow meter (Marine Advisers model B-7) mounted 15 cm from the net rim and on the same plane as the rim. Unimpeded flow was measured by a similar meter mounted in the central open space between the two nets. Permanent magnets embedded in the margins of the 5 impeller blades, depressed a reed switch 5 times each revolution to complete a low voltage electrical circuit. The number of switch contacts in 10 seconds was simultaneously accumulated on an electronic event counter (HEWLETT-PACKARD, model 5211 b) for each of the three meters. The reading for each flow meter was converted to m/sec by calibration constants.

The instantaneous filtration efficiency (F_i) was calculated as a percentage by comparing the velocity of the water within or "accepted" at the net mouth (U_a) with the velocity of water at the free stream meter, *i.e.* "presented" to the net mouth (U_p) by the formula:

$$F_i = \frac{U_a}{U_p} 100$$

The volume of water accepted by the net (V_a) as well as the volume presented to the net (V_p) was estimated by the following formulas:

$$V_a = A\,(U_{a_1} t_1 + U_{a_2} t_2 + U_{a_3} t_3 + \ldots\ldots + U_{a_n} t_n) \qquad (3)$$

$$V_p = A\,(U_{p_1} t_1 + U_{p_2} t_2 + U_{p_3} t_3 + \ldots\ldots + U_{p_n} t_n) \qquad (4)$$

Where A is the area of the net mouth (0·7854 m^2 in this study), t is the time interval represented by a particular velocity reading, and n is the last velocity reading of interest.

The net was considered to be clogged when water acceptance fell, and remained, below 85%. Two measures of sustained filtration efficiency were calculated for these tests; 1) the time that filtration efficiency was 85% or more and, 2) the volume of water which had been filtered at 85% or greater efficiency. The filtration efficiency of all nets but one initially was greater than 85% and ranged as high as 95%. One net (10, Table 1) was designed to be less efficient than 85% by constructing it with an R of 1·6.

Cable length needed for telemetry restricted tows to the upper 10 m of water, but the nets were always below and outside the turbulent influence of the ship's wake. Mean towing speed was 1·13 ± 0·2 m/sec (2·2 ± 0·4 knots).

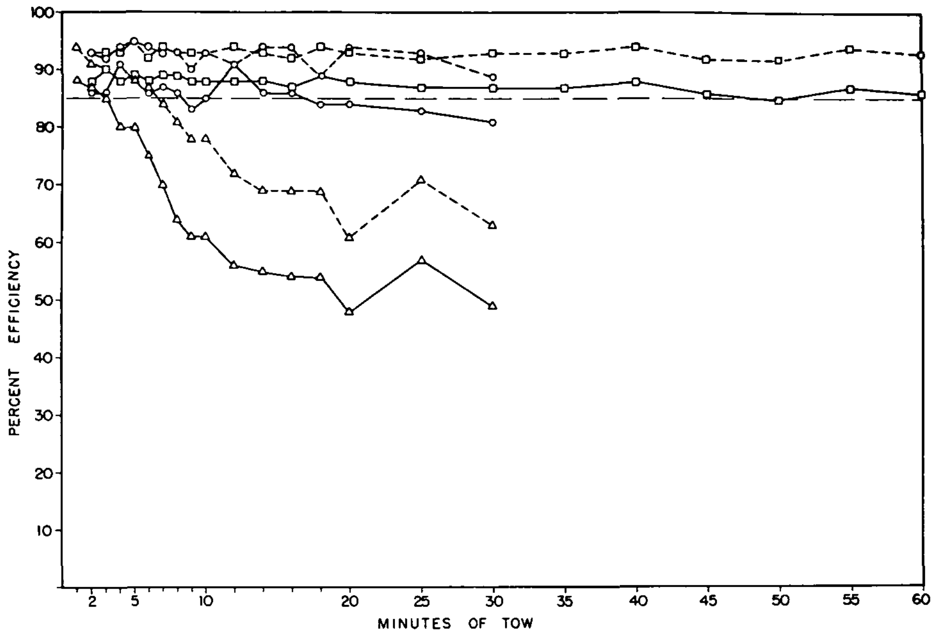

Figure 1. Net filtration efficiency – water clarity series. Three paired tows comparing two nets with 0·550 mm mesh aperture width, silk cylinder-cone. Nets number 7 (R = 3·2) and 8 (R = 4·8) (see Table 1) at three towing sites. Dashed line = efficiency criterion of 85 per cent. Triangle, Secchi depth 4·5 m, at San Pedro I, tow three, 8. October; square, Secchi depth 24 m at Catalina, tow 30, 12. October; circle, Secchi depth 6.25 m at San Pedro II, tow 32, 13. October. (See Tables 2 and 3).

FACTORS WHICH AFFECT CLOGGING RATE

Clogging rate was affected, in decreasing order of importance in these tests, by 1) the composition and density of suspended materials in the water, 2) mesh size, 3) the ratio (R) of filtering area to mouth area, and 4) the form of the net. Each of the nets designed for this study was clogged to a filtration efficiency below 85% and then returned to the initial efficiency by washing before each succeeding test.

THE EFFECT OF TOWING SITE ON CLOGGING RATE

Estimates of water clarity for the three test sites are summarized in Table 2. One pair of silk nets (7 and 8) was towed at the San Pedro I, Catalina and San Pedro II sites. In the relatively clear water off Catalina, neither of these nets clogged enough to lower filtration efficiency, even after being towed for 1 hour. At the San Pedro I site the silk net, 7, (R of 3·2) clogged in 4 minutes after filtering 194 m^3 water: the silk net, 8, (R of 4·8) clogged in 6 minutes after filtering 322 m^3 water. Five days later at San Pedro II net 7 clogged in 16 minutes after filtering 786 m^3 water and 8 had not yet clogged after filtering 1,465 m^3 water in 30 minutes (Figure 1).

Figure 2. Net filtration efficiency – mesh size series. Comparison of nylon cylinder nets, $R = 6 \cdot 4$, numbered 13, 14, and 15 (see Table 1).

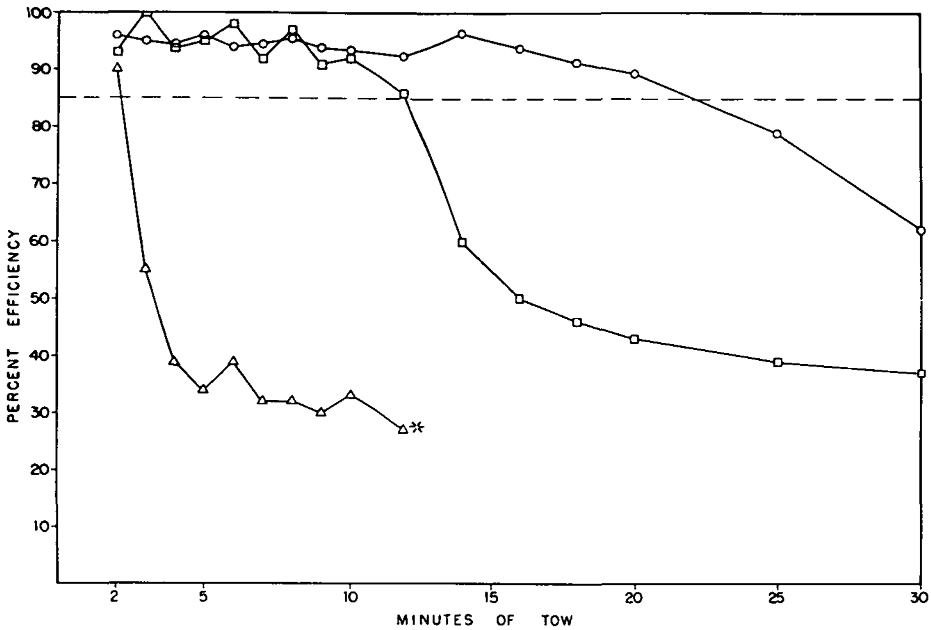

Figure 2A. Secchi depth 6·25 m at San Pedro, II 13. October (triangle, net number 15, 0·101 mm apertures, tow 36; square, net number 14, 0·201 mm apertures, tow 35; circle, net number 13, 0·333 mm apertures, combined results of tows 35 and 36).* Splitting of net number 15 prevented completion of the series.

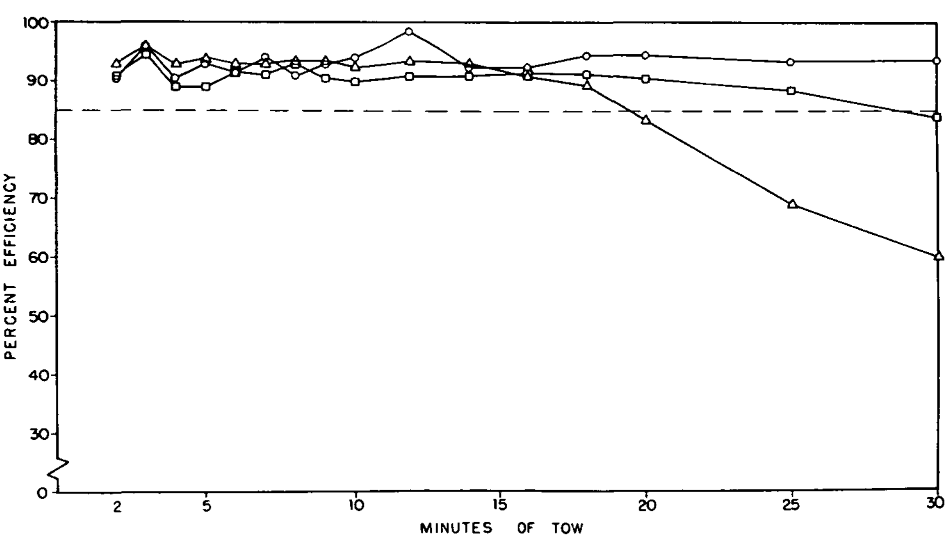

Figure 2B. Secchi depth 24 m at Catalina, 11. October (triangle, net number 15, 0·101 mm apertures, combined results of tows 23 and 25; square, net number 14, 0·201 mm apertures, combined results of tows 24 and 25; circle, net number 13, 0·333 mm apertures, combined results of tows 23 and 24).

Figure 3. Net filtration efficiency – mesh amount series. Comparison of nylon, cylinder-cone nets numbered 3, 4, and 5 (see Table 1).

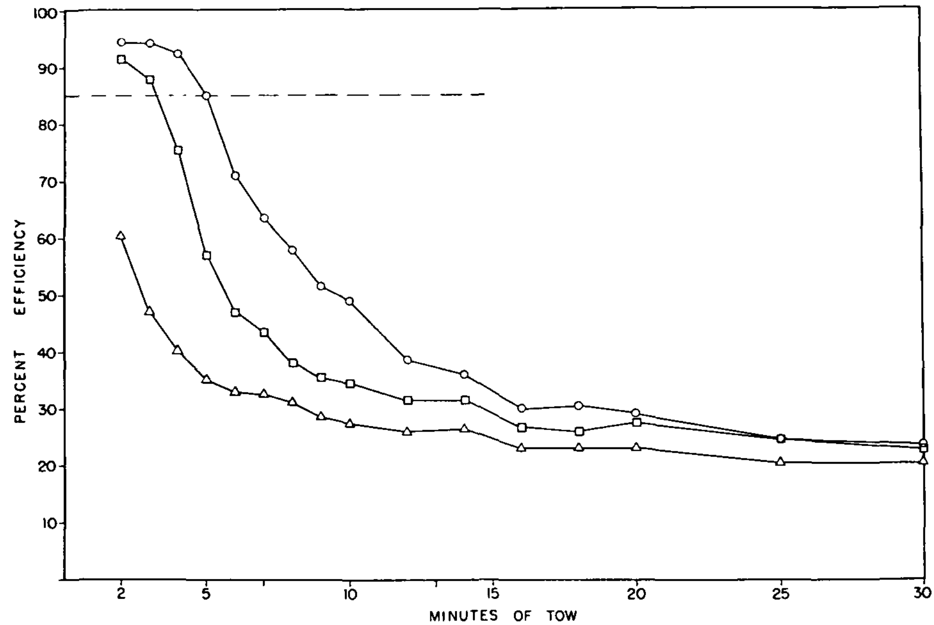

Figure 3A. Secchi depth 4·5 m at San Pedro I, 8. and 9. October (triangle, net number 3 $R = 3{\cdot}2$ combined results of tows 6 and 12; square, net number 4, $R = 4{\cdot}8$, combined results of tows 6 and 11; circle, net number 5, $R = 6{\cdot}4$, combined results of tows 11 and 12).

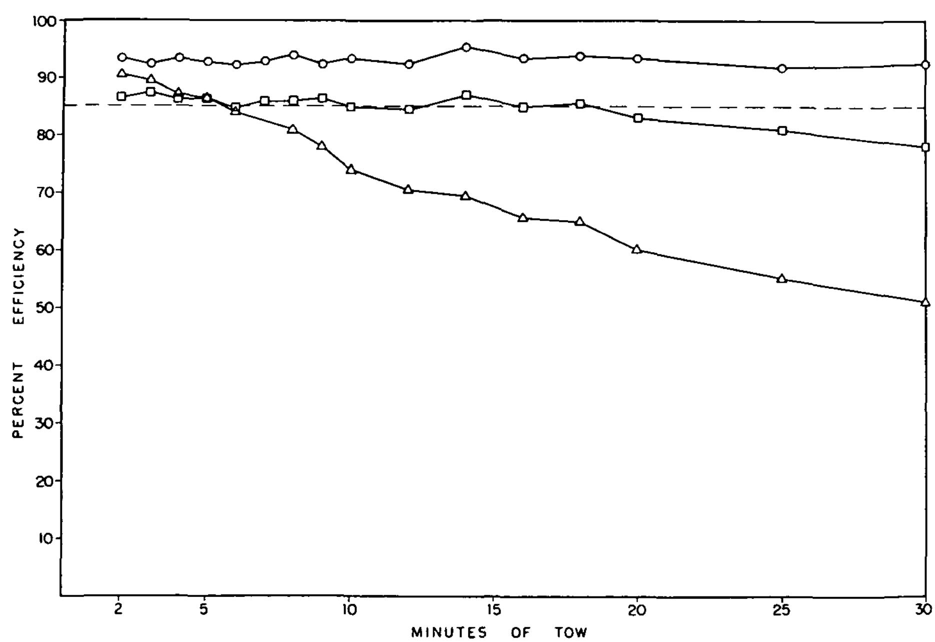

Figure 3B. Secchi depth 24 m at Catalina, October 10. and 11. (triangle, net number 3, $R = 3{\cdot}2$, combined results of tows 20 and 27; square, net number 4, $R = 4{\cdot}8$, combined results of tows 20 and 28; circle, net number 5, $R = 6{\cdot}4$, combined results of tows 27 and 28).

EFFECT OF MESH SIZE ON CLOGGING RATE

Fine mesh nets with comparable filtering areas, filter as well initially as nets with larger mesh sizes but clog more rapidly. Filtration efficiency versus time is shown in Figure 2 for three cylindrical form nylon nets, with mesh sizes of 0·101, 0·201 and 0·333 mm wide. Each net had an R of 6·4. In the turbid water off San Pedro II (Figure 2A) the 0·101 mm mesh net filtered at 90% efficiency for the first 2 minutes of tow and then clogged to less than 60% efficiency before the end of the third minute. The 0·201 mm net remained above 85% efficiency 12 minutes and then declined to 60% in the next 2 minutes. The 0·333 mm net retained high efficiency 20 minutes before declining to less than 85%. In the relatively clear water off Catalina Island (Figure 2B) all three nets maintained high efficiency for 18 minutes, after which the 0·101 mm net clogged to 83% at 20 minutes and the 0·201 mm net clogged to 84% at 30 minutes. The 0·333 mm net had better than 85% filtration efficiency during an hour of towing.

RELATION OF CLOGGING RATE TO FILTERING AREA

The period of efficient filtration is extended by the addition of filtering area to the net. Figure 3A and 3B show the results of three paired tows taken at each of two sites with nets of mesh size 0·333. The three nets had R's of 3·2, 4·8, and 6·4. To minimize the effects of small scale differences in clogging rate, each net was paired with each of the other nets in the series and the results for each net are the combination of two tows. The ratios of the volume of water filtered at greater than 85% were 1:2:4 at San Pedro I and 1:3:8 at Catalina for the three nets. Both ratios exceed the ratio of the filtering area in the nets (1:1½:2).

We attribute this effect to "self-cleaning" although we cannot determine whether the "cleaning" results from forcing clogging material through the apertures or its movement rearward inside the net. Figure 3A shows that the reserve mesh area of this form of net is inadequate for self-cleaning in extremely turbid waters. It should be noted that the 0·333 mm nets with an R of 6·4 in the A sections of Figures 2 and 3 are not comparable, even though both were at San Pedro, due to the different dates and clogging rates mentioned above.

EFFECT OF NET SHAPE ON FILTRATION EFFICIENCY

These tests showed that the conical net was inferior to the cylinder and cylinder-cone nets in the ability to maintain efficient filtration. The sustained-filtration relation between the cylinder and cylinder-cone nets was not established in these tests. At San Pedro the cylinder-cone filtered longer than the cylinder net (Figure 4A), but in the clear water off Catalina Island, the cylinder net filtered longer than the cylinder-cone net (Figure 4B). The ratio of volumes filtered above 85% efficiency through the cone, cylinder-cone and cylinder nets was 1:1·9:1·5 at San Pedro I and 1:2·0:3·9 at Catalina. In addition to the series in Figure 4 (R = 4·8), five other paired tows compared nets of different form with other aperture ratios (R = 3·2 and 6·4) in incomplete series. In the only comparison between cone and cylinder nets of (R = 3·2), both nets clogged before 2 minutes but the cylinder net filtered 6% more water above 85% efficiency. The cylinder net was lost during this tow (nets 1 and II, tow 4, Table 3). The cone and cylinder-cone nets (1 and 3) of (R = 3·2) were compared

Figure 4. Net filtration efficiency – form series. Comparison of 0·333 mm mesh aperture, $R = 4{\cdot}8$, nylon nets numbered 2, 4, and 12 (see Table 1).

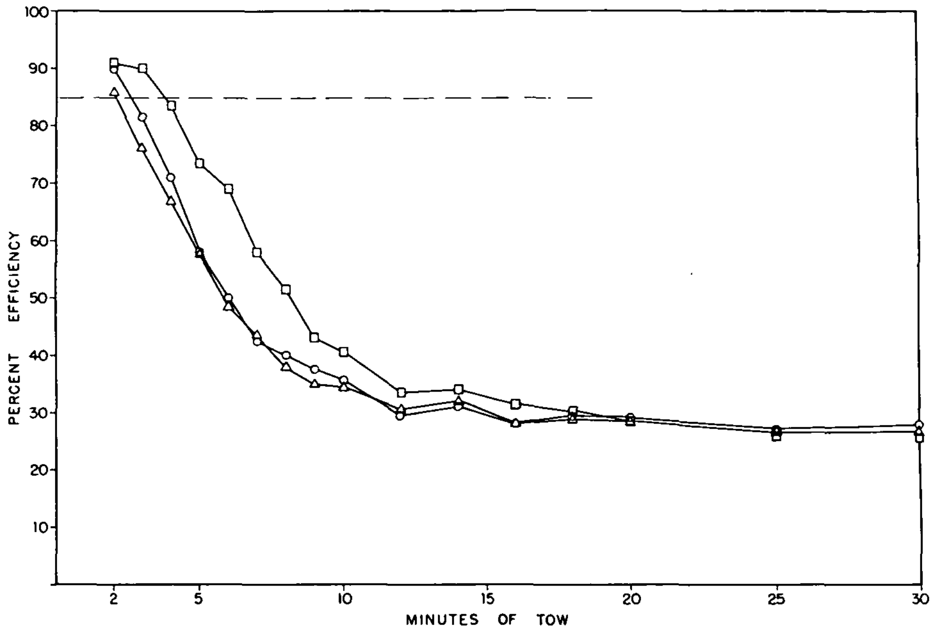

Figure 4 A. Secchi depth 4·5 m at San Pedro I, 9. October (triangle, net number 2, cone, combined results of tows 9 and 10; square, net number 4, cylinder-cone, combined results of tows 8 and 10; circle, net number 12, cylinder combined results of tows 8 and 9).

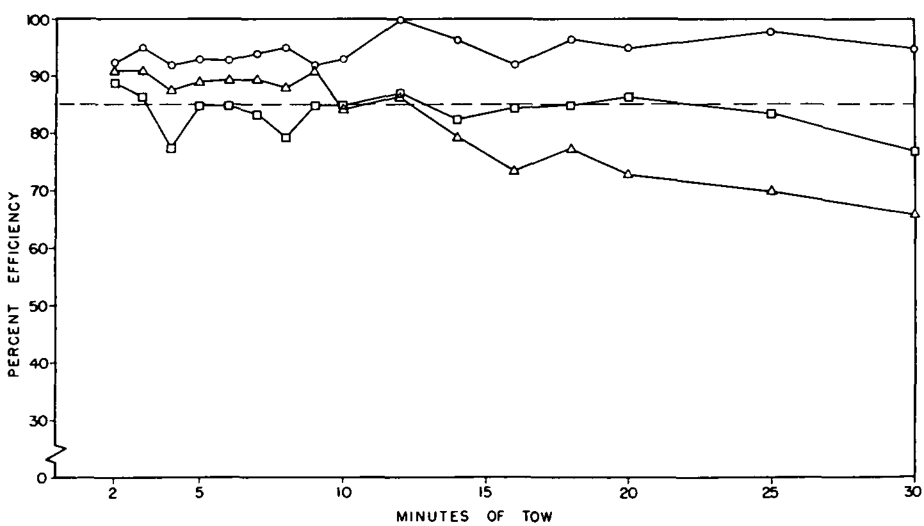

Figure 4 B. Secchi depth 24 m at Catalina, 10. October (triangle, net number 2, cone, combined results of tows 17 and 19; square, net number 4, cylinder-cone, combined results of tows 18 and 19; circle, net number 12, cylinder, combined results of tows 17 and 18).

TABLE 3. Summary of all paired tows

	Net		Site	Tow number	Volume[1] (m^3)	Time[2] (min)	Velocity (knots)
1.	3·2:1	0·333 mm Nylon Cone	San Pedro I	4	48	<2	2·6
				5	47	<2	2·4
				7	22	<2	1·9
			Catalina	21	87	<2	2·3
				22	137	3	2·2
2.	4·8:1	0·333 mm Nylon Cone	San Pedro I	7	79	3	1·9
				9	99	2	2·2
				10	88	2	2·1
			Catalina	17	459	9	1·8
				19	625	12	2·2
				22	542	10	2·2
3.	3·2:1	0·333 mm Nylon Cylinder-Cone	San Pedro I	5	49	<2	2·4
				6	43	<2	2·1
				12	65	2	2·1
			Catalina	20	292	5	2·1
				21	390	7	2·3
				27	441	8	2·3
4.	4·8:1	0·333 mm Nylon Cylinder-Cone	San Pedro I	1	121	3	2·1
				6	137	3	2·1
				8	123	3	2·0
				10	239	5	2·1
				11	115	3	1·9
			Catalina	18	1172	25	2·0
				19	962	20	2·2
				20	928	18	2·1
				28	1282	25	2·2
				29	1805	35	2·4
			San Pedro II	34	513	10	2·3
				38	600	10	2·6
5.	6·4:1	0·333 mm Nylon Cylinder-Cone	San Pedro I	11	178	5	1·9
				12	300	6	2·1
				13	375	8	1·9
			Catalina	26	2564	50	2·2
				27	>3188	>60	2·3
				28	2543	50	2·2
6.	4·8:1	0·571 mm Nylon Cylinder-Cone	San Pedro I	2	71	2	2·1
			Catalina	30	>3270	>60	2·2
			San Pedro II	33	1137	20	2·2
7.	3·2:1	0·550 mm Silk Cylinder-Cone	San Pedro I	3	194	4	2·2
			Catalina	31	>3210	>60	2·5
			San Pedro II	32	786	16	2·2
8.	4·8:1	0·550 mm Silk Cylinder-Cone	San Pedro I	2	317	7	2·1
				3	322	6	2·2
			Catalina	30	>3206	>60	2·2
				31	>3426	>60	2·5
			San Pedro II	32	>1465	>30	2·2
				33	>1456	>30	2·2
9.	4·8:1	0·450 mm Silk Cylinder-Cone	San Pedro I	1	238	5	2·1
			Catalina	29	>3069	>60	2·4
			San Pedro II	34	961	18	2·3
				38	1565	25	2·6
10.	1·6:1	0·333 mm Nylon Cylinder	Catalina	16	<61	<2	1·9
11.	3·2:1	0·333 mm Nylon Cylinder	San Pedro I	4	51	<2	2·6
12.	4·8:1	0·333 mm Nylon Cylinder	San Pedro I	8	103	3	2·0
				9	171	4	2·2
				14	88	2	2·1
			Catalina	15	1075	25	1·8
				16	>1331	>30	1·9
				17	2048	45	1·8
				18	2173	45	2·0

TABLE 3 (continued)

	Net	Site	Tow number	Volume[1] (m³)	Time[2] (min)	Velocity (knots)
13.	6·4:1 0·333 mm Nylon Cylinder	San Pedro I	13	558	12	1·9
			14	207	5	2·1
		Catalina	15	>2391	>60	1·8
			23	2436	45	2·3
			24	>3419	>60	2·5
			26	>3033	>60	2·2
		San Pedro II	35	1430	25	2·3
			36	>778	>14	2·6
			37	1194	20	2·4
14.	6·4:1 0·201 mm Nylon Cylinder	Catalina	24	1506	25	2·5
			25	1601	30	2·3
		San Pedro II	35	654	12	2·3
15.	6·4:1 0·101 mm Nylon Cylinder	Catalina	23	1011	18	2·3
			25	1134	20	2·3
		San Pedro II	36	95	2	2·6[3]
16.	6·4:1 0·550 mm Silk Cylinder	San Pedro II	37	>3294	>60	2·4

[1] Volume filtered at greater than 85% efficiency.
[2] Towing time before efficiency decreased to below 85% efficiency.
[3] Net damaged.

at the San Pedro I and Catalina sites. At San Pedro both clogged before 2 minutes at which time the cylinder-cone had filtered 4% more water than the cone (tow 5). At Catalina (tow 21) the cone filtered 87 m³ and the cylinder-cone filtered 390 m³ before clogging. In seven tows that included cone nets, this type clogged faster than any cylinder or cylinder-cone net with which it was paired. Two tows compared the cylinder-cone and cylinder nets of ($R = 6{\cdot}4$) (nets 5 and 13), one each at San Pedro I and Catalina. At San Pedro (tow 13) the cylinder-cone filtered 375 m³ and the cylinder 558 m³ before clogging. At Catalina the cylinder-cone filtered 2,564 m³ before clogging and the cylinder net had not yet clogged after filtering 3,033 m³ in 1 hour (tow 26). The cylinder filtered more water than the cylinder-cone before clogging in three of the four direct comparisons.

COMPARISON OF NETTING MATERIAL – SILK VS NYLON

Although comparisons of nets made of silk and nylon are recorded in Table 3, the results are not considered conclusive. The 40 XXX silk grit gauze had not yet shrunk to the size of 0·333 mm nylon mesh at the completion of the tests. Three comparisons were made between the 0·571 mm nylon net (6) and the 0·550 mm silk (8) net at the San Pedro I, Catalina and San Pedro II towing sites. At San Pedro I, the nylon net filtered 71 m³ in the 2 minutes before it clogged (tow 2). At Catalina, neither net had clogged at the end of a 1 hour tow (tow 30). At San Pedro II, the nylon net clogged after filtering 1,137 m³ in 20 minutes but the silk net had not yet clogged at the end of the 30 minute tow after having filtered 1,456 m³ (tow 33). These data indicate three possible explanations of the apparent superiority of silk in resistance to clogging; 1) silk mesh is "self-cleaning" at a higher rate, 2) the greater variability in sizes of silk apertures causes the clogging rate to be slower, or 3) the apertures in the silk mesh may be larger under tow than they are when examined under a miscroscope, thus making the comparison with nylon mesh inappropriate.

TABLE 4. Median performance values for all nets at all sites

Net number	R^1	Mesh size (mm)	Mesh material	Net form	Initial efficiency percentage	San Pedro I[2] Volume (m^3)	San Pedro I[2] Time (min)	Catalina Volume (m^3)	Catalina Time (min)	San Pedro II Volume (m^3)	San Pedro II Time (min)
1	3·2	0·333	nylon	cone	92	47	2	112	2	–	–
2	4·8	0·333	nylon	cone	91	88	2	542	10	–	–
3	3·2	0·333	nylon	cylinder-cone	91	49	2	390	7	–	–
4	4·8	0·333	nylon	cylinder-cone	89[3]	123	3	1172	25	557	10
5	6·4	0·333	nylon	cylinder-cone	92	300	6	2564	50	–	–
6	4·8	0·571	nylon	cylinder-cone	94	71	2	3270	60	1137	20
7	3·2	0·550	silk	cylinder-cone	87[3]	194	4	3210	60	786	16
8	4·8	0·550	silk	cylinder-cone	93	320	7	3316	60	1461	30
9	4·8	0·450	silk	cylinder-cone	94	238	5	3069	60	961	18
10	1·6	0·333	nylon	cylinder	71	–	–	61	2	–	–
11[4]	3·2	0·333	nylon	cylinder	85	51	2	–	–	–	–
12	4·8	0·333	nylon	cylinder	92	103	3	2048	45	–	–
13	6·4	0·333	nylon	cylinder	93	383	9	3033	60	1194	20
14	6·4	0·201	nylon	cylinder	92	–	–	1554	28	654	12
15[5]	6·4	0·101	nylon	cylinder	92	–	–	1073	19	95	2
16	6·4	0·550	silk	cylinder	94	–	–	–	–	3294	60

[1] R is the ratio of filtering area to mouth area.
[2] Volumes and times are those filtered before trend of efficiency went below 85%.
[3] Used net.
[4] Net lost after one tow.
[5] Net torn by high filtration pressure.

SUMMARY OF RESULTS

The towing time and volume filtered before clogging for all 38 paired tows are listed in Table 3 with the mean tow velocity for each. In addition to the direct comparisons of nets mentioned above, we have collated the median results of all tows by form, mesh size, and mesh amount at the three towing sites in Table 4. We have omitted the comparison of mesh material for the reasons stated above.

Our predetermined performance requirement was that a net 1·0 m diameter at the mouth must filter 500 m^3 at greater than 85% efficiency at 2·25 knots (116 cm/sec), to be acceptable for oblique survey tows. (This requirement represents a tow approximately 750 m long). By this standard, none of the nets was adequate for the turbid waters at San Pedro I. The 0·333 mm nylon mesh nets with an R of 3·2 were inadequate at all sites. All the other nets performed to standard in the Catalina tows (Table 4).

In the cylinder-cone nets of 0·333 mm mesh the volume filtered at more than 85% efficiency was increased six-fold by doubling the amount of mesh. This increase held at both the San Pedro I and Catalina sites. Figure 5 represents an attempt to estimate the amount of mesh necessary to sustain efficient filtration in waters like those at San Pedro I. The ordinate is the $\log_{10}$ of the volume filtered above 85% efficiency per square meter of mouth area and the abscissa is R. By extrapolation, an R of 7·8 would be necessary to filter 500 m^3 efficiently through a 1 m diameter ring net at San Pedro I. Interpolation of the Catalina curve would lead one to predict that an R of 3·5 would have been adequate there.

DESIGN CRITERIA FOR PLANKTON NETS

It is not possible to specify design criteria for plankton nets without knowing the specific research problem for which the nets are to be used. A primary

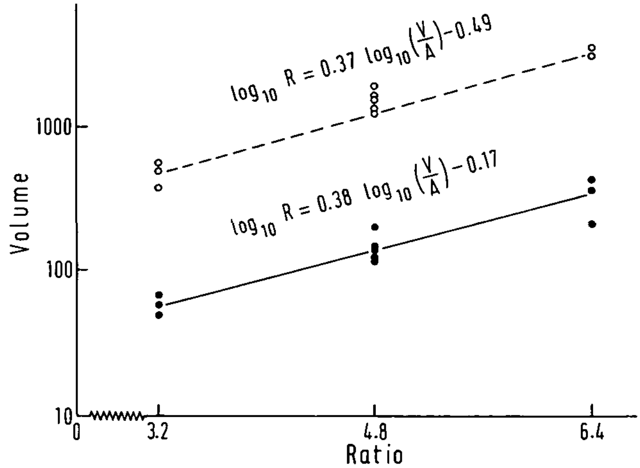

Figure 5. Sustained net performance and mesh amount. A comparison of the volume filtered per m^2 mouth area at greater than 85% efficiency at San Pedro I (solid dots) and Catalina (clear dots). (Net 3–3·2 times as much mesh aperture area as mouth area, tows 5, 6, 12, 20, 21, 27; net 4–4·8 times as much as mesh aperture area as mouth area, tows 1, 6, 8, 10, 11, 18, 19, 20, 28, 29; and, net 5–6·4 times as much mesh aperture area as mouth area, tows 11, 12, 13, 26, 27, 28). "Ratio" is the comparison of filtering area and mouth area; "Volume" is the logarithm of the cubic metres of water filtered per square metre of net mouth opening before clogging. The dashed line and the accompanying formula represent the median values of tows at the Catalina site (Secchi disc 24 m) and the solid line and the accompanying formula represent the median values for tows at the San Pedro I site.

design criterion for any quantitative plankton sampling net calls for sustained efficient filtration. Our results show that the most important design features in regard to sustained filtration efficiency are mesh size and filtering area. Changes in filtration efficiency during a tow affects the representation of the water column. It also affects the probability of capture of sensitive and motile organisms and the retention of the small and soft-bodied plankton.

It is necessary to have direct means of determining when significant clogging has occurred during a tow. We found that indirect means of judging whether clogging will take place, such as taking a Secchi disc reading, was not a suitable substitute for monitoring filtration efficiency. Inspection of the net after a tow was not reliable for determining whether it had clogged. After heavy clogging at San Pedro, the net was discolored but no indication of clogging appeared at the Catalina Island site, even when the net had been accepting less than half of the water presented to it at the end of the tow.

Ordinary flow meters (TSK or equivalent) mounted so that one is in the net mouth and one is isolated from the effects of the net and bridle, permit detection of significant clogging during the tow. If the flow rate can be telemetered to the ship, the instantaneous filtration efficiency can be obtained at any time during the tow as it was in this study.

This experiment was not extensive enough to define precisely the relation between mesh aperture size and clogging rate. This relation undoubtedly varies with changes in the size and species composition of the plankton. The best approximation that can be deduced from the present data is that clogging rate is roughly an inverse linear function of the individual mesh aperture area if all other net dimensions are constant. For example, the individual mesh aperture areas of 0·550 mm wide silk, 0·333 mm nylon, 0·201 mm nylon and 0·101 mm nylon are 0·30 mm^2, 0·11 mm^2, 0·04 mm^2 and 0·01 mm^2, respectively. At San Pedro II (Table 3) these nets filtered 3294, 1194, 654, and 95 m^3 before clogging.

One must determine carefully the minimum size of organism to be retained in designing a plankton net which will maintain high filtration efficiency over the entire course of the tow. SAVILLE (1959), in laboratory and field studies, demonstrated the size of silk mesh necessary for retention of fish eggs, fish larvae and crustaceans. It appears from his data that the maximum cross-sectional diameter of an organism must be greater than the diagonal of the mesh if it is to be retained. For the 0·550 mm silk and the 0·333 mm, 0·201 mm, and 0·101 mm nylon used in this study the diagonals are 0·78 mm, 0·47 mm, 0·28 mm and 0·14 mm respectively. Very few organisms having the same maximum cross-sectional diameter as the mesh *width* are retained.

One must have an estimate of the volume to be filtered and the clogging to be encountered before determining the ratio of filtering area to mouth area (R). Our tests show that the initial filtration efficiency is more than 85% whenever R is greater than 3·2. To this filtering area, which furnishes a high initial efficiency, must be added a reserve of mesh so that high efficiency can be maintained over the whole tow. To estimate the amount of reserve filtering area needed to sustain efficient filtration in conditions like those at San Pedro and Catalina, we have used the equations for the lines fitted in Figure 5, for 0·333 mm nylon mesh. For the "green" water at San Pedro the equation is:

$$\log_{10} R = 0{\cdot}38 \log_{10}\left(\frac{V}{A}\right) - 0{\cdot}17 \qquad (5)$$

and for the "blue" water off Catalina Island the equation is:

$$\log_{10} R = 0{\cdot}37 \log_{10}\left(\frac{V}{A}\right) - 0{\cdot}49 \qquad (6)$$

Where

R = the ratio of filtering area to mouth area;
A = the mouth area of the net in m^2; and,
V = the volume to be filtered in m^3.

Nets of similar proportions should be useful in any mouth size; only the volumes to be filtered need to be changed. For instance, Figure 6 illustrates net designs with a mouth diameter of 1 m. To convert these designs to a 5-in. CLARKE-BUMPUS sampler, the designated volume must change according to the proportionate mouth areas. For example, the 500 m^3 volume through the 1 m diameter net is similar to 8 m^3 through a CLARKE-BUMPUS sampler.

We have found that the cylinder-cone net is preferable to either the cylinder or cone nets. The cylinder net was difficult to tow and recover. These tests show that all net forms had some degree of self-cleaning. The conical net was the least effective in this regard. We think that the cylindrical mesh has the greatest self-cleaning potential because it is aligned with the direction of the tow and is not subjected to the direct force of water impinging on the mesh as on any part of a cone. Furthermore, the mesh wall of the cylinder net oscillated. This oscillation induces a fluctuation of pressure across the mesh, which we

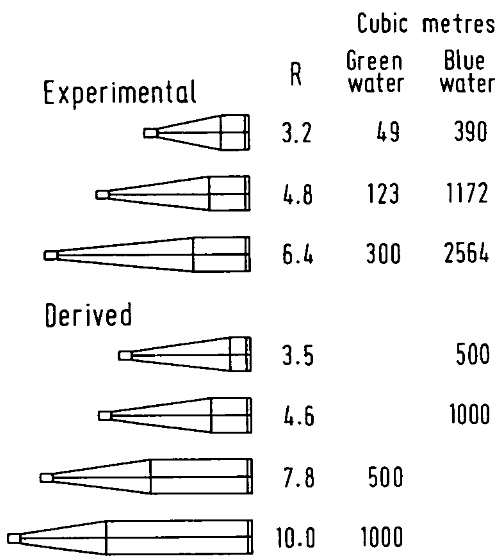

Figure 6. Net Design.

The upper section represents the proportions of the nets used in this study with 1 m diameter and 0·333 mm mesh size and the median values of the volume filtered at greater than 85% efficiency at the San Pedro I ("green water") and the Catalina ("blue water") towing sites. The lower section represents the interpolations and extrapolations of the "blue" and "green" formulas to provide ample filtering area in 1 m diameter nets to filter 500 m^3 and 1000 m^3 of water at greater than 85% efficiency at these towing sites. The derived net dimensions incorporate the recommendations of this paper that the conical section of the net contains an *R* of 3 and that the reserve filtering area be added in a forward cylinder.

believe to be responsible for the higher rate of self-cleaning. Since a net which is totally conical is inferior for sustained high filtration efficiency and a net which is totally cylindrical is unwieldy, we recommend design and use of a cylinder-cone net with a terminal conical section having an *R* of 3 and an anterior cylindrical section with enough reserve filtering area to sustain high filtration efficiency.

As an example of our approach to the design of a plankton net we describe the procedure by which we designed a net to sample the eggs of the northern anchovy (*Engraulis mordax*). The eggs are cylindrical with rounded ends with an average width of 0·65 mm. It was known that most of these eggs passed through or were extruded from the standard CalCOFI net whose mesh apertures have an opening 0·550 mm across and 0·78 mm on the diagonal. In operation, the new net was to be towed side by side with the standard net whose length of tow is fixed at about 14·5 minutes. The mesh size and *R* remained to be determined.

The mesh size of 0·333 mm was selected because the diagonal of 0·47 mm would retain anchovy eggs. It was decided that a mouth diameter of 0·5 m (0·2 m^2 mouth area) would obtain a sample containing a sufficient number of the eggs from 125 m^3 of water. Because some of the stations on each survey cruise are in inshore water where conditions are similar to those at San Pedro we decided to build the net with an R as determined by the "green" water formula (5):

$$\mathrm{Log}_{10} R = 0{\cdot}38 \log_{10}(125/0{\cdot}2) - 0{\cdot}17$$

The net constructed had 7·8 times as much filtering area as mouth area. The porosity of 0·333 mm monofilament Nitex* nylon is 0·46 thus the combined area of the mesh panels must total 3·39 m^2 (0·2 × 7·8/0·46). The terminal cone contained 1·30 m^2 of mesh (0·2 × 3/0·46) and the remainder was added anteriorly as a cylinder. The terminal cone was truncate, 1·36 m long The reserve mesh area was a cylinder with a radius of 25 cm and a length of 1·33 m.

The filtration performance of this net has been checked for more than 2,000 tows on 11 monthly survey cruises of the CalCOFI in 1966. This net accepts 95% of the water presented to it in all the types of water found in the California Current at all seasons.

REFERENCES

AHLSTROM, E. H., 1948. "A record of pilchard eggs and larvae collected during surveys made in 1939 to 1941". Spec. scient. Rep. U.S. Fish Wildl. Serv. Fisheries, (54) 76 pp.

AHLSTROM, E. H., 1954. "Distribution and abundance of egg and larval populations of the Pacific sardine". Fish. Bull., U.S., **56**: 84–140.

FLEMINGER, A. and R. I. CLUTTER, 1965. "Avoidance of towed nets by zooplankton". Limnol. Oceanogr., **10**: 96–104.

HENSEN, U., 1895. *Methodik der Untersuchungen. Ergebnisse der Plankton-Expedition der Humbolt-Stiftung*. Lipsius und Tischer, Kiel und Leipzig, 200 pp.

KOFOID, C. A., 1897. "On some important sources of error in the plankton method". Science, N.Y., **6**: 829–32.

LANGFORD, R. R., 1953. "Methods of plankton collection and a description of a new sampler". J. Fish. Res. Bd Can., **10**: 238–52.

MARINE RESEARCH COMMITTEE. 1955. Part 1: The Marine Research Committee, 1947–1955. Prog. Rep. Calif. coop. ocean. Fish. Invest., 52 pp. see p. 7–9.

BIOLOGICAL METHODS PANEL, COMMITTEE ON OCEANOGRAPHY, 1964. "Recommended interim procedures for measurements in biological oceanography". National Academy of Sciences – National Research Council, Washington, D.C., 23 pp.

REIGHARD, J. 1897. "Methods of plankton investigation in relation to practical problems". Bull. U.S. Fish. Commn, **17**: 169–75.

SAVILLE, A., 1959. "Mesh selection in plankton nets". J. Cons. perm. int. Explor. Mer, **23**: 192–201.

TRANTER, D. J. and A. C. HERON, 1965. "Filtration characteristics of Clarke-Bumpus samplers". Aust. J. mar. Freshw. Res., **16**: 281–91.

YENTSCH, C. S. and A. C. DUXBURY, 1956. "Some factors affecting the calibration number of the Clarke-Bumpus quantitative plankton sampler". Limnol. Oceanogr., **1**: 268–73.