SEWAGE TREATMENT PLANTS

BY

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. . . How dare
Your daintie nostrills (in so hot a season,
When every clerke eats artichokes, and peason,
Laxative lettuce, and such windie meate)
Tempt such a passage? when each privies seat
Is filled with buttock? And the walles doe sweate
Urine, and plaisters? when the noise doth beate
Upon your eares, of discords so un-sweet?
And out-cryes of the damned in the Fleet?
Ben Jonson: 'On the Famous Voyage'

Introduction

Disposal of waste from ships was discussed at the London conference of the UNO Intergovernmental Maritime Consultative Organization, (formerly IMCO, now IMO) in 1973. Seventy-nine States approved a Convention which was supposed to be implemented twelve months after being ratified by fifteen nations which registered between them at least 50% of the world's merchant shipping. The Convention is not yet in force.

Sewage regulations are included in Annex IV of the Convention and there has been some understandable confusion because a State may ratify the Convention as a whole but not Annex IV. Some nations have grown impatient with the delay in international agreement and among those which have unilaterally introduced regulations are Canada, Japan, Sweden, USSR, and USA. Other nations require effluent standards to be better than, or different from, those proposed by IMO and this has caused problems for visiting ships.

Long before 1973 however, MOD(N) had commissioned studies on 'hold' or 'treatment' plants. By then it was thought that biological treatment offered the best solution for ships of the Royal Navy and 'Biogest' plants began to appear. The Institute of Naval Medicine was concerned with testing the effluents from these units and became increasingly involved with the operational problems through Naval Medical Officers of Health.

This paper is a result of that experience and its objectives are to:

(*a*) outline the regulations in Annex IV of the Convention;

(*b*) review the R.N. experience with biological sewage treatment plants;

(*c*) briefly examine the options for the future and discuss the operational and logistic implications.

IMO Regulations

Annex IV of the Convention stipulates precisely to whom the regulations will apply and under what circumstances. Thus ships may discharge:

(*a*) Sewage that has been comminuted and disinfected by a system approved by the relevant administration, provided that the ship is at least 4 nautical miles from the nearest land.

(*b*) Sewage that has been treated by an approved and certified sewage treatment plant.

(*c*) Raw sewage, provided that the ship is at least 12 miles from land and is making at least 4 knots.

INM has noted some confusion over the term 'sewage system' in (*a*) and 'sewage treatment plant' as used in (*b*). The two are different but in practice few operators appear to be interested in systems which merely comminute and disinfect sewage and which can be used more than 4 miles from land. They would be suitable for passenger ferries but most navies have either developed plants which can discharge effluents of the required quality direct to controlled waters, or use Collect, Hold and Transfer (CHT) systems discharging to shore, to barges, or to sea beyond the 12 mile limit.

Annex IV also deals with the testing and certification of marine sewage treatment plants (STP) by the relevant administration which, in U.K., is the Department of Transport (DOT), formerly the Board of Trade. Guidelines for performance testing and the proposed effluent standards are published as minutes of the Marine Environmental Protection Committee of the IMO[1,2,3]

In summary, the testing procedures are concerned with:

(*a*) Standardization of influent under normal operational loads and flush waters.

(*b*) Duration of testing; the suggested minimum is for 10 days after steady state conditions are achieved.

(*c*) The parameters to be measured and their frequency; a minimum of 40 effluent samples are to be assayed in order to determine modal means and variance for the control parameters. There are also proposals for the recording of other indices which some States have asked to be included.

(*d*) The use, nature, and measurement of any disinfectants.

Under the defined conditions of testing and using accepted analytical procedures, the IMO standards for effluent from marine STP are:

(*a*) The geometric mean faecal coliform count of the sample should not exceed 2500 organisms/litre.

(*b*) The geometric mean suspended solids should not exceed 100 mg/l above the suspended solids content of the water used for flushing purposes.

(*c*) The geometric mean of the 5 day Biochemical Oxygen Demand (BOD_5) should not exceed 50 mg/l.

(*d*) If chlorine is used as a disinfectant, the residual should not exceed 5 mg/l as free available chlorine.

These performance tests and quality standards will be discussed with reference to the plants in R.N. ships.

Main Sewage Treatment Plants

The simplest option for ships would appear to be a CHT system but the main problems are the sheer bulk of material to be contained and the risk of putrefaction yielding toxic and inflammable gases. The U.S. Coast Guard estimates the average daily sewage flow aboard ship as 230 litres/man and storing this volume would be a major problem. This figure includes black water (human excreta) and grey water (laundry, wash waters) and it could be considerably reduced if the latter were diverted and the heads flush volumes diminished.

Treatment plants can be broadly divided into:

(*a*) Physico/mechanical units which include comminution, filtration, ultrasonic disintegration, and incineration.

(*b*) Chemical processes using acids, alkalis, hypochlorites, phenols, and other biocides.

(*c*) Biological processes which include degradation by the purified enzymes of micro-organisms.

Many commercial plants use a combination of these and the wide variety of designs suggests that the best system is not yet evolved. In the R.N. the emphasis has been on biological plants but others have also been tested. Unfortunately the term 'biological' is loosely applied and it is evident from manufacturers' literature and even technical papers that the biological degradation of sewage is not well understood. The means by which this is accomplished is fundamental to understanding the operational problems and is summarized below.

Biological Sewage Treatment Plants

Marine designs are based on the activated sludge principle used in shore stations for 60 years and a typical flow sheet is shown in FIG. 1. Raw sewage is delivered to the aeration chamber where biolysis of faecal matter is achieved by micro-organisms in the presence of oxygen delivered by air diffusers. After vigorous aeration the liquor is transferred to the settlement hopper where the activated sludge agglomerates and falls to the bottom of the tank. The processes which transform sewage are complex but in a properly operating plant should result in a floc which is a light brown precipitate that settles in its mother liquor leaving a clear, colourless, sparkling, odourless, supernatant liquid.

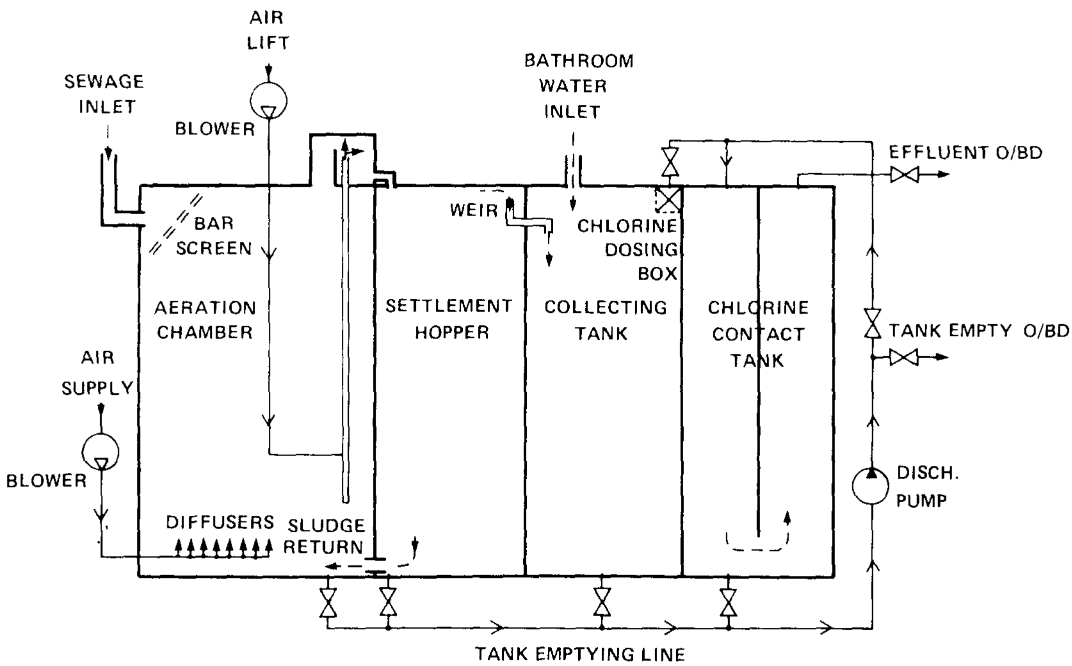

FIG. 1—TYPICAL BIOLOGICAL SEWAGE TREATMENT PLANT AS USED ASHORE

Periodically, some of the sludge is returned from the settling hopper to the aeration chamber and this helps to maintain biolysis. Liquid effluent overflows into the collecting tank where, in some plants, it is diluted with grey water before being chlorinated and discharged overboard.

In shore stations clear non-putrescible effluents are produced. Upwards of 90% of bacteria, viruses, and other pollutants including toxic metals are removed and in U.K. it is policy not to disinfect effluents by chlorination or other chemicals because excessive quantities of these cause considerable damage to the ecology of rivers, lakes, estuaries, and inshore fishing grounds. The principle does not work nearly so well in ships and apart from the large variations in load and the unavailability 'on demand' there are other factors which mitigate using these plants in warships. Before discussing these it is necessary to examine what happens to sewage if it is not aerated.

Anaerobic Degradation

Microscopically, fresh sewage contains many bacilli, cocci and filamentous bacteria. Fungi, algae, protozoa, and higher organisms are not ordinarily evident except as spores, cysts, or larvae. The little free oxygen is rapidly utilized and the sewage is said to have a biochemical demand for oxygen ranging from 300 to 10 000 mg/l depending on dilution. (For comparison, a clear mountain stream would have a BOD of less than 1 and even a highly industrialized river would be unlikely to consistently exceed 5 mg/l).

If sewage is inadequately oxygenated, putrefaction sets in. Anaerobic bacteria multiply and produce enzymes which attack protein to form urea and ammonia, foul-smelling mercaptans, hydrogen sulphide, and aromatic hydrocarbons. Carbohydrates are degraded to fatty acids, water, carbon dioxide, and methane, whilst fats and soaps are similarly attacked but at a slower rate. Black sediment appears, a greasy scum rises to the surface, and offensive odours are given off. Putrefaction is a slow process and although accelerated anaerobic digestion in reactors is being actively used in shore applications, it is highly dangerous in ships.

Aerobic Degradation

Lockett[4] is generally credited with the activated sludge process but it has been actively studied for the last 60 years. It was originally assumed that flocculation, clarification, and nitrification were carried out by bacterial enzymes but then it became apparent that the major difference between putrefacted and aerated sludge was the presence in the latter of large numbers of protozoa. In a series of papers[5,6,7,8,9] quoted by Sridhar and Pillai[10], these workers showed that it was only when certain species of protozoa were present in large numbers that a flocculent sludge formed and effluents became clear. In experiments in which they studied the effects of enzymes on raw sewage, activated sludge, and septic tank sludge they showed that the initial decomposition was due to bacterial activity but that the later oxidative changes were due to protozoa such as *Epistylis* and *Vorticella*. They also stressed that even under intensely aerobic conditions, bacteria have only limited ability to flocculate and oxidize organic matter.

In other laboratory studies[11] it was concluded that protozoa play a vital role in the process and that in their absence the plants produce turbid effluents containing large numbers of bacteria which are reduced by an inoculum of ciliated protozoa including *Opercularia*.

The ecology of the process and the design of plant was discussed in detail by Hawkes[12] and it is clear that the microbial population is specialized and has a relatively low diversity of species. At the basic level, bacteria and saprobic (feeding on dead material) protozoa dominate, but then come the holozoic protozoa (feeding on bacteria) and there may be low numbers of rotifers and nematode worms. Curds and Fey[13] confirmed that protozoa play the major role in the removal of *Escherichia coli* (intestinal bacteria) and Mishoe[14] emphasized the relative importance of both bacteria and protozoa in the purification process.

The latter author also stressed the importance of an adequate supply of oxygen. The generally accepted requirement for dissolved oxygen in effluent is 1 mg/l and Mishoe found that when the air diffusion rate was reduced from 150 to 55 m^3/kg BOD the values for dissolved oxygen fell to 0.1 mg/l or less. (The BOD of raw sewage varies but the average daily sewage produced by an individual gives rise to a BOD of 115 g and most of this is due to faeces). Under these conditions effluent soon resembled influent and microscopic examination of the sludge showed only bacteria and no protozoa, but when the air diffusion rate was again increased the effluent became sparkingly clear and numerous *Vorticella* were apparent.

Clearly then, the biological processes occurring in the aeration tank are complex and delicately balanced. They can be affected by change in the BOD of raw sewage, (which in turn is related to quantity and dilution), by the type of flushing water (fresh or sea), by temperature, pH, and the amount of daylight (the latter is absent in ship systems but has been shown to have an effect in shore plants), by the quantity of air diffused, and by the relative concentrations of bacteria and protozoa.

Biological Plants in H.M. Ships

Because of requests from Naval Medical Officers of Health and Marine Engineer Officers, INM has examined samples from activated sludge plants in R.N. ships over the past decade. Routine tests include pH, suspended solids, five day BOD, residual chlorine, and faecal coliform counts by standard methods[15] on spot samples of effluent. Sometimes it was possible to obtain serial samples over a few days but this is difficult to arrange in an operational ship with the plant under normal loads.

TABLE I—*BOD_5 and suspended solids in 250 effluent samples from activated sludge plants in 15 R.N. ships*

	BOD_5 mg/l	*Suspended Solids* mg/l
Mean	125	464
Geometric mean	105	220
Range*	10–420	5–3500

*excluding samples which appeared to be either raw sewage or flush water (see text).

TABLE I summarizes the results of BOD_5 and suspended solids on effluent samples from 15 ships. At least as many samples were rejected because they were either raw sewage ($BOD_5 > 500$ g/l, suspended solids > 5000 mg/l) or simply flush water. It was apparent from the comments made by engineers and Fleet Health Inspectors collecting these samples that most of the plants were anaerobic for long periods. Although some operators claimed that plants had worked for a few days this seemed to be because they were fed substances to 'keep the bugs alive' by manufacturers' agents. The *raison d'être* behind this seemed to be to achieve a continuous culture of bacteria and certainly some of the substances used, (dried milk, for example), would encourage the growth of certain species of bacteria. Much of the advice given seemed to be based on medical microbiology, and as has been shown above, bacteria are only one component of an extremely complex system. Feeding selective nutrients would therefore probably do more to unbalance the system than maintain it.

Because of these observations, arrangements were made for INM to carry out more detailed studies of the plants in a Type 42 destroyer and an aircraft carrier. Attempts were made to maintain the regimen of testing recommended by IMO, with INM staff working alongside ships' operators to collect 4-hourly samples for periods of ten days. There were mechanical problems in the Type 42 and operational commitments interrupted the carrier trial; nevertheless these were very useful studies because they allowed the observers to carry out macroscopic and microscopic examinations of the aeration tank contents under operating conditions. TABLE II presents the results of BOD_5 suspended solids and coliform counts on samples from each of the forward (110-man), midships (30-man) and after (220-man) STP in the Type 42. These results do not satisfy the IMO recommendations and it was noticeable that floc levels, although initially satisfactory in the forward plant, were generally low and there was little protozoal activity. The air diffusion rates seemed to be very low, there was a thick scum covering the surface of the aeration chambers, and the chlorination systems were malfunctioning.

TABLE II—*BOD_5 suspended solids and coliform counts in STP effluent from a Type 42*

		BOD_5 mg/l	*Susp. solids* mg/l	*Coliform counts* organisms/l
Fwd plant 44 samples	mean	177	345	1.97×10^8
	geom. mean	152	177	
	range	40–262	16–1205	4.5×10^6 to 1.8×10^9
Midships plant 44 samples	mean	45	136	1.29×10^7
	geom. mean	37	102	
	range	12–143	29–1049	1.1×10^7 to 3.7×10^8
After plant 44 samples	mean	141	599	5.10×10^7
	geom. mean	127	282	
	range	47–262	70–3584	1.5×10^6 to 1.3×10^8
IMO Regs	geom. mean of 40 samples	50	100	2.5×10^3

The results of the trial on the 600-man STP fitted in the carrier were not a great improvement although it was hoped that the larger size of the unit would help to maintain a steady state by dampening fluctuations in the aeration tank. The trial was in two phases, the first for 8 days while the ship was alongside, and the second for 6 days whilst the ship was carrying out trials. The results are in TABLE III. A cursory scan of this data might suggest that the plant was almost meeting IMO specifications with respect to effluent BOD and suspended solids, but when they are examined in greater detail it is apparent that the low results were obtained when less than one third of the complement were using the ships' heads. All the parameters exceeded the control limits when the plant was on normal loads and although

TABLE III—*BOD suspended solids and coliform counts in STP effluent from an aircraft carrier*

		BOD_5 mg/l	*Susp. solids* mg/l	*Coliform counts* organisms/l
Days 1 to 8 32 samples	mean	43	84	2.9×10^5
	geom. mean	34	63	
	range	3–106	6–243	2.8 to 30.0×10^5
Days 9 to 15 20 samples	mean	69	146	4.6×10^5
	geom. mean	50	120	
	range	1–234	8–239	6.0×10^3 to 2.4×10^6

the aeration seemed to be more efficient than that in the frigate, the protozoal activity was still low compared with that in samples from aeration units in shore activated sludge plants.

Summarizing these studies on biological plants in warships it is evident that there are several factors which affect their performance which have been insufficiently researched. Their effects can only be ascertained in pilot scale plant using conditions which pertain at sea and with laboratory resources readily available. (There is evidence, for example, that the inimical effects of sea water on microbes is different when tested with fresh sea water compared with sea water delivered to the laboratory). No such facilities are available within MOD at present and it is unsatisfactory that plant performance can only be assessed after installation in an operational ship.

Physico/Chemical Plants in H.M. Ships

In view of the difficulties in operating activated sludge plants some navies have turned to physico/chemical units. In these, coarse screens separate solids and the liquor is then either treated with a flocculant or passed through fine filters for further clarification before being disinfected and discharged overboard. Solids are retained whilst the ship is in restricted waters and then either dumped in the open sea or to shore facilities when opportunity arises.

Two plants of similar design have been tested, one in a survey ship, the other in a training ship; the results are presented in TABLE IV. These results were sufficiently consistent to suppose that if some mechanical improvements could be made to the filters, the plants could achieve the IMO standards. Moreover these units have the overriding advantage of being available 'on demand'. When, however, the plant fitted in the training ship was being evaluated for a D.O.T. Certificate, mechanical defects prevented the completion of the test and only the results of 8 samples analysed by an independent laboratory were received in INM. These are summarized in TABLE V and are evidently unsatisfactory.

Future Options

Assuming that some form of on board sewage treatment will be necessary, (although this is by no means agreed by many marine biologists), a number of other options are being examined. Electrocatalytic processes have not yet gained much recognition but appear to offer many advantages for shipboard use. In these, macerated sewage is pumped to a cell where salt water causes a flow of current between the electrodes. This oxidizes the solids and produces chlorine ions which, as hyperchlorite, disinfect the effluent. Sea water, which is a disadvantage in a biological system, is necessary in the catalytic process and the other advantages are that the chemical is produced within the plant, (eliminating the need for storage), the system does not need settling tanks, and it can be switched on and off as required.

Vacuum flush systems are being evaluated with the object of reducing the bulk of material to be processed. In these, excreta are introduced via reduced flow vacuum flush closets and transported to collection tanks under a negative pressure of 14 to 20″ Hg. The material may then be macerated, stored on board until conditions permit, aerated in a secondary biological system (especially if the reduced flush was fresh water), or even incinerated.

Health and Safety

Whichever system is fitted, there are certain precautions to be taken. If sewage is not inactivated and it is stored for more than a few hours it must be thoroughly aerated. A rough calculation indicates that as much as 1000 to 1500 m^3 air/day may be required to keep the waste from 100 men in an aerobic condition. Lardis and Geyer[16] studied the chemical processes during anaerobic digestion and list the potentially hazardous gases in TABLE VI.

TABLE IV—*BOD_5 and suspended solids in the effluent from two physico/chemical plants*

		BOD_5 mg/l		Suspended solids mg/l	
Survey ship 40 samples	mean geom. mean range	52 46 20–191	45* 42* 20–86*	147 124 23–599	125* 112* 23–292*
Training ship 40 samples	mean geom. mean range	60 57 17–99		85 66 12–410	

*results when 3 atypically high samples were excluded.

TABLE V—*BOD and suspended solids in 8 samples from the plant fitted in a training ship*

	BOD_5 mg/l	Susp. solids mg/l
Mean Range	248 36–470	61 45–87

TABLE VI—*Characteristics, threshold limit values (TLV)*[17]*, tentative short term exposure limits (TSTEL), and hazardous properties of the gases commonly associated with anaerobic degradation of sewage*

Gas	Formula	Threshold Odour p.p.m.	TLV p.p.m.	TSTEL p.p.m.	Remarks
Methane	CH_4	Odourless	None adopted		Flammable, explosive in air (5.5–14%). Asphyxiant, causes nausea, narcotic at 9%.
Hydrogen sulphide	H_2S	0.0011 rotten egs	0	15	Explosive in air (4.3–46%). Human toxicity, 0.07% for 2 minutes
Ammonia	NH_3	0.0037 sharp, pungent	25	35	Explosive in air. Human toxicity 0.01%
Hydrogen cyanide	HCN	Not known pungent, characteristic almond odour	10	15	Flammable in air. Human toxicity 150 p.p.m., death at 300 p.p.m.
Methyl mercaptan	CH_3SH	0.0001 rotten cabbage	0.5	0.5	Flammable in air, causes nausea, narcotic.
Ethyl mercaptan	C_2H_5SH	as for methyl mercaptan.			
Carbon dioxide	CO_2	Odourless	5000	15 000	Non flammable. High concentrations cause death by suffocation.
Carbon monoxide	CO	Odourless	50	400	Flammable, explosive in high concentrations. Human toxicity, prolonged exposure causes death.

In addition to gases, the potentially infective nature of stored sewage will need to be considered and the appropriate precautions taken. Microbes which are normal inhabitants of the gastro-intestinal tract may be dangerous when inhaled or when they infect cuts and abrasions. Forced ventilation systems may disperse such infected aerosols around the ship and both Medical Officers and Marine Engineer Officers need to be aware of the hazards, have monitoring facilities available, and take the appropriate precautions if spills occur.

STP operators and maintainers should wear protective clothing such as coveralls, rubber boots, and gloves. Masks should be worn when the plants are being cleaned, and CCBA may be required if there is any risk of the gases in TABLE VI being present. The usual precautions for entering closed spaces such as hold tanks are mandatory and there should be no open flames, flashlights, or other electrical apparatus in or near open tanks until they have been certified gas free.

Spaces which become contaminated with sewage should be thoroughly washed with detergent. Living areas and food storage spaces should also be disinfected. Contaminated bilges should be well flushed and bacteriological tests will be required on potable water tanks which may have become polluted.

Signs should be displayed in STP spaces warning operators not to consume beverages or food and to wash with soap and water on leaving the area. Protective clothing should be removed before entering mess spaces and laundered frequently. No special laundry precautions are necessary.

These guidelines may seem onerous but they are only commonsense hygiene practice. Accidents, including a few deaths, have occurred in the vicinity of STP and there is a high probability that one of the authors of this paper contracted an infection as a result of his work in a naval ship.

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References

1. IMCO Effluent standards and guidelines for performance tests for Sewage Treatment Plants; *Marine Environmental Protection Committee*—6th Session, June 1976 MEPC VI/9.
2. IMCO Form of certificate of type test for Sewage Treatment Plants. *Marine Environmental Protection Committee Circ.* 51 of July 1977.
3. IMCO Draft recommendation on guidelines for type testing and approval of Sewage Treatment Systems. *Marine Environmental Protection Committee*—16th Session, October 1981. XVI/12.
4. Ardern, E. and Lockett, W. T.: Experiments on oxidation of sewage without the aid of filters; *J. Soc. Industrial Chemistry*, 1914, vol. 33, pp. 523-528.
5. Pillai, S. C.: The function of protozoa in the activated sludge process; *Current Science,* 1941, vol. 10, pp. 84-85.
6. Pillai, S. C.: Further studies on the role of protozoa in the activated sludge process; *Current Science,* 1942, vol. 11, pp. 437-438.
7. Pillai, S. C.: The role of protozoa in the activated sludge process; *Indian medical Gazette,* 1942, vol. 77, pp. 118-120.
8. Pillai, S. C. and Subrahmanyan, V.: Role of protozoa in the activated sludge process; *Nature, London,* 1942, vol. 150, pp. 525.
9. Pillai, S. C. and Subrahmanyan, V.: Role of protozoa in the aerobic purification of sewage; *Nature, London,* 1944, vol. 154, pp. 179-180.

10. Sridhar, M. K. C. and Pillai, S. C.: An enzymic approach to the study of sewage and sludges; *Environmental Pollution* 1974, vol. 6, pp. 195-220.
11. Ministry of Technology, U.K.: *Notes on water pollution: protozoa in sewage treatment processes*: 1968, no 43.
12. Hawkes, H. A.: *The Ecology of Waste Water Treatment*; Pergammon Press, Oxford, 1963.
13. Curds, C. R. and Fey, G. J.: The effect of ciliated protozoa on the fate of *Escherichia coli* in the activated sludge process; *Water Resources,* 1969, vol. 3, p. 853.
14. Mishoe, G. L.: Active sludge plants are weird; *Highlights Water Pollution Control Federation,* 1972, vol. 9, pp. d6-d7.
15. *Standard methods for examination of water and wastewater.* 14th Ed, 1975; Published jointly by American Public Health Association, American Water Works Association, and the Water Pollution Control Federation.
16. Lardis, A. E. and Geyer, A. T.: *Biodegradation of shipboard waste water in collection, holding and transfer tanks*: David Taylor Naval Ship Research and Development Centre, Bethesda. DTNSRDC 78/041.
17. Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with intended changes for 1983/84; *American Conference of Governmental Industrial Hygienists,* 1983.